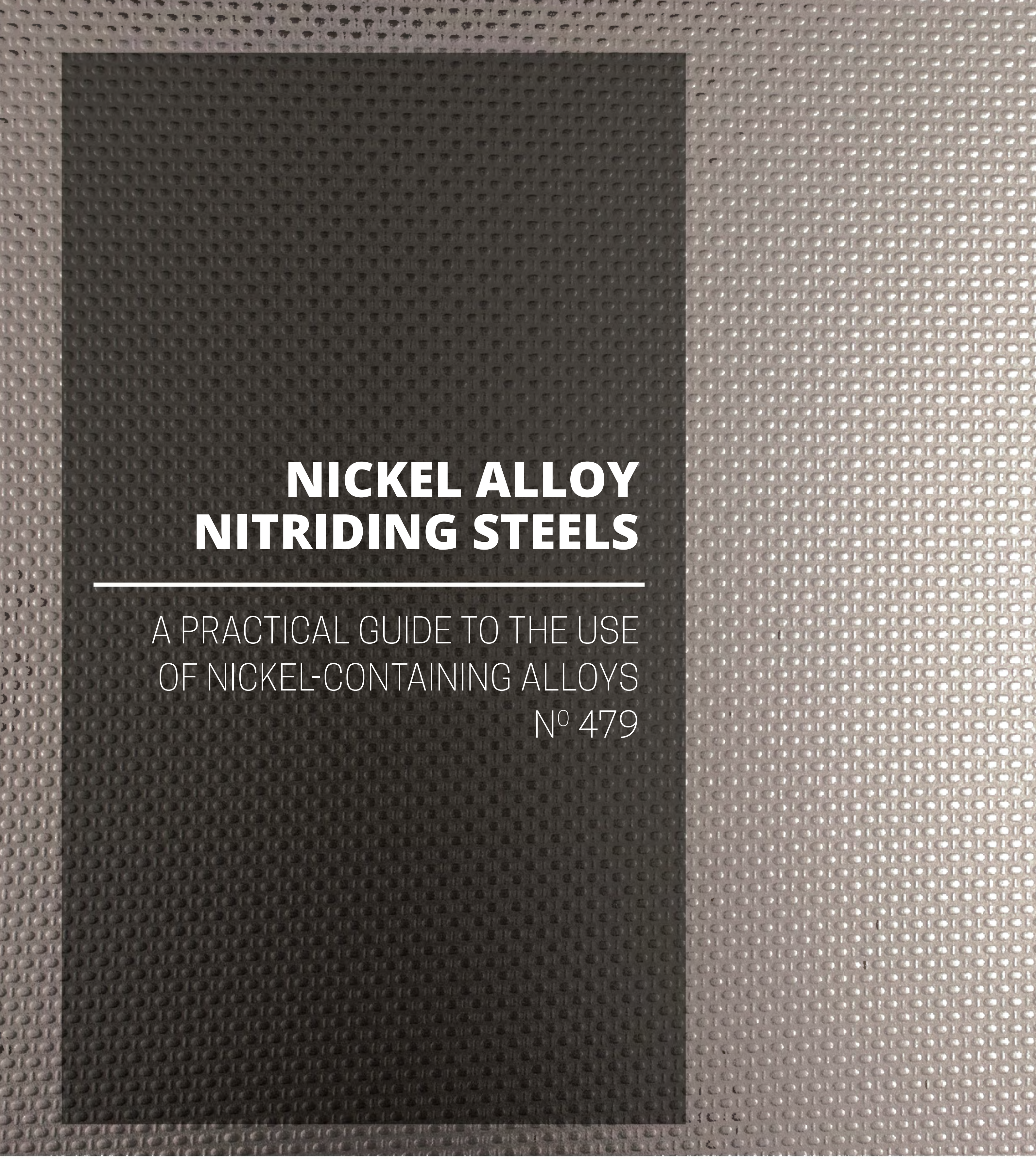

NICKEL ALLOY NITRIDING STEELS

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 479

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NICKEL ALLOY
NITRIDING STEELS

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[a] The AISI-SAE system for numbering steels is used if applicable.

[b] AISI-SAE Standard Steel, 1968 SAE Handbook.

[c] Aerospace Materials Specification.

[d] Tool steel designation of American Iron and Steel Institute.

Nickel Alloy Nitriding Steels

INTRODUCTION

This bulletin covers nickel-containing steels suitable for surface hardening by nitriding with gaseous or liquid media.[1,2] The nickel alloy nitriding steels fall into two general classes:

1. Compositions that were developed primarily for nitriding and that contain aluminum as one of the alloying elements.

2. Alloy constructional or tool and die compositions that are not alloyed specifically for nitriding, but that are sometimes surface hardened by this process.

The bulletin deals with the mechanical and metallurgical properties of steels given typical nitriding treatments, but does not attempt to present details of the characteristics or control of the numerous commercial nitriding processes. Information of this type may be found in some of the references[1-10] at the end of this bulletin, or can be obtained from the manufacturers of nitriding equipment and materials.

Nickel alloy steels are nitrided to increase hardness, resistance to wear and galling, and to improve fatigue properties.[11,12] Nitrided cases are generally .005 to .020-inch thick, which is less than usually produced by other surface hardening methods. Consequently, the strength of the supporting core material becomes of particular importance in applications where components carry high compressive or bending stresses. The nickel nitriding steels containing aluminum develop higher core strengths than do nickel-free nitriding grades, because the nickel-aluminum steels age harden during the nitriding cycle to produce tensile strengths in the range of 160,000 to 200,000 psi. Nickel also increases the toughness of nitrided cases, as shown in Figure 1. Useful supplementary references are 13 and 14.

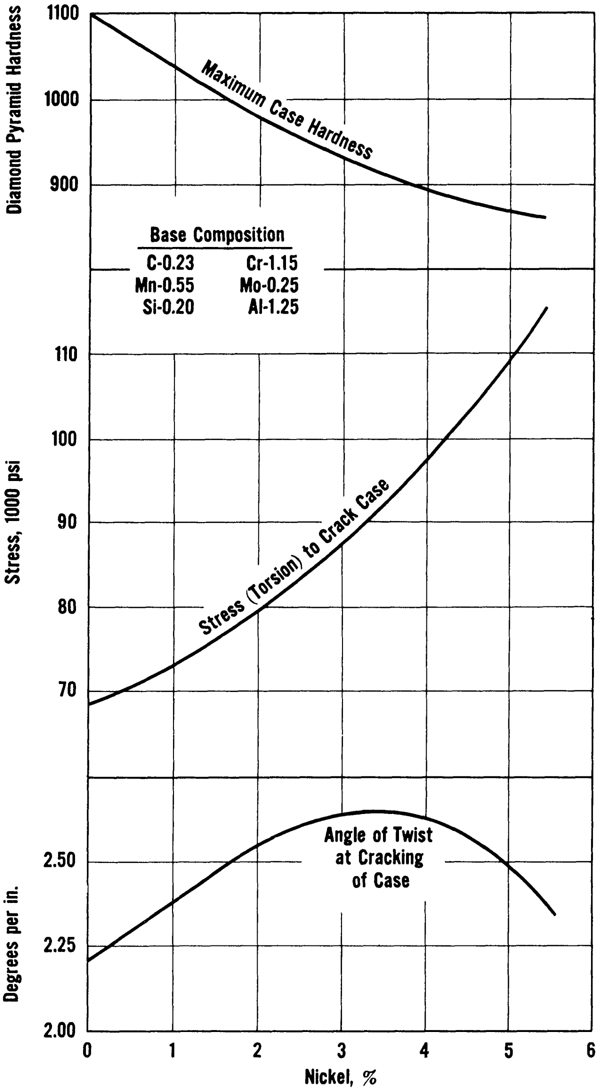


Fig. 1. Effect of nickel on the case properties of chromium-molybdenum-aluminum steels nitrided 48 hours at 975 F.

HEAT TREATMENT

One of the major advantages of the nitriding process over other methods of surface hardening is that final hardening is carried out at temperatures no higher than 1100 F. Therefore, the danger of distortion, inherent in case hardening methods requiring heating and quenching from much higher temperatures, is minimized and parts can be hardened after finish machining.

