IN-787— A PRECIPITATION HARDENING ALLOY STEEL, PROPERTIES AND APPLICATIONS

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 1278

Produced by INCO

Distributed by NICKEL INSTITUTE

knowledge for a brighter future

IN-787—A PRECIPITATION HARDENING ALLOY STEEL, PROPERTIES AND APPLICATIONS

A PRACTICAL GUIDE TO THE USE
OF NICKEL-CONTAINING ALLOYS
Nº 1278

Originally, this handbook was published in 1978 by INCO, The International Nickel Company Inc. Today this company is part of Vale S.A.
The Nickel Institute republished the handbook in 2021. Despite the age of this publication the information herein is considered to be generally valid.

Nickel Institute

communications@nickelinstitute.org
www.nickelinstitute.org

IN-787 Steel's Design and Fabricating Advantages

IN DESIGN

- Combined high strength and notch toughness
- Improved base metal and weld fatigue strength
- Resistance to hydrogen induced cracking
- Ability to form tight bend radii without cracking
- Broad range of heat treated properties
- HAZ toughness with or without post weld stress relief
- Improved corrosion resistance over carbon steel
- Capability from light gauge to heavy section
- High ductility and low work hardening characteristics
- High efficiency butt welded joints

IN FABRICATION

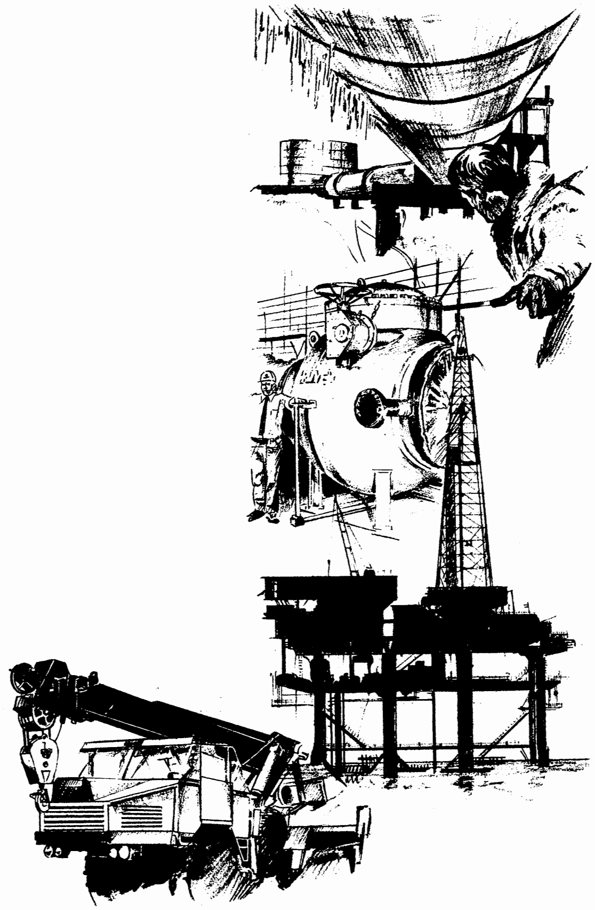
- Substantially reduced welding costs
- Improved formability
- Workable in all conditions of heat treatment
- Combined precipitation hardening and stress relief
- Unhardened HAZ on welding and flame cutting
- Flexible forming, welding and heat treating schedules
- Weldable under extreme conditions of cold and moisture

COVER PHOTO:

Shown on the cover is an upset forging of an IN-787 bloom. The excellent mechanical properties, weldability and low temperature toughness combine to make IN-787 an ideal choice for severe arctic service.

IN-787 is a low carbon precipitation hardenable alloy steel that uniquely combines high strength, low temperature toughness and excellent notch ductility, with unprecedented fabricability. U.S. Patent Number 3,692,514 has been issued for this alloy steel.

This combination allows IN-787 to serve a broad range of design engineering and fabricating requirements. The alloy's highly adaptive heat treatment, forming characteristics and weldability clearly indicate IN-787's cost saving potential.



PRODUCT FORMS

IN-787 has been produced as sheet, plates up to 4 inches thick, seamless and welded pipe, tubing, structural shapes and forgings. All products, produced to the same nominal composition, have shown consistency in engineering properties.

APPLICABLE SPECIFICATIONS

IN-787 is covered by the following ASTM Standards:

A 707: Flanges, Forged, Carbon and Alloy Steel for Low Temperature Service.

A 710: Low-Carbon Age-Hardening Nickel-Copper-Chromium-Molybdenum-Columbium and Nickel-Copper-Columbium Alloy Steels.

A 736: Pressure Vessel Plates, Low-Carbon Age-Hardening Nickel-Copper-Chromium-Molybdenum-Columbium Alloy Steel.

CHEMICAL REQUIREMENTS

The chemical composition of IN-787 is listed in Table 1.

The low carbon requirement is principal to the alloy's excellent weldability, low temperature impact toughness and forming characteristics. Copper is the precipitation strengthening element, while nickel is added to increase strength and toughness and to prevent hot shortness. Both chromium and molybdenum are added to retard auto-aging while columbium inhibits grain growth on heating to high working temperatures. As with other alloy steels, particularly those specified for use in low temperature environments, both phosphorus and sulfur are kept to the lowest practicable levels.