Steels to be nitrided are conditioned for machinability by quenching and tempering, usually to a hardness within the range 300 to 350 Brinell. The core strengths of the alloy constructional steels cannot be increased beyond the levels established by the prenitriding treatment and the additional tempering effects of the nitriding cycle. The nickel-aluminum steels, on the other hand, are conditioned equally for machinability by quenching and tempering, but final core strengths are increased substantially by the aging that occurs during nitriding. Figure 2 is a schematic representation of a typical heat-treating cycle for a nickel-aluminum steel. A stress relieving treatment at a temperature equivalent to or slightly below the original tempering temperature is often incorporated between rough and finish machining to maintain dimensional stability.

It should be noted that the nitriding process causes an increase in volume and, therefore, a dimensional growth. The growth is consistent for a given part and, thus, can be compensated for in machining operations. As a general guide, growth can be predicted to be about .0005 inch per inch of length and about .0015 inch per inch of diameter in solid rounds.

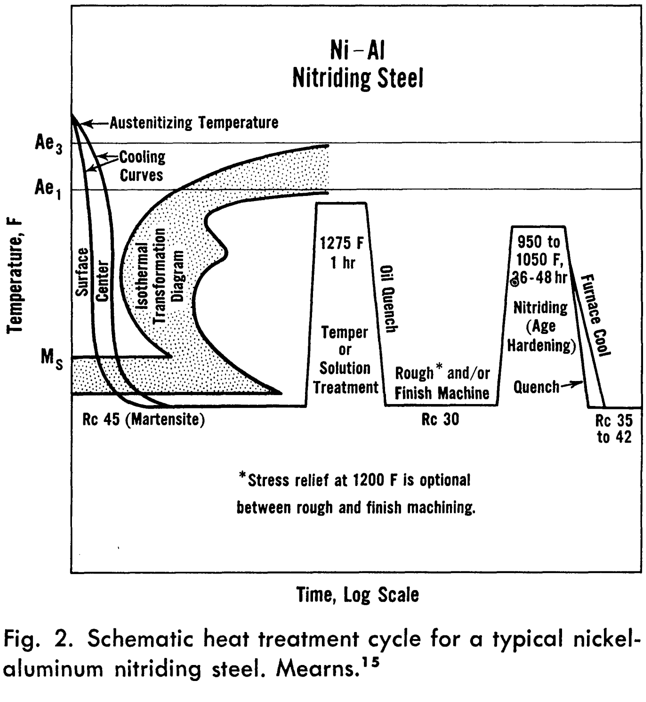


Fig. 2. Schematic heat treatment cycle for a typical nickel-aluminum nitriding steel. Mearns.[15]

NICKEL-ALUMINUM STEELS

3.5 Nickel-1.2 Aluminum (AMS 6475)

The optimum composition range, in weight per cent, of this nitriding steel is:

Carbon	0.21-0.26
Manganese	0.50-0.70
Silicon	0.20-0.40
Nickel	3.25-3.75
Chromium	1.00-1.25
Molybdenum	0.20-0.30
Aluminum	1.10-1.40

Core Properties

Representative mechanical properties of the core of the 3.5 nickel-1.2 aluminum nitriding steel are given in Table I for two conditions: before nitriding (solution treated) and pseudo-nitrided (solution treated and aged). Also, these typical properties are compared to the minimum properties required in AMS 6475. The heat treatment recommended for developing optimum properties in the core is:

Preliminary Treatment: Normalize 1700 F, austenitize 1650 F, oil quench.

Solution Treatment (temper): 1200 F, air cool or faster cooling rate.

Stress Relief (optional): 1200 F, air cool or faster cooling rate.

Aging (during nitriding): 975 F minimum, 10 hours or longer.

The 3.5 nickel-1.2 aluminum nitriding steel hardens during aging after any conditioning cycle ending with cooling at a moderately fast rate from 1200 F, or higher. However, maximum toughness in the age hardened

TABLE I

Typical Mechanical Properties of Core of 3.5 Nickel-1.2 Aluminum Nitriding Steel

Property	Before Nitriding[a]	Pseudo-Nitrided[b]	AMS 6475 (Aged)[c]
Tensile Strength, psi	132,000	180,000	165,000 min
Yield Strength, psi	115,000	170,000	120,000 min
Elongation (2 in.), %	22	16	13 min
Reduction of Area, %	59	50	40 min
Brinell Hardness	275	370	352-401
Rockwell C Hardness	29	41	—

[a] Oil quenched from 1650 F, solution treated (tempered) at 1200 F.

[b] Same as (a) plus aging at 975 F during pseudo nitriding for 20 to 48 hours.

[c] Same as (a) plus aging at 975 ± 10 F for 20 hours.

condition is achieved only if the preliminary treatment produces a martensitic structure containing little, if any, proeutectoid (free) ferrite. The formation of free ferrite, resulting from inefficient quenching or insufficient hardenability for the section, impairs the notch-impact properties of the age-hardened steel. Figure 3 shows a hardenability band based on five heats. Figure 4 shows the hardness of an end-quenched bar in three conditions:

1. As quenched.
2. As quenched and solution treated (tempered).
3. As quenched, solution treated (tempered) and aged (pseudo-nitrided).

Figure 5 shows that, for a heat on the low side of the hardenability band, air cooling of a bar with a diameter as small as 1-inch can result in low impact values. Positions in the end-quench bar at which the cooling rates are equivalent to those at the center of a 1-inch diameter bar oil quenched or air cooled are shown in Figures 3 and 4.

The core properties of the 3.5 nickel-1.2 aluminum nitriding steel are affected significantly by the duration and temperature of the nitriding cycle. Although this steel shows aging response in the range 900 to 1100 F, maximum core hardness is reached by nitriding at 975 F for a minimum of 15 hours, as shown in Figure 6. Extending the nitriding time at 975 F beyond 15 hours does not alter the core hardness appreciably, whereas extending the nitriding period at higher temperatures does make a significant difference. Effects of various

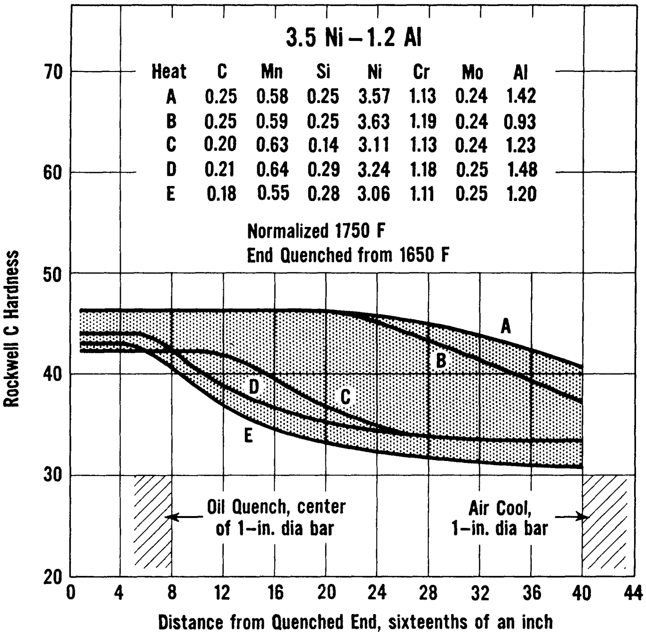


Fig. 3. End-quench hardenability band for 3.5 nickel-1.2 aluminum nitriding steel (based on five heats).

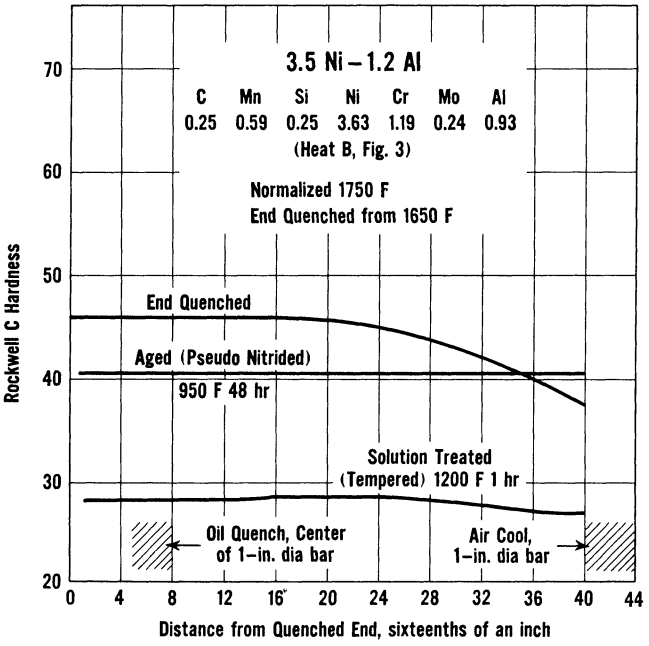


Fig. 4. Hardness of end-quench hardenability bar of 3.5 nickel-1.2 aluminum nitriding steel in three conditions.

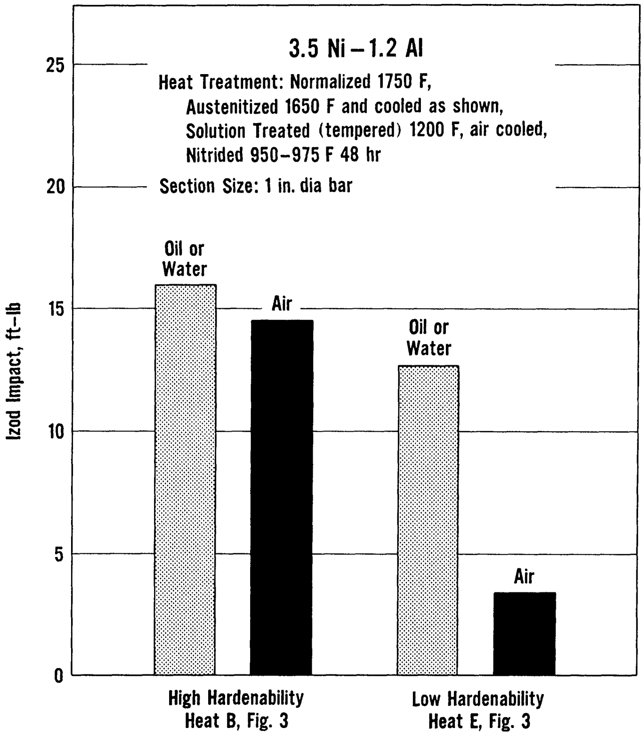


Fig. 5. Effect of hardenability and method of cooling from austenitizing temperature on notch toughness of core of 3.5 nickel-1.2 aluminum nitriding steel aged to Rockwell C 40 to 41 during nitriding.

nitriding cycles on the core hardness are shown in Table II. Increasing the nitriding temperature to 1000 F results in a considerable increase in notch-impact energy absorbed and a decrease in transition temperature, with only a moderate loss in hardness, as shown in Table III. Aging at higher temperatures after nitriding (overaging) also improves the impact properties but with a greater loss in core hardness, as shown in Table IV. The hot hardness at 600 F is 30 to 32 Rockwell C for this steel which has a hardness of 38 to 39 Rockwell C at 75 F, both after aging (pseudo-nitriding) at 975 F for four hours.

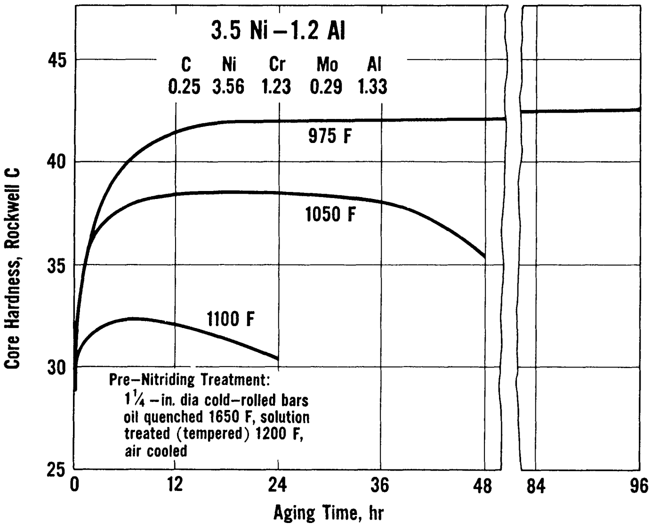


Fig. 6. Aging behavior of core of 3.5 nickel-1.2 aluminum nitriding steel during nitriding. Doble.[16]

TABLE II

Case Depth and Hardness of 3.5 Nickel-1.2 Aluminum Nitriding Steel after Various Nitriding Cycles

Nitriding Treatment[a]	Nitrided Case Depth, in.	Nitrided Case Rockwell 15-N Hardness	Core Rockwell C Hardness
Gas Nitrided			
975 F, 36 hr, 20-30% dissoc (1)	.012-.015	93-94	41
975 F, 48 hr, 20-30% dissoc (1)	.020-.025	93-94	41
950 F, 60 hr, 20-30% dissoc (2)	.030-.035	93	39
Pressure Nitrided			
1000 F, 4 hr, 800 psig (3)	.0055	94	—
1000 F, 15 hr, 800 psig (3)	.0095	94	35
1000 F, 45 hr, 800 psig (3)	.019	94	35
Floe Process			
975 F, 36 hr, 20% dissoc; 1025 F, 30 hr, 85% dissoc (1)	.012	90	38
975 F, 30 hr, 20% dissoc; 1050 F, 40 hr, 80% dissoc (1)	.027	89	34
1025 F, 6 hr, 20% dissoc; 1025 F, 30 hr, 80% dissoc (1)	.017	93	34

[a] Pre-Nitriding Treatments and Abbreviations:
(1) Quenched, tempered 1200 to 1250 F.
(2) Quenched, tempered 1100 F.
(3) Quenched, tempered.
dissoc = ammonia dissociation.
psig = pounds per square inch gage.

Case Properties

The 3.5 nickel-1.2 aluminum nitriding steel generally develops case hardnesses of 90 Rockwell 15-N or higher, depending somewhat on the nitriding cycle used. Representative hardness gradients through the case of this steel, gas nitrided at 975 F for 22, 35 and 48 hours, are shown in Figure 7. Additional data from other nitriding cycles are given in Table II.

TABLE III

Effect of Nitriding (Aging) Temperature on Impact Properties and Transition Temperature of Core of 3.5 Nickel-1.2 Aluminum Nitriding Steel[a]

48-Hour Nitriding (Aging) at Temp,[b] F	Rockwell C Hardness	Charpy Impact (V-Notch) at 75 F, ft-lb	Transition Temperature, F (Charpy V-Notch) 50% Brittle Fracture	 15 ft-lb
940	42	12	325	275
970	42	14	275	135
1000	40	18	150	–50

[a] Composition, %:

C	Mn	Si	Ni	Cr	Mo	Al
0.25	0.59	0.25	3.63	1.19	0.24	0.93

[b] Pre-Nitriding Treatment: ¾-inch square bars normalized 1750 F, oil quenched 1650 F, solution treated (tempered) 1200 F, air cooled.

TABLE IV

Effect of Aging after Nitriding on Hardness and Impact Properties of 3.5 Nickel-1.2 Aluminum Nitriding Steel at Two Aluminum Levels

Aging Treatment after Nitriding	Core Hardness, Rockwell C	Charpy Impact (Keyhole Notch) of Nitrided Specimens, ft-lb
0.87% Aluminum[a]		
As Nitrided[b]	38	12
1050 F, 2 hours	36	15
1100 F, 2 hours	33	24
1.40 % Aluminum[a]		
As Nitrided[b]	41	15
1050 F, 2 hours	38	18
1100 F, 2 hours	34	26

[a] Composition, %:

C	Mn	Si	Ni	Cr	Mo	Al
0.21	0.70	0.34	3.53	1.16	0.25	0.87
0.25	0.49	—	3.36	1.11	0.23	1.40

[b] Pre-Nitriding Treatment: 1-inch dia (0.87 aluminum) or 1¼-inch dia (1.40 aluminum) bars normalized 1700 F, oil quenched 1650 F, solution treated (tempered) 1225 F. Pressure nitrided 1000 F 15 hours, 7 g/sq ft ammonia.