TABLE 1
IN-787 CHEMICAL COMPOSITION
(Heat Analysis)

Element	Composition, %
Carbon, max	0.07
Manganese	0.40-0.70
Phosphorus, max	0.025
Sulfur, max	0.025
Silicon, max	0.40
Nickel	0.70-1.00
Chromium	0.60-0.90
Molybdenum	0.15-0.25
Copper	1.00-1.30
Columbium, min	0.02

PROPERTIES

Tensile and Impact

The tensile and impact properties for several product forms—light and heavy plate, structural shapes, seamless tubing and heavy forgings—are summarized in Tables 2 through 6. The various combinations of strength, notch toughness and ductility are shown as a function of heat treatments.

TABLE 2

MECHANICAL PROPERTIES OF IN-787 — LIGHT PLATES

Plate Thickness, in.	Heat Treatment	YS ksi	TS ksi	% Elong. in 2"	Charpy V-Notch, ft-lb[3] L −55 F	T −55 F	L −80 F	T −80 F
⅜	P.H.[1] @ 1000 F 30 min & AC[2]	95	115	35	83	31	—	—
⅜	P.H. @ 1100 F 30 min & AC	96	110	37	82	32	70	24
⅜	P.H. @ 1200 F 30 min & AC	94	102	34	99	46	81	29
⅜	P.H. @ 1200 F 60 min & AC	92	99	35	105	40	94	34
½	P.H. @ 1000 F 60 min & AC	93	112	38	47	28	23	15
½	P.H. @ 1100 F 60 min & AC	95	108	36	62	34	18	21
½	P.H. @ 1200 F 60 min & AC	90	99	42	32	45	29	26
1¼	Normalized — 1650 F 75 min	52	84	30	—	—	—	—
1¼	Normalized — 1650 F 75 min P.H. @ 1100 F 60 min AC	73	89	28	119	91	44	11
—	Normalized — 1650 F 75 min P.H. @ 1200 F 60 min AC	63	80	28	234	89	67	28
1¼	W.Q.[4] from 1650 F 75 min	80	105	25	46	36	—	—
1¼	W.Q. from 1650 F 75 min P.H. @ 1100 F 30 min & AC	90	104	25	92	48	132	92
1¼	W.Q. from 1650 F 75 min P.H. @ 1200 F 30 min & AC	83	93	27	114	99	113	45

[1] P.H.—Precipitation Hardened.
[2] AC—Air Cooled.
[3] L—Longitudinal Direction.
T—Transverse Direction.
[4] W.Q.—Water Quenched.

TABLE 3

MECHANICAL PROPERTIES OF IN-787 — HEAVY PLATES

Plate Thickness, in.	Heat Treatment	YS ksi	TS ksi	% Elong. in 2"	% RA	Charpy V-Notch, ft-lb[1] L −50 F	T −50 F	L −100 F	T −100 F
3¼	Normalized — 1650 F 195 min	53	76	32	72	37	28	—	—
3¼	Normalized — 1700 F 115 min	54	76	31	—	88	59	—	—
3¼	W.Q.[2] from 1650 F 195 min	60	87	28	67	64	44	—	—
3¼	W.Q. from 1700 F 115 min	60	85	26	—	97	56	55	36
3¼	Normalized — 1650 F P.H.[3] 1150 F 60 min	66	80	27	70	167	57	—	—
3¼	W.Q. from 1650 F P.H. 1200 F 60 min	75	87	26	69	164	74	—	—

[1] L—Longitudinal.
T—Transverse.
[2] W.Q.—Water Quenched.
[3] P.H.—Precipitation Hardened.

TABLE 4

MECHANICAL PROPERTIES OF IN-787 — WIDE FLANGE BEAMS (18" x 77 lb)[1]

Test Condition[2]	YS ksi	TS ksi	% Elong. in 8"	CVN Toughness, ft-lb[3] 13/16" Flange Average/Minimum Values, Full Size, Longitudinal Direction			
				0 F	–20 F	–50 F	–80 F
As-rolled & P.H.[4] 1150 F	87	107	18	62/52	41/12	33/30	9/4
As-rolled & P.H. 1300 F	82	97	19	86/54	74/56	14/6	9/6
Normalized 1650 F	50	84	28	143/124	123/96	91/68	59/44
Normalized 1650 F & P.H. 1150 F	68	83	26	N.B.[5]	N.B.	240/224	187/122

[1] Sampling and specimens per ASTM A 6.
[2] Laboratory heat treatments.
[3] Sampling per ASTM A 673.
[4] P.H.—Precipitation Hardened.
[5] N.B.—no break.

TABLE 5

MECHANICAL PROPERTIES OF IN-787 TUBING (6½" O.D. x 0.350" wall)

	Normalized at 1650 F and P.H.[1] 1 hour at — 1100 F	1200 F
YS, ksi	74	68
TS, ksi	85	74
Elongation (%)	32	32
Hardness, Rb	87	83
CVN (¾ Size) @ –50 F, ft-lb	158	160
Lateral Expansion, mils	88	89
Shear (%)	99	99
	Water quenched from 1650 F and P.H. 1 hour at — 900 F	**1100 F**
YS, ksi	85	77
TS, ksi	100	88
Elongation (%)	28	32
Hardness, Rb	98	90
CVN (½ Size) @ –50 F, ft-lb	70	87
Lateral Expansion, mils	79	81
Shear (%)	70	80

[1] P.H.—Precipitation Hardened.