Pressure nitriding with ammonia gas at relatively high pressures provides a means for controlling the "white layer" which usually develops at the surface.[1] It also yields relatively high surface hardness and toughness. Table II gives some data on pressure nitriding.

Another modification of the nitriding process, known as the Floe Process,[10] incorporates two temperature and two ammonia dissociation stages to minimize the "white layer" and increase the depth of penetration. Case hardness and depth of penetration for several variations of the Floe Process are given in Table II.

Molten salt baths also can be used to nitride steels.[2] Figure 8 shows representative case hardness gradients obtained in a proprietary salt bath.

Fatigue Properties and Wear Resistance

Nitriding can be used to improve the fatigue life of components subjected to cyclic loading in service. This improvement is caused both by the hardness increase and by the development during nitriding of compressive stresses in the range of 30,000 to 60,000 psi or higher.[17] Table V shows the effect of nitriding upon the fatigue or endurance limit of the 3.5 nickel-1.2 aluminum nitriding steel for both smooth and notched specimens. In these tests nitriding gives a greater improve-

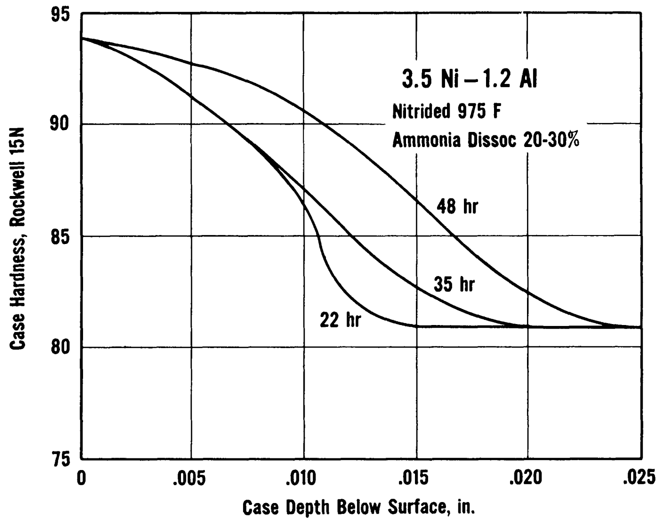


Fig. 7. Representative hardness gradients through case of 3.5 nickel-1.2 aluminum nitriding steel nitrided by the usual ammonia process.

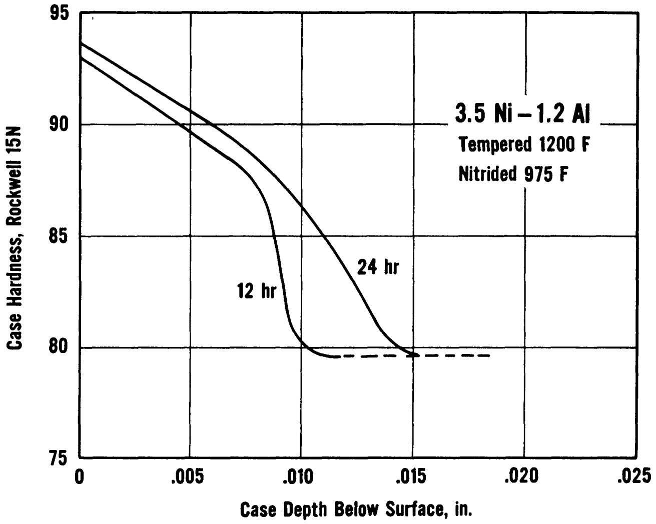


Fig. 8. Hardness gradients through case of 3.5 nickel-1.2 aluminum nitriding steel nitrided in a molten proprietary salt (Holden).

TABLE V

Effect of Nitriding on Fatigue Properties of 3.5 Nickel-1.2 Aluminum Steel[a]

Heat and Nitriding Treatments	Case Hardness, Rockwell 15-N	Core Hardness, Rockwell C	Fatigue Properties		
			Specimen[b]	Fatigue Limit, psi	Number of Cycles
Specimens Not Nitrided—True Fatigue Limit					
Oil quenched 1650 F; tempered 1200 F; pseudo-nitrided 975 F, 48 hr	—	38	Smooth	86,000	$>10^7$
			Notched	28,000	$>10^7$
Nitrided Specimens—No True Fatigue Limit[c]					
Oil quenched 1650 F; tempered 1200 F; nitrided 975 F, 48 hr	94	38	Smooth	124,000[c]	$>1.3 \times 10^7$
			Notched	80,000[c]	$>2.0 \times 10^7$
Oil quenched 1650 F; tempered 1200 F; nitrided 975 F, 10 hr and 1050 F, 40 hr	89	34	Smooth	118,000[c]	1.6×10^8[d]
			Notched	78,000[c]	$>3.2 \times 10^8$

[a] Composition, %:

C	Mn	Ni	Cr	Mo	Al
0.20	0.63	3.11	1.13	0.24	1.23

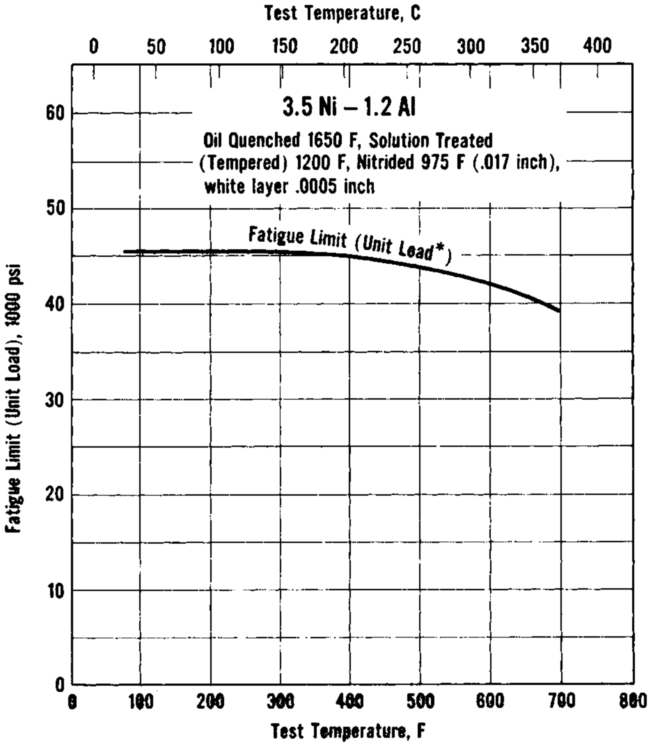
[b] R. R. Moore rotating beam fatigue specimens, minimum diameter 0.230 in. for all specimens. Notched specimens have 45-degree, .010-in. root-radius notch, .020-in. deep; notching preceded nitriding.

[c] Nitrided specimens do not show a true endurance or fatigue limit but give an "asymptotic" type of S-N curve; however, the notched specimens come closer to showing a true fatigue limit than the smooth ones.

[d] Specimen failed at 118,000 psi.

ment in the fatigue limit of notched specimens than smooth ones; this is in agreement with a broad spectrum of experience.[17] Figure 9 shows that the fatigue limit of the nitrided 3.5 nickel-1.2 aluminum steel is well maintained as test temperature rises to 700 F.

Nitrided cases show remarkably good wear resistance up to at least 750 F, because the case does not lose appreciable hardness until heated above this temperature.[17] Consequently, galling and seizing are minimized under conditions where faulty lubrication may produce a marked increase in temperature.



* *Unit load* is a common expression in the gear industry. It is the equivalent load in lb/in. of face on a tooth of 1 pitch in the normal plane having 1-in. face width. Its units are lb/in./in. but it is not a stress. It is related to root stress by means of a gear tooth-stress formula.

Gear tooth-stress formulas give varying results depending on assumptions relative to stress concentration, sharing of load between teeth, and so on. The unit load term has the advantage that the results of the test can be given in simple terms and all the ingredients of unit load are positively measurable quantities. The formula for unit load (U_l) is

$$U_l = \frac{W_t}{F} \times P_d, \text{ spur gear} \qquad (1)$$

$$U_l = \frac{W_t}{F} \times \frac{P_d}{\cos \Psi}, \text{ helical gear} \qquad (2)$$

Where: W_t = tangible driving force, lb = $\frac{\text{pinion torque}}{\text{pinion pitch radius}}$

F = contacting face width, in.

P_d = diametral pitch

Ψ = helix angle

$\frac{P_d}{\cos \Psi} = P_{nd}$, normal diametral pitch

Fig. 9. Effect of temperature on estimates of bending fatigue limit for 10 per cent failure of gear teeth of nitrided 3.5 nickel-1.2 aluminum nitriding steel. Seabrook and Dudley.[18]

4.1 Nickel-1.2 Aluminum (AISI P21)

A typical composition, in weight per cent, of this nitriding steel is:

Carbon	0.20
Manganese	0.30
Silicon	0.30
Nickel	4.10
Chromium	0.25
Vanadium	0.20
Aluminum	1.20

Behavior and properties are quite similar, but not identical, to those of the 3.5 nickel-1.2 aluminum nitriding steel. Gas nitriding and aging simultaneously at 950 to 975 F for 20 to 24 hours give hardnesses of 39 to 40 Rockwell C in the core and 94 Rockwell 15-N in the case, and normally should produce a case depth of .006 to .008 inch.

5 Nickel-2 Aluminum

The recommended composition range,[19] in weight per cent, for this steel is:

Carbon	0.20-0.25
Manganese	0.25-0.45
Nickel	4.75-5.25
Chromium	0.40-0.60
Molybdenum	0.20-0.30
Vanadium	.08-0.15
Aluminum	1.80-2.20

Core Properties

Typical mechanical properties of the core of the 5 nickel-2 aluminum steel after nitriding are given in Table VI. The 1¼-inch section, showing the best properties, was quenched to martensite, whereas the larger sections show a decrease in properties because of the effects of slack quenching.

The recommended heat treatment for developing optimum properties in the core of this steel is:

Preliminary Treatment: Normalize 1700 F, austenitize 1650 F, oil quench.

Solution Treatment (temper): 1275 F, air cool or faster cooling rate.

Stress Relief (optional): 1200 F, air cool or faster cooling rate.

Aging (during nitriding): 1050 F minimum, 8 hours or longer.

Figure 10 gives the aging response of the 5 nickel-2 aluminum steel at temperatures ranging from 950 to 1100 F. Comparison with Figure 6 shows that this steel has a wider range of aging temperatures for optimum

TABLE VI

Mechanical Properties of Core of 5 Nickel-2 Aluminum Steel in Three Section Sizes[a]

Property	Section Size 1¼ in.	2¼ in.	10 in.
Tensile Strength, psi	206,000	203,000	160,000
Yield Strength (0.2% Offset), psi	202,000	195,000	150,000
Elongation (2 in.), %	15	14	15
Reduction of Area, %	46	42	37
Brinell Hardness	420	420	321
Charpy Impact (V-Notch), ft-lb	14	6	4

[a] Oil quenched from 1650 F, solution treated (tempered) 1275 F 3 hours, air cooled, nitrided (aged) 1050 F 8 to 9 hours. Exception: 10-inch section, tempered 12 hours, furnace cooled 3 hours before air cooling.

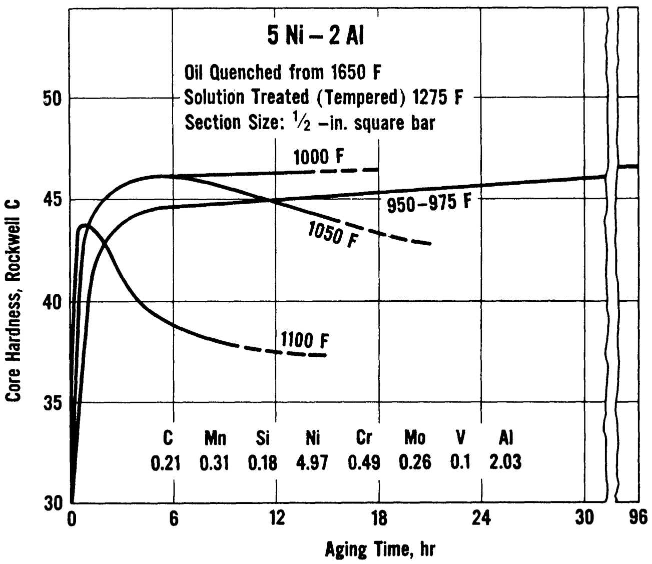


Fig. 10. Aging behavior of core of 5 nickel-2 aluminum steel during nitriding.

hardness and resists overaging at higher temperatures than the 3.5 nickel-1.2 aluminum steel. Hardenability of a typical heat of the 5 nickel-2 aluminum steel is shown in Figure 11, which also gives the hardness of the end-quenched bar after solution treating (tempering) and after solution treating and aging (pseudo-nitriding).

Tensile and impact properties obtained with various aging treatments are given in Table VII. The effect of aging after nitriding (overaging) is shown in Table VIII.

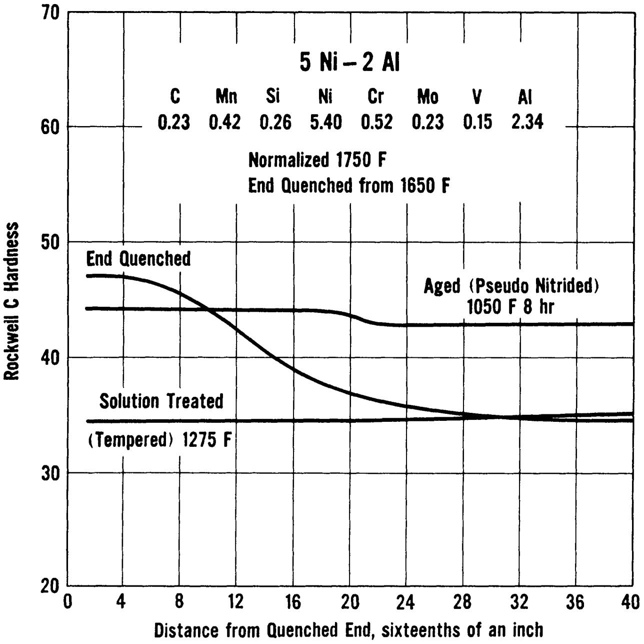


Fig. 11. Hardness of end-quench hardenability bar of 5 nickel-2 aluminum nitriding steel in three conditions. Mounce and Miller.[20]

TABLE VII

Effect of Aging during Nitriding on Tensile and Impact Properties of Core of 5 Nickel-2 Aluminum Steel[a]

Nitriding (Aging) Temperature, F	Time, hr	Rockwell C Hardness	Tensile Properties: Tensile Strength, psi	Yield Strength (0.5% Extension), psi	Elongation, %	Reduction of Area, %	Charpy Impact (Keyhole Notch), ft-lb
950	4	44	202,000	182,000	5	4.5	6
	8	45	205,000	188,000	—	5.5	5
1000	4	46	214,000	190,000	7.5	4.5	6
	8	46	210,000	192,000	3.5	6	5
1050	4	46	208,000	194,000	15	43	10
	8	46	210,000	195,000	13	31	10
1100	1	44	199,000	188,000	16	46	13

[a] Pre-Nitriding Treatment: ¾-inch square bars oil quenched from 1650 F, solution treated (tempered) 1275 F 1 hour, water quenched.

Composition, %:	C	Mn	Si	Ni	Cr	Mo	V	Al
	0.22	0.34	0.23	4.95	0.48	0.26	.09	2.04

TABLE VIII

Effect of Aging after Nitriding on Hardness and Impact Properties of 5 Nickel-2 Aluminum Steel

Aging Treatment after Nitriding[a]			
Temp, F	Time, hr	Core Hardness, Rockwell C	Charpy Impact (Keyhole Notch) of Nitrided Specimens, ft-lb
As Nitrided		44	3.5
1050	8	43	5.5
1100	8	40	14
1150	8	37	16

[a] Pre-Nitriding Treatment: 1¼-inch dia bars normalized 1750 F, oil quenched from 1650 F, solution treated (tempered) 1275 F. Nitrocycle pressure nitrided 1000 F 15 hours, 7.5 g/sq ft ammonia.

Case Properties

The 5 nickel-2 aluminum nitriding steel develops case hardnesses in the range 91 to 93 Rockwell 15-N, depending upon the nitriding cycle used. A representative hardness gradient through the case of this steel, nitrided by the Floe Process, is shown in Figure 12. The results obtained by nitriding under several procedures are given in Table IX.