TABLE 6

MECHANICAL PROPERTIES OF IN-787 WELD NECK FLANGE[1] 26", 600 LB WELD NECK FLANGE

Direction	0.2% YS ksi	TS ksi	% Elong.	% RA	–50 F CVN ft-lb	% Shear	Lat. Exp. mils
Tangential	75.0	87.0	28.5	79.0	197	100	.078
Axial	67.0	81.0	30.7	78.9	190	100	.078

Heat Treatment: austenitized at 1650 F, 7 hr, water quench and precipitation hardened at 1150 F, 8 hr, air cool

[1] See Figure 8.

HEAT TREATMENT

IN-787 is generally specified in one of three basic heat treated conditions: as-rolled and precipitation hardened, solution treated (normalized) and precipitation hardened and solution treated (quenched) and precipitation hardened. Solution treatment is accomplished at 1650 F minimum; precipitation hardening in the range of 900-1300 F depending upon the combination of strength and toughness desired. Unlike tempering of conventional alloy structural steels which lowers yield strength, the precipitation hardening cycle both strengthens and toughens IN-787.

In the as-rolled, normalized or quenched conditions, the yield strength of IN-787 is lower than when subsequently precipitation hardened. It is often desirable to procure IN-787 in these conditions to further facilitate forming. Note also that IN-787 is fully ductile and weldable in the as-rolled, normalized or quenched conditions. Subsequent precipitation hardening after forming or welding allows for the development of specified properties and may be utilized as the stress relief* thus saving a second heat treatment.

This material has been precipitation hardened in the temperature range of 900-1300 F. When the lower end of the range is utilized, the higher yield strengths are obtained. However, if the prime interest is maximum toughness at low temperatures, then the precipitation hardening should be performed at the higher end of the temperature range, and also for times longer than one hour.

Where low temperature toughness is a basic engineering requirement, solution treatment is recommended for IN-787 in thicknesses over ½ inch. Generally, excellent toughness can be obtained in control rolled plates ½ inch thick and less by applying precipitation hardening treatments at 1200 F or higher.

* It is important to note that best properties are developed by air cooling IN-787 immediately after precipitation hardening. Typical stress relieving practice of "slow" or furnace cooling should not be applied if the design is based on properties of precipitation hardened material.

FATIGUE - ROTATING BEAM

The fatigue strength of IN-787 is excellent. Rotating beam tests conducted on parent metal and welded specimens indicate endurance limits of 75 and 55 per cent of yield strength, respectively. Table 7 summarizes the mechanical properties of the materials tested and Figure 1 shows fatigue curves.

TABLE 7

MECHANICAL PROPERTIES OF IN-787 FATIGUE TESTED MATERIAL
½" PLATE — AS ROLLED AND PRECIPITATION HARDENED

Specimen[1]	Ultimate Tensile Strength ksi	Yield Strength ksi	Elongation (% in 2")	Fracture Location
Base Plate	101	89	28	—
Base Plate	102	91	26	—
Gas Metal Arc Weldment	100	—	—	Base Plate
	101	—	—	Base Plate

[1] Reduced section-tensile specimens.

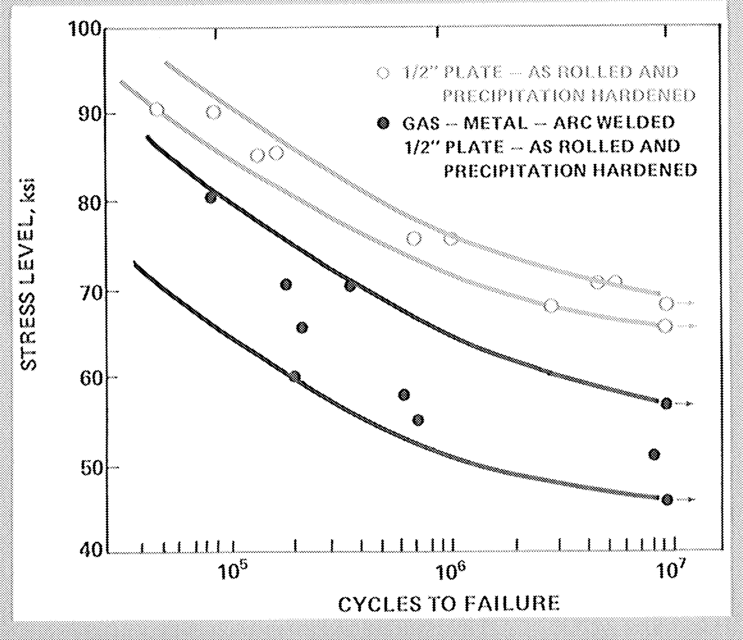


Figure 1—Fatigue properties of rotating beam specimens of IN-787 plate and gas metal arc weldment.

FATIGUE - AXIAL

A modified Goodman Diagram representing axial fatigue tests on base plate and weldments is shown in Figure 2. The tests were conducted for 2 million cycles and at stress ratios of 0.1, 0.5 and –1.0. The as-welded specimen tested at R = –1.0, stress range of 46 ksi, gave excellent results. The tension-compression stress of 23 ksi is superior to other alloy grades, with 20 per cent higher strength, tested under similar conditions. As can be readily seen in Figure 2, if the weld reinforcement is removed, still better fatigue properties are obtained.