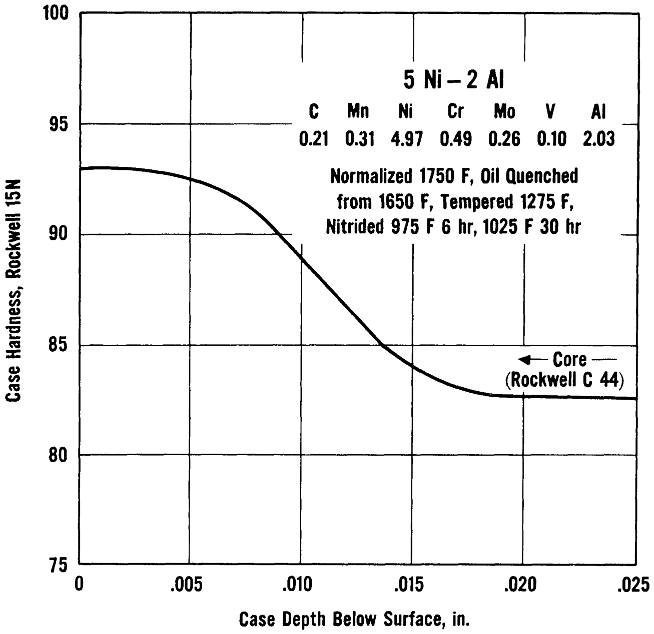


Fig. 12. Hardness gradient through case of 5 nickel-2 aluminum steel nitrided by the Floe Process. Mounce and Miller.[20]

TABLE IX

Case Depth and Hardness of 5 Nickel-2 Aluminum Steel after Various Nitriding Cycles

	Nitrided Case		Core
Nitriding Treatment	Depth, in.	Rockwell 15-N Hardness	Rockwell C Hardness
Gas Nitrided			
975-1000 F, 24 hours	.012	92	50
975-1000 F, 48 hours	.015	93	49
975-1000 F, 48 hours (.0002 in. white layer)	.020	91	50
Nitrocycle Pressure Nitrided[a]			
1000 F, 15 hours, 7.5 g/sq ft ammonia	.010	93	46
1025 F, 21 hours, 53 g/sq ft ammonia	.015	93	46
Floe Process[b]			
975 F, 6 hours, 20-30% ammonia dissociation; 1025 F, 30 hours, 85% ammonia dissociation	.015	93	45
Chapman Ni-20 Malcomizing Process[c]			
1020 F, 20 hours	.012	93	46

[a] Patented process of Oil Well Division, United States Steel Corporation.[21]

[b] Patented process of The Nitralloy Corporation.[22]

[c] Patented process of Chapman Division, Crane Company.[23]

Creep, Fatigue and Wear at Elevated Temperatures

The resistance to tempering in both the core and nitrided case of the 5 nickel-2 aluminum steel has made it particularly attractive for bearings, gears, cams and shafts that require good fatigue and wear resistance up to 1000 F. In fact, the nitrided case of this steel is particularly useful for moving parts of machinery where lubrication is faulty or lacking and the friction causes a marked increase in temperature. Short-time tensile properties of the aged (pseudo-nitrided) core at testing temperatures up to 1100 F are given in Figure 13. Hot hardness measurements of the aged core show 38 to 40 Rockwell C (352 to 370 Brinell) at 600 F, in close agreement with the elevated-temperature tensile strength of 180,000 psi at 600 F.

Various types of fatigue and wear tests at elevated temperatures have shown the 5 nickel-2 aluminum steel to have excellent properties. In fact, it led a group of steels in a special gear fatigue test in which its fatigue limit, in terms of unit load,* was reported to be 52,000 psi at 700 F.[18,24] As shown in Figure 14, its fatigue limit drops only a small amount as temperature is raised from 75 to 700 F.

As indicated in Figure 13, aging (pseudo-nitriding) at 1050 F for four hours produces a core hardness of 44 Rockwell C at 75 F. In this condition creep strength is 38,000 psi at 900 F for a creep rate of one per cent in 100,000 hours. A 10,000-hour exposure during the creep testing at 900 F caused no perceptible drop in the initial room-temperature hardness of 44 Rockwell C.

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* Unit load is defined in Figure 14.

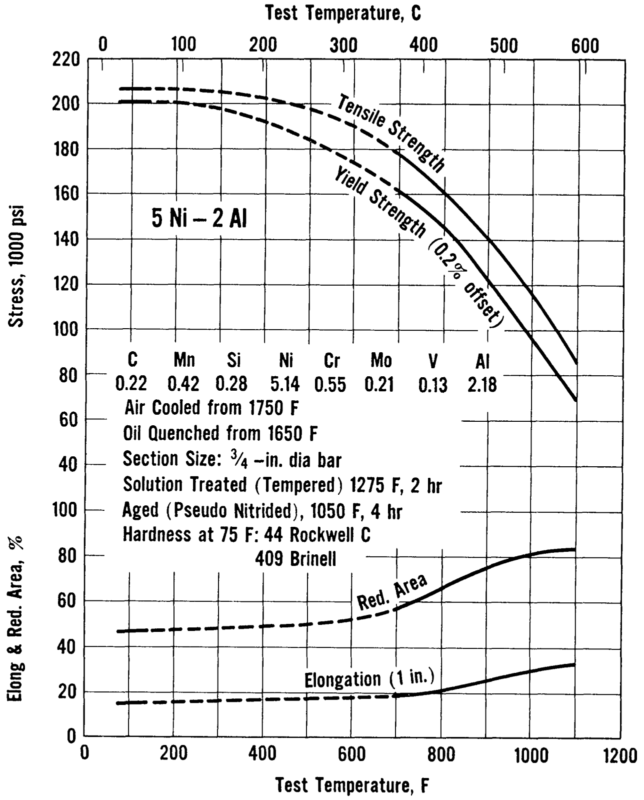
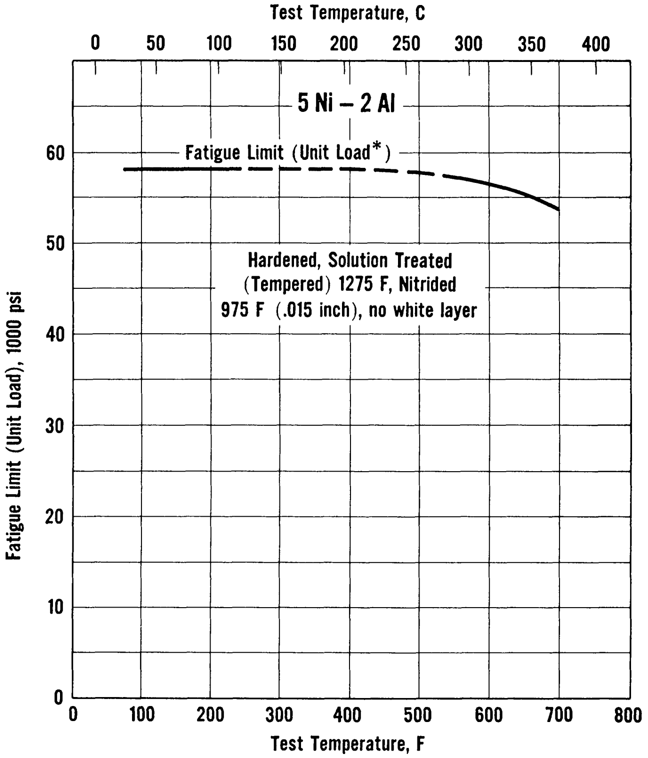


Fig. 13. Short-time elevated-temperature tensile properties of aged (pseudo-nitrided) 5 nickel-2 aluminum nitriding steel. Mounce and Miller.[20]



* *Unit load* is a common expression in the gear industry. It is the equivalent load in lb/in. of face on a tooth of 1 pitch in the normal plane having 1-in. face width. Its units are lb/in./in. but it is not a stress. It is related to root stress by means of a gear tooth-stress formula.