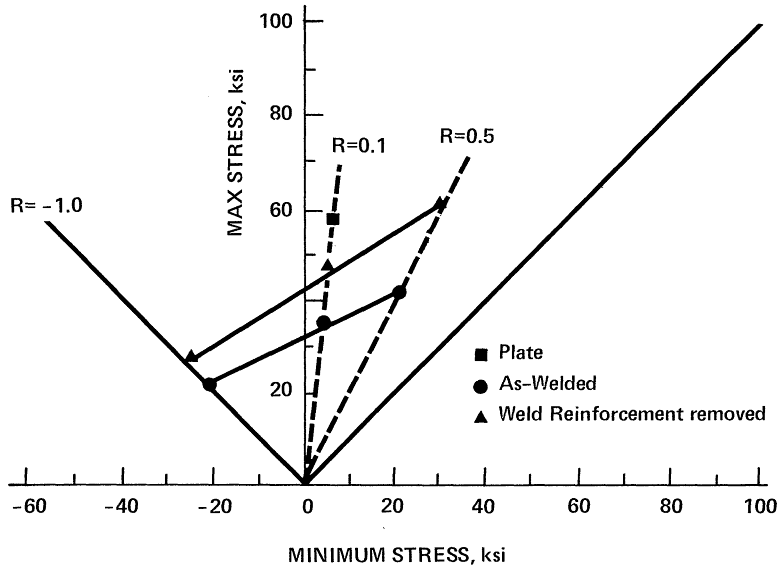


Figure 2—Modified Goodman Diagram 2 million cycles axial fatigue tests on IN-787 butt welded specimens.

CORROSION

IN-787 shows a distinctive advantage over carbon steel in marine atmosphere corrosion tests. The product of corrosion is tight and adherent as opposed to the loose, flaky deposit of carbon steel. Figures 3 and 4 summarize three-year exposure data for IN-787 and carbon steel at distances of 80 and 800 feet from the ocean. These data suggest potential applications for IN-787 in marine environments, particularly offshore platforms.

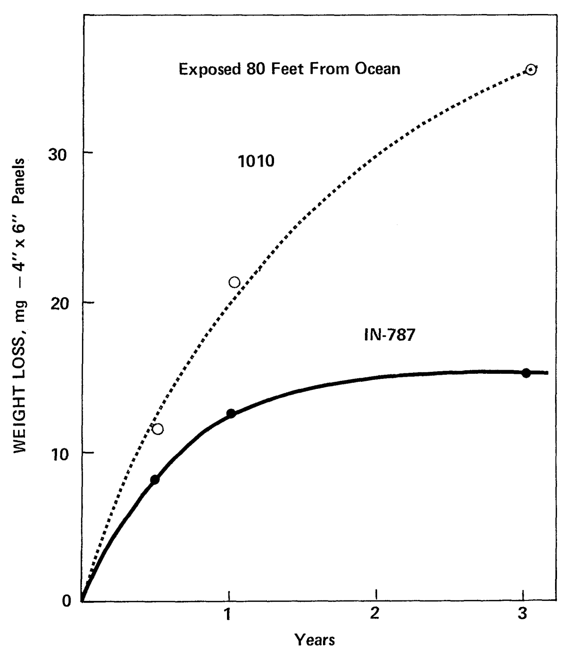


Figure 3—Corrosion of IN-787 and 1010 steels in marine atmospheres.

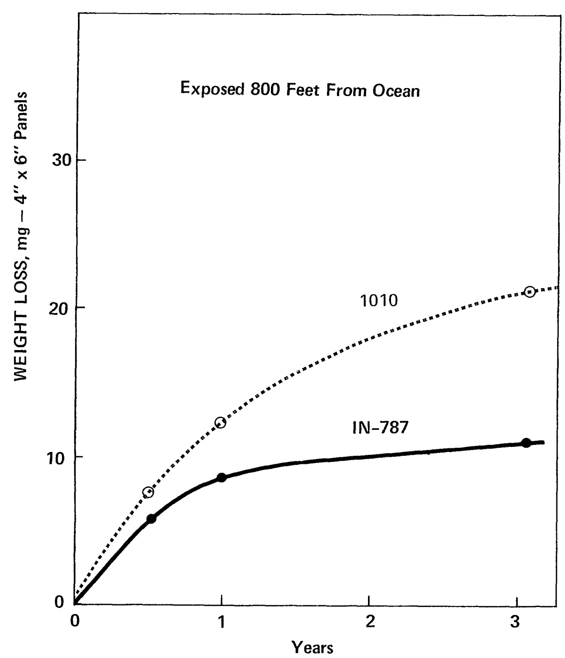


Figure 4—Corrosion in IN-787 and 1010 steels in marine atmospheres.

FRACTURE TOUGHNESS

Crack Opening Displacement (COD) type tests have been made on the steel at temperatures down to −238 F. Transverse and longitudinal tests on ⅝ and 1 inch plate in the water-quenched and precipitation hardened condition and on 1 inch plate in the normalized and precipitation hardened condition all showed massive plasticity at temperatures down to at least −99 F, COD values generally being in excess of 0.0236 inch, the limit of the particular clip displacement gauge. This value gives a crack size parameter $\frac{COD}{Yield}$ strain of 6.6-7.8 inches. At −148 F, all tests attained general yield conditions followed in some cases by fast fracture; but at −238 F, rapid cracking occurred below yield.

Fracture characteristics have also been determined by the Battelle Drop Weight Tear Tests and by pressure burst tests on large diameter pipe containing artificial crack defects 0.37 inch long. The results indicate that rolled, normalized or quenched skelp which is welded into pipe and then precipitation hardened will not suffer rapid brittle fracture at +28 F, −27 F or − 65 F, respectively.

FABRICATION

Welding

The weldability of IN-787 steel is superior to that of many alloy steels. The alloy is highly adaptable to extensive and complex weld fabrications. This is due to IN-787's weldability in all conditions of heat treatment, minimal hardening in heat-affected zones, insensitivity to hydrogen associated cracking and constant composition over the complete available product range. IN-787 can be welded using standard welding processes. Additionally, suitable filler metals and wire/flux combinations are commercially available to match desired base plate properties.

The cost of fabrication can be reduced because IN-787 requires no preheat, postheat, special interpass temperature control or bead sequence procedure. The alloy is insensitive to hydrogen underbead cracking and has shown an ability to be welded under extreme conditions of low temperature and moisture. These latter characteristics make the alloy ideally suited for difficult fabrication and equipment maintenance in the field.

Other weld characteristics are noteworthy. Highest efficiency joints are possible, heat-affected zones do not act as stress risers and HAZ toughness can be maintained with or without post weld precipitation hardening. Fatigue strength of weldments is excellent even with as-deposited weld bead contour. It is equal to or greater than most structural steel grades—even those having higher yield strengths.

These qualities can be translated into cost savings in fabrication while expanding the design potential for high strength steels which is often inhibited by higher fabrication costs.

Tables 8-10 show mechanical properties of IN-787 welded joints made using coated electrodes, submerged arc and gas metal arc processes.

TABLE 8

MECHANICAL PROPERTIES OF COVERED ELECTRODE WELDMENTS IN ½″ THICK IN-787 STEEL PLATE

Electrode[1]	Preweld Condition	Postweld Condition	UTS ksi	Failure Location	Weld-CVN ft-lb 0 F	Weld-CVN ft-lb −50 F	HAZ-CVN ft-lb 0 F	HAZ-CVN ft-lb −50 F
E9018M	Rolled +	None	95.8	Plate	79	75	111	70
	P.H.[2] 1200 F		96.0		87	52	94	71
E9018M	Rolled +	1200 F	92.1	Plate	100	29	98	109
	P.H. 1200 F	1 hr AC[3]	92.0		102	33	80	64
E8016C1	Rolled +	None	97.4	Plate	64	45	80	84
	P.H. 1200 F		97.6		53	46	79	76
E8016C1	Rolled +	1200 F	93.9	Plate	66	44	90	54
	P.H. 1200 F	1 hr AC	94.2		62	46	91	83
E8018C2	Rolled +	None	94.8	Weld	(−50 F)	(−80 F)	—	—
	P.H. 1200 F		—		86	63	—	—

[1] AWS Designation for Low Hydrogen Electrodes (A5.5 Specification).
[2] P.H.—Precipitation Hardened.
[3] AC—Air Cooled.

TABLE 9

MECHANICAL PROPERTIES OF AUTOMATIC GAS METAL ARC WELDMENTS IN ½" THICK IN-787 STEEL PLATE

Welding Process	Preweld Condition	UTS ksi	Failure Location	Weld-CVN ft-lb –50 F	Weld-CVN ft-lb –80 F
Spray Arc[1] (.062")	Rolled + P.H.[3] 1200 F	95.4	Plate	—	63
Short Circuiting Arc[2] (.045")	Rolled + P.H. 1200 F	95.0	Plate	70	(–100 F) 38
Short Circuiting Arc[2] (.045")	1650 F — W.Q.[4] + P.H. 1200 F	119.5	Plate	—	57

[1] Wire—1.7 Ni, Gas—Argon.
[2] Wire—1.7 Ni, Gas—60% Helium + 38% Argon + 2% Oxygen.
[3] P.H.—Precipitation Hardened.
[4] W.Q.—Water Quenched.

TABLE 10

MECHANICAL PROPERTIES OF SUBMERGED ARC WELDMENTS IN ½" THICK IN-787 STEEL

Preweld Condition	Postweld Condition	UTS ksi	Failure Location	Weld-CVN ft-lb 0 F	Weld-CVN ft-lb –50 F	HAZ-CVN ft-lb 0 F	HAZ-CVN ft-lb –50 F
Rolled + P.H.[1] 1200 F	As Welded	93.8 93.2	Plate	73 104	45 27	101 118	89 76
Rolled + P.H. 1200 F	P.H. at 1200 F 1 Hr	92.6 90.0	Plate	37 29	15 11	124 93	84 80
Rolled + P.H. 1200 F	As Welded	94.2 94.6	Plate	107 107	31 45	100 103	52 55
Rolled + P.H. 1200 F	P.H. at 1200 F 1 Hr	89.9 90.0	Plate	109 118	75 51	97 109	73 95

[1] P.H.—Precipitation Hardened.

FLAME CUTTING

IN-787 steel is readily flame cut and, unlike conventional alloy steel grades, there is minimal heat-affected zone. With hardnesses ranging between 250 and 280 DPH at .0393 inch from the flame cut edge, there is no difficulty in machining weld preparations where necessary. Sound joints have been made in plate prepared with a 30° bevel, then power wire brushed prior to welding with coated electrodes. Figure 5 summarizes hardness data on IN-787 plate taken at various intervals from the flame cut edge of plates in both as-rolled and rolled and precipitation hardened conditions.