Gear tooth-stress formulas give varying results depending on assumptions relative to stress concentration, sharing of load between teeth, and so on. The unit load term has the advantage that the results of the test can be given in simple terms and all the ingredients of unit load are positively measurable quantities. The formula for unit load (U_l) is

$$U_l = \frac{W_t}{F} \times P_d\text{, spur gear} \qquad (1)$$

$$U_l = \frac{W_t}{F} \times \frac{P_d}{\cos \Psi}\text{, helical gear} \qquad (2)$$

Where: W_t = tangible driving force, lb = $\dfrac{\text{pinion torque}}{\text{pinion pitch radius}}$

F = contacting face width, in.

P_d = diametral pitch

Ψ = helix angle

$\dfrac{P_d}{\cos \Psi} = P_{nd}$, normal diametral pitch

Fig. 14. Effect of temperature on estimates of bending fatigue limit for 10 per cent failure of gear teeth of nitrided 5 nickel-2 aluminum nitriding steel. Seabrook and Dudley.[18]

ALLOY CONSTRUCTIONAL STEELS

Some of the standard medium-carbon alloy constructional steels and some tool and die compositions are nitrided to improve wear and galling resistance or fatigue properties. Among these are the AISI 4340, 8640, 9840 and 9850 steels which do not age harden and whose core properties are limited to those produced by the conventional quenching and tempering that precede nitriding. These steels develop somewhat lower case hardnesses than the nickel-aluminum steels, depending upon prior heat treatment and the nitriding cycle.

4340

Core Properties

Typical properties of 4340 after tempering at temperatures above 975 F (its usual nitriding temperature) are given in Table X. If the tempering temperature is below about 1100 F, the core may be softened somewhat during the extended period of time required

TABLE X

Tensile Properties of 4340 Steel Tempered at Several Temperatures[a]

Property	One-Inch Sections Oil Quenched and Tempered at 1000 F	1100 F	1200 F	1250 F
Tensile Strength, psi	185,000	170,000	150,000	145,000
Yield Strength (0.2% Offset), psi	160,000	145,000	130,000	126,000
Elongation (2 in.), %	15	17	18	20
Reduction of Area, %	53	55	57	58
Brinell Hardness	380	343	306	290
Rockwell C Hardness	41	37	33	31

[a] Composition, %:

C	Mn	Si	Ni	Cr	Mo
0.38-0.43	0.60-0.80	0.20-0.35	1.65-2.00	0.70-0.90	0.20-0.30

TABLE XI

Effect of Tempering Temperature upon the Case and Core Hardness of 1-Inch Sections of Oil Quenched and Tempered 4340 Steel Subsequently Nitrided

Tempering Temperature, F	Maximum Case Hardness, DPH	Core Hardness, Rockwell C As Tempered	After Nitriding at 970 F for 40 Hours
1000	620	41	38
1050	620	39	37
1100	610	37	36
1150	530	34	34
1200	520	32	32
1250	470	30	30

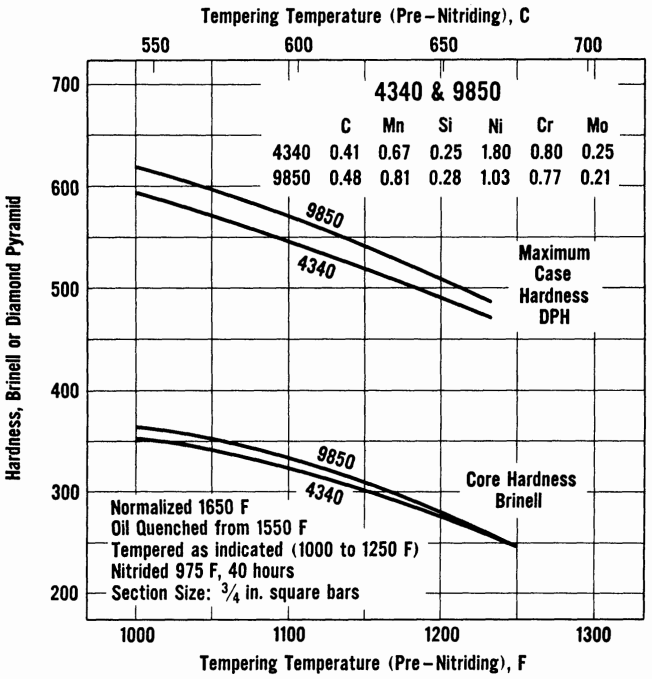


Fig. 15. Effect of pre-nitriding tempering on case and core hardness of 4340 and 9850 steels after nitriding.

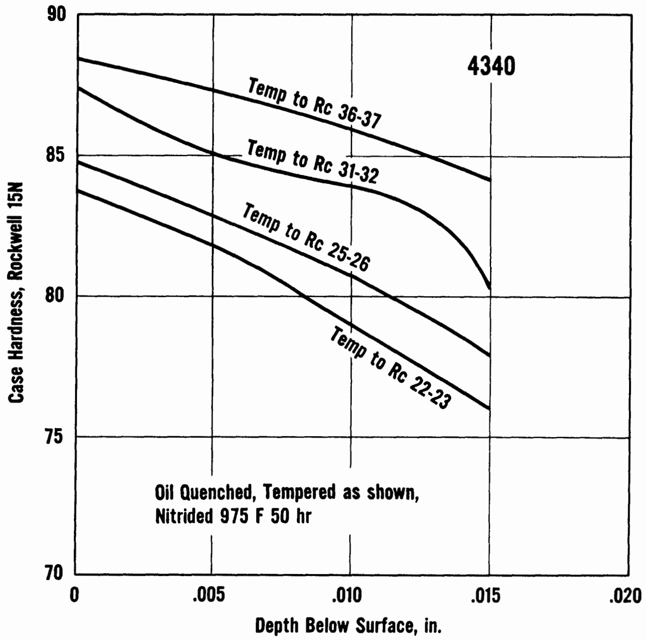


Fig. 16. Hardness gradients in case of 4340 steel nitrided by the usual ammonia process. Schwarzkopf.[25]

for nitriding; the degree of softening is indicated in Table XI and Figure 15. Core hardness values resulting from commercial nitriding processes are given in Table XII.

Case Properties

Case hardness depends on the hardness of the tempered steel before nitriding, as shown in Figure 15. Representative hardness gradients through the cases of 4340, tempered to different hardness levels, are shown in Figure 16. The maximum case hardness is a function of hardness in the tempered condition and, as shown in Table XI and Figure 15, decreases with increasing tempering temperature. Case depth and hardness resulting from commercial nitriding processes are given in Table XII.

Fatigue Properties

Table XIII summarizes the effect of nitriding on the fatigue or endurance limit of 4340. The effect is more pronounced on notched specimens than on smooth ones and this trend is confirmed in the published literature. In fact, nitriding improves smooth fatigue specimens in bending only 15 to 50 per cent, but it can strengthen notched specimens so greatly that they become practically as strong as nitrided smooth specimens.[17]

The marked improvement that nitriding can give to the fatigue life of 4340 crankshafts is illustrated in Figure 17.

TABLE XII

Case Depth and Hardness of Representative Constructional Steels after Nitriding

AISI-SAE Steel	Starting Condition	Nitriding Treatment[a]	Nitrided Case		Core
			Depth, in.	Rockwell 15-N Hardness	Rockwell C Hardness
4340	Quenched, tempered 1000 F	975 F, 40 hours, 20-30% dissoc	.025-.030	86-88	33-35
		975 F, 48 hours, 20-30% dissoc	.030-.035	86-88	33-35
		975 F, 10 hours, 20% dissoc; 1050 F, 40 hours, 80% dissoc	.029	86	32
4340	Quenched, tempered to 350 BHN	975 F, 60 hours, 20-30% dissoc	.035-.040	89	35
		975 F, 90 hours, 20-30% dissoc	.045	88	32
		975 F, 270 hours, 20-30% dissoc	.065	86	35
8640	Quenched, tempered	975 F, 48 hours, 20-30% dissoc	.020	88	35
9840	Quenched, tempered 1000 F	975 F, 40 hours, 20-30% dissoc	.025-.030	88	35

[a] dissoc = ammonia dissociation.