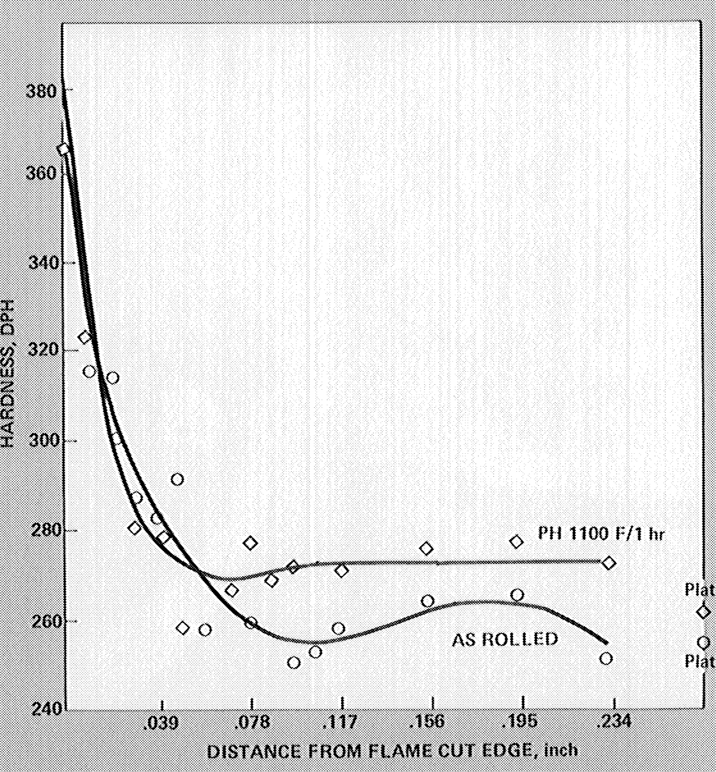
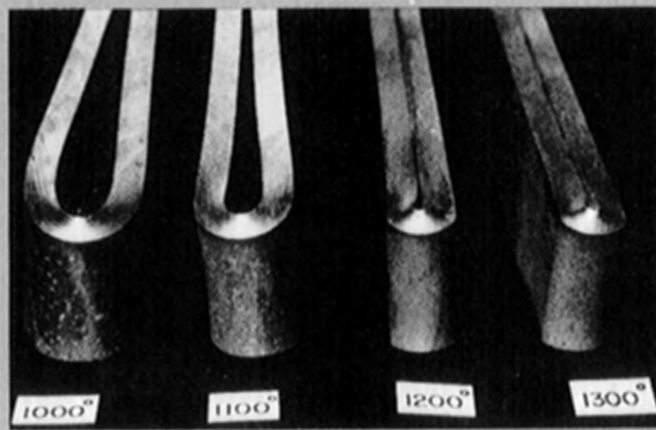


Figure 5—Hardness of flame cut IN-787 plates.

FORMING

Forming characteristics of IN-787 steel are unique for its strength level. Tests conducted on fully precipitation hardened plate showed that 180° bends could be made over 1t radius. Figure 6 shows the tension surface of bend specimens of 5/16 inch thick IN-787 plate in the fully precipitation hardened condition.

Figure 7 shows a large 1¾-inch thick cylinder with extruded weld necks. Cold extrusion was accomplished without splitting or tearing.



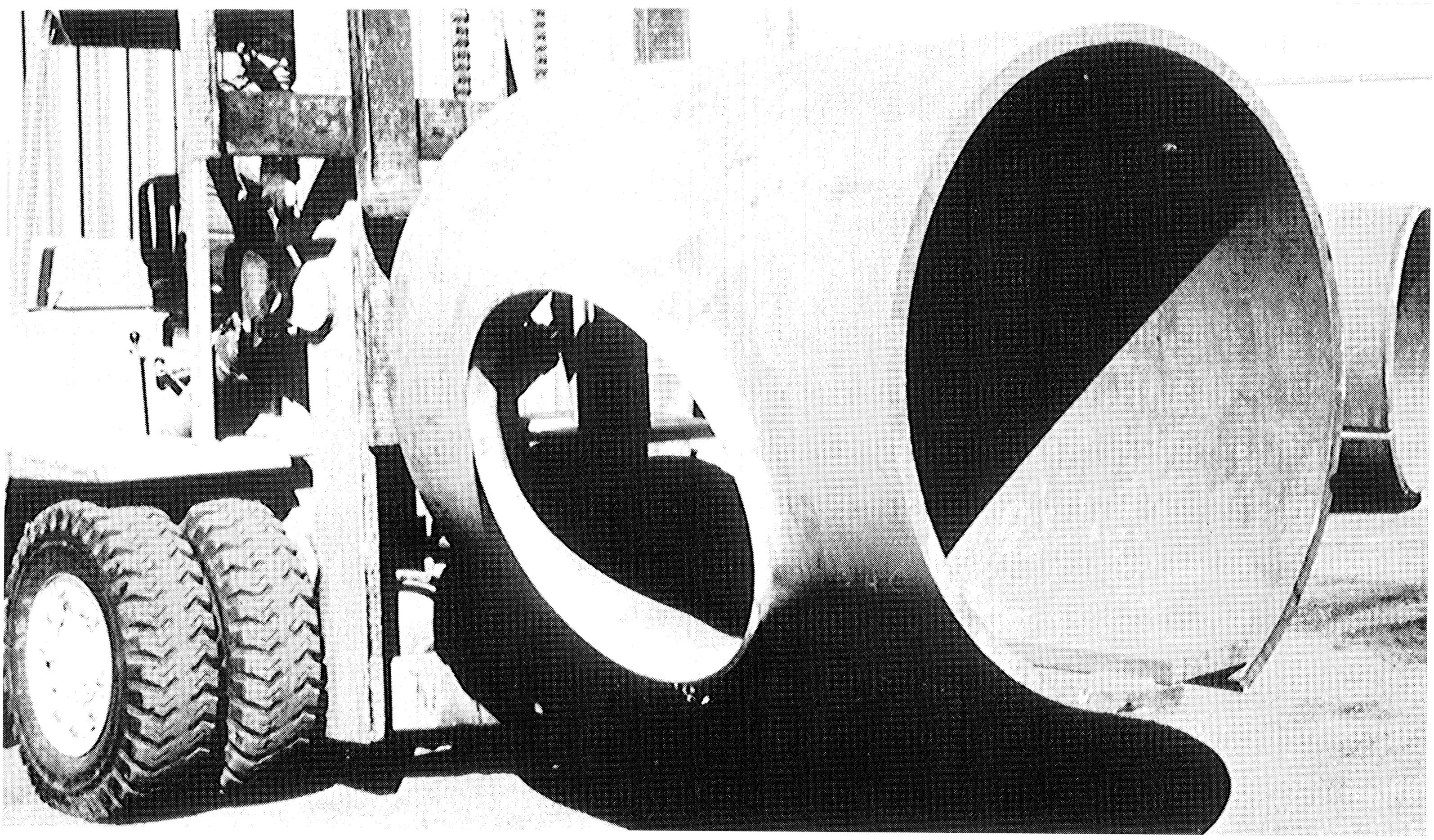
MECHANICAL PROPERTIES

YS, ksi	92.8	93.2	95.2	83.4
TS, ksi	104.2	104.5	100.6	89.9
% EL-2"	38.2	35.0	35.0	37.5
% EL-8"	20.0	18.5	19.0	20.0
Hardness BHN	228.0	228.0	217.0	187.0
CVNL @ –50 F, ft-lb	39.0	39.0	42.0	60.0

[1] Precipitation hardened ½ hour at temperatures shown.

Figure 6—Transverse bend tests of 5/16" thick IN-787 plate as rolled and precipitation hardened.[1]

Figure 7—Ductility and low work hardening characteristics of IN-787 make it a most desirable material for use in extruded headers used in pipelines, refineries and power plants. Shown here is a prototype which demonstrates the suitability of IN-787 for this service.



APPLICATION

An unusual combination of engineering properties and fabricability makes IN-787 ideally suited for a full spectrum of designs for trucks, off-highway vehicles, valves, fittings, and pressure vessels, offshore rigs, construction and lifting equipment, motor shafting, heavy duty wheels and rims, rail car structural assemblies, rudders and selected ship hull plates. It is especially suitable for service in the Arctic or other areas where low temperature toughness is important.

In-787's applicability extends to virtually all fields of metalworking where high strength structural alloy steel can be effectively utilized. The value of IN-787, however, lies in the designer's optimum usage of mechanical properties, and the fabricator's ability to recognize and apply specific cost saving advantages. Table 11 summarizes distinctive advantages in design and fabrication.

Many of the factors listed in Table 11 have been successfully applied to concepts and products that have taken full advantage of the design potential and cost savings implicit in this new steel. A few examples are shown in Figures 8-12.

TABLE 11
IN-787 STEEL'S DESIGN AND FABRICATING ADVANTAGES

IN DESIGN

- Combined high strength and notch toughness
- Improved base metal and weld fatigue strength
- Resistance to hydrogen induced cracking
- Ability to form tight bend radii without cracking
- Broad range of heat treated properties
- HAZ toughness with or without post weld stress relief
- Improved corrosion resistance over carbon steel
- Capability from light gauge to heavy section
- High ductility and low work hardening characteristics
- High efficiency butt welded joints

IN FABRICATION

- Substantially reduced welding costs
- Improved formability
- Workable in all conditions of heat treatment
- Combined precipitation hardening and stress relief
- Unhardened HAZ on welding and flame cutting
- Flexible forming, welding and heat treating schedules
- Weldable under extreme conditions of cold and moisture

Figure 8—Large forgings, 26"—600 lb weld neck flanges of IN-787 were used in the Alyeska oil line because of the excellent combination of strength and low temperature notch toughness. The section thicknesses ranged from 2¼" to 7⅝".