TABLE XIII

Effect of Nitriding on Fatigue Properties of 4340 Steel[a]

Heat and Nitriding Treatments[b]	Case Hardness, Rockwell 15-N	Core Hardness, Rockwell C	Fatigue Properties		
			Specimen[c]	Fatigue Limit, psi	Number of Cycles
Specimens Not Nitrided—True Fatigue Limit					
Oil quenched 1525 F; tempered 1000 F	—	37	Smooth	74,000	$>10^7$
			Notched	30,000	$>10^7$
Oil quenched 1525 F; tempered 1000 F; pseudo-nitrided 975 F, 48 hr	—	33	Smooth	68,000	$>10^7$
			Notched	26,000	$>10^7$
Nitrided Specimens—No True Fatigue Limit[d]					
Oil quenched 1525 F; tempered 1000 F; nitrided 975 F, 48 hr	89	33	Smooth	86,000[d]	3.5 x 10^8[e]
			Notched	51,000[d]	$>1.6 \times 10^9$
Oil quenched 1525 F; tempered 1000 F; nitrided 975 F, 10 hr and 1050 F, 40 hr	86	32	Smooth	90,000[d]	$>4.6 \times 10^8$
			Notched	52,000[d]	$>4.6 \times 10^8$

[a] Composition, %:

C	Mn	Si	Ni	Cr	Mo
0.39	0.65	0.25	1.85	0.82	0.25

[b] Preliminary Treatment: Normalized 1725 to 1750 F.

[c] R. R. Moore rotating beam fatigue specimens, minimum diameter 0.230 in. for all specimens. Notched specimens have 45-degree, .010-in. root-radius notch, .020-in. deep; notching preceded nitriding.

[d] Nitrided specimens do not show a true endurance or fatigue limit but give an "asymptotic" type of S-N curve; however, the notched specimens come closer to showing a true fatigue limit than the smooth ones.

[e] Specimen failed at 86,000 psi.

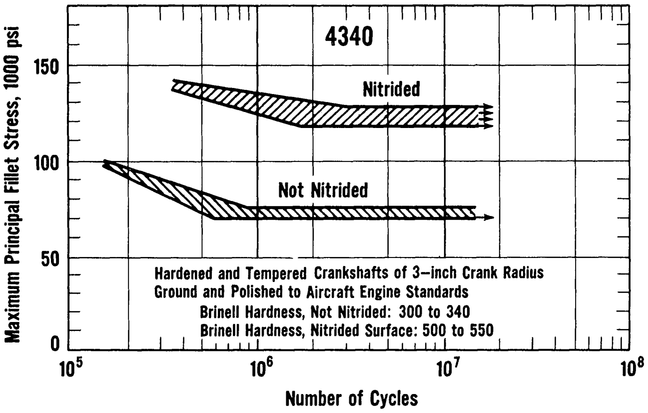


Fig. 17. Effect of nitriding on fatigue life of 4340 steel in full-scale bending fatigue tests of individual "throws" of crankshafts. Gadd and Ochiltree.[26]

8640, 9840 and 9850

Properties of the 8640 and 9840 steels, after tempering at temperatures above 975 F, are given in Tables XIV and XV and approximate the core strengths after nitriding at the same temperature. Representative case and core hardness values and case depths resulting from commercial nitriding are given in Table XII. Figure 15 shows the effect of tempering temperature before nitriding on the case and core hardnesses of 9850 after nitriding.

Nickel Alloy Steels Containing Vanadium

Vanadium improves the nitrided case properties of nickel alloy steels. Properties of AMS 6416 (300-M), a vanadium-containing silicon-nickel-chromium-molybdenum grade, are given in Table XVI. Properties of a British 1.8 nickel-1.3 chromium-1 molybdenum-0.3 vanadium nitriding steel appear in Table XVII.

Hardness, tensile and fatigue properties are presented in Table XVIII for gears of a 2.4 nickel-1.1 chromium-0.5 molybdenum-0.2 vanadium steel. The data show that nitriding substantially improves both the bending and pitting fatigue limits of these gears.

TABLE XIV

Tensile Properties of 8640 Steel Tempered at Several Temperatures[a]

Property	One-Inch Sections Oil Quenched and Tempered at		
	1000 F	1100 F	1200 F
Tensile Strength, psi	170,000	156,000	140,000
Yield Strength (0.2% Offset), psi	145,000	135,000	120,000
Elongation (2 in.), %	16	17	18
Reduction of Area, %	45	50	52
Brinell Hardness	341	317	280
Rockwell C Hardness	37	34	29

[a] Composition, %:

C	Mn	Si	Ni	Cr	Mo
0.38-0.43	0.75-1.00	0.20-0.35	0.40-0.70	0.40-0.60	0.15-0.25

TABLE XV

Tensile Properties of 9840 Steel Tempered at Several Temperatures[a]

Property	One-Inch Sections Oil Quenched and Tempered at		
	1000 F	1100 F	1200 F
Tensile Strength, psi	180,000	160,000	140,000
Yield Strength (0.2% Offset), psi	160,000	140,000	120,000
Elongation (2 in.), %	15	16	19
Reduction of Area, %	54	56	60
Brinell Hardness	361	321	280
Rockwell C Hardness	39	34	29

[a] Composition, %:

C	Mn	Si	Ni	Cr	Mo
0.38-0.43	0.70-0.90	0.20-0.35	0.85-1.15	0.70-0.90	0.20-0.30

TABLE XVI

Effect of Aging after Nitriding on Hardness and Impact Properties of AMS 6416 (300-M) Steel[a]

Nitriding[b] Process	Aging Treatment after Nitriding		Core Hardness, Rockwell C	Charpy Impact (Keyhole Notch) of Nitrided Specimens at 75 F, ft-lb
	Temp, F	Time, hr		
Floe[c]	As Nitrided		46	3
Pressure[d]	As Nitrided		46	5
Floe[c]	1050	2	46	4
Pressure[d]	1050	2	45	5
Floe[c]	1100	2	44	4
Pressure[d]	1100	2	44	6

[a] Composition, %:

C	Mn	Si	Ni	Cr	Mo	V
0.38	0.77	1.57	1.82	0.84	0.32	.08

[b] Pre-Nitriding Treatment: 1-inch dia bars normalized 1700 F, oil quenched from 1650 F, tempered 1050 F.

[c] Floe: 985 F 58 hours, ammonia dissociation 25 to 75%.

[d] Pressure: 1000 F 15 hours, 7 g/sq ft ammonia.

TABLE XVII

Tensile Properties of a British 1.8 Nickel-1.3 Chromium-1 Molybdenum-0.3 Vanadium Nitriding Steel Tempered at Two Temperatures[a]

Property	Oil Quenched from 1600 F and Tempered at		Air Cooled from 1600 F and Tempered at	
	1110 F	1200 F	1110 F	1200 F
Tensile Strength, psi	213,000	174,000	210,000	170,000
Yield Point, psi	201,000	168,000	194,000	159,000
Elongation, %	17	18	17	18

[a] Composition, %:

C	Mn	Ni	Cr	Mo	V
0.40-0.45	0.40-0.65	1.50-2.00	1.00-1.50	0.80-1.20	0.30 max.

After austenitizing at 1580 to 1630 F, quenching in oil or air, tempering at 1050 F minimum, and nitriding at 925 F for 25 hours, the case hardness ranges from 600 to 650 Diamond Pyramid Hardness.

TABLE XVIII

Effect of Nitriding on Bending and Pitting Fatigue Limits of a 2.5 Nickel-1 Chromium-0.5 Molybdenum-0.2 Vanadium Steel[a,b]

Heat and Nitriding Treatments[c]	Brinell Hardness	Fatigue Limit, psi
Bending Fatigue Test of Specimens with Simulated Gear-Tooth Root with 0.125-Inch Smooth Fillets		
Normalized and tempered	283	39,000
Normalized, tempered and nitrided 975 F 100 hours	Surface 560	67,000
Pitting Fatigue Data from Contact Roller Test		
Normalized and tempered	283	60,000[d]
Normalized, tempered and nitrided 975 F 100 hours	Surface 560	>250,000[d]

[a] Gross.[27]

[b] Composition, %:

C	Mn	Si	Ni	Cr	Mo	V
0.24	0.72	0.17	2.37	1.07	0.47	0.22

[c] Specimens are from an 18-inch diameter forging which was normalized and tempered to a tensile strength of 134,000 psi.

[d] Hertz theoretical maximum compressive stress.

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