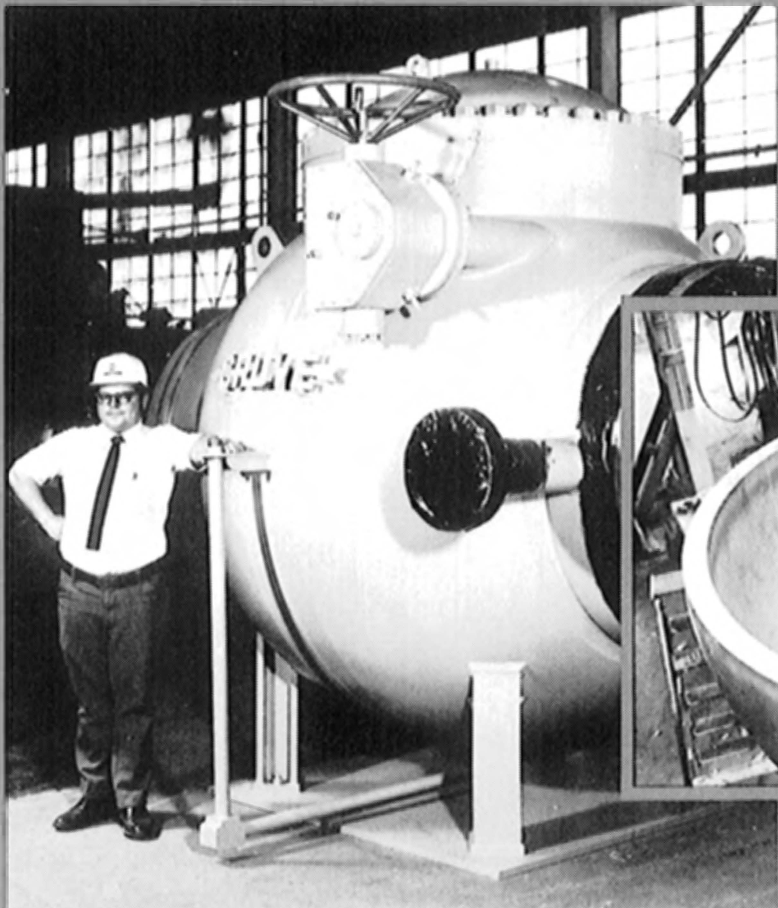


Figure 9—Large check valves for use in the Alyeska oil line were fabricated entirely from IN-787 plate up to 4" thickness. The strength and excellent toughness at temperatures as low as −80 F were achieved by precipitation hardening after forming and welding.

Figure 10—Shown here is a portion of the check valve, Figure 9, being submerged arc welded.

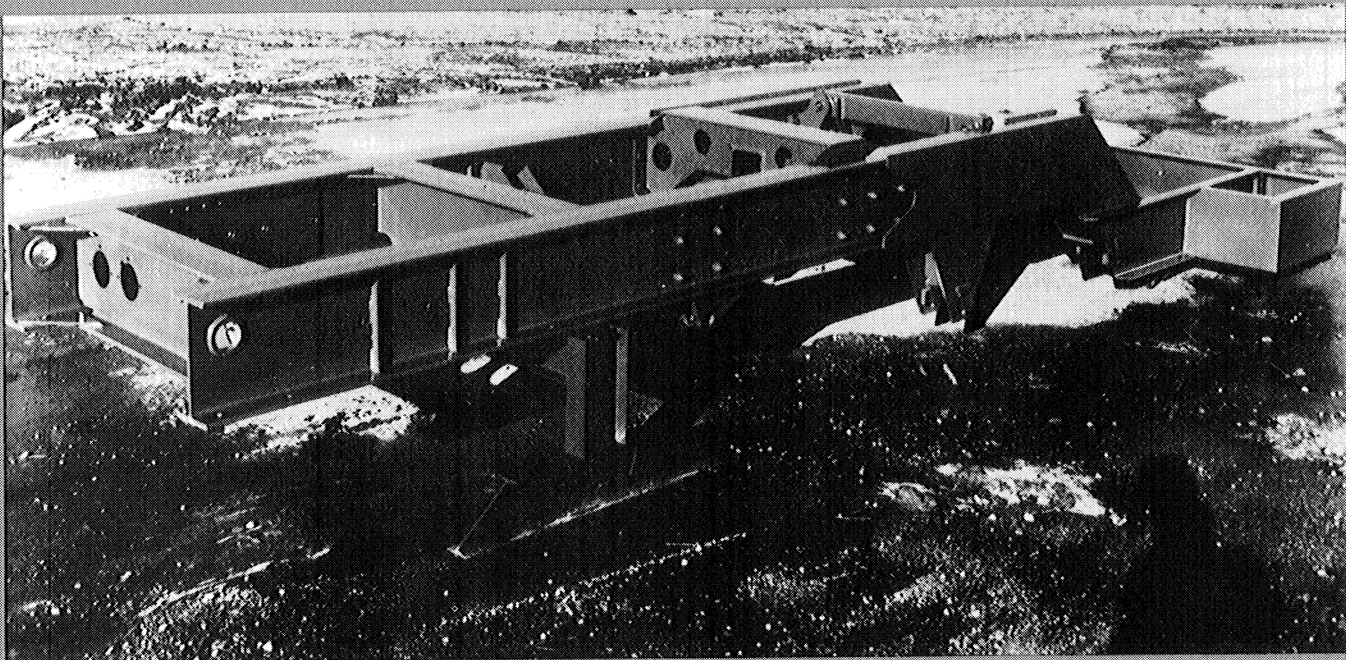


Figure 11—Wide flange beams are fabricated into tough, heavy duty frames for mining trucks. Notch toughness, high strength and improved fatigue properties mark IN-787's design capability.

Figure 12—Structural members of large coal and ore haulers are a rapidly developing application for IN-787. Extensive use of IN-787 saves on forming, welding and flame cutting. Improved fatigue properties with combined strength and toughness provide customers with higher payload and durability over wide range of service conditions.