36% NICKEL-IRON ALLOY

For Low Temperature Service

Introduction

36 per cent nickel-iron alloy possesses a useful combination of low thermal expansion, moderately high strength and good toughness at temperatures down to that of liquid helium, -452 ºF (-269 ºC). These properties coupled with good weldability and desirable physical properties make this alloy attractive for many cryogenic applications. A modified form of 36 per cent nickel-iron alloy known as INVAR* M 63 has been used for LNG membrane tanks. It is available as plate, strip, sheet, pipe, tubing, bars, billets, forgings and wire.

Specifications

ASTM Designation A 658 covers 36 per cent nickel-iron alloy plates intended primarily for welded pressure vessels. The material is supplied in the annealed condition to meet the requirements of the ASME Boiler and Pressure Vessel Code. The maximum allowable stress value in tension for the ASME counterpart, SA-658, given in Section VIII, Division 1 of the ASME Code is 16,200 psi (112 N/mm^2).

A proposed ASTM specification for 36 per cent nickel-iron alloy piping is under development.

Chemical Composition

The chemical composition as given in the ASTM standard is as follows:

Element	Composition, %
Carbon	0.10 max
Manganese	0.50 max
Phosphorus	0.025 max
Sulfur	0.025 max
Silicon	0.35 max
Nickel	35.5-36.5
Iron	Balance

Notes: Phosphorus and sulfur each 0.010 max if specified. Chromium, molybdenum and cobalt each 0.50 max but not intentionally added.

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Tensile Requirements

The following tensile properties are specified in the ASTM standard:

Tensile Strength .... 65,000-80,000 psi
.... 448-552 N/mm^2

Yield Strength
(0.2% Offset), min .... 35,000 psi
.... 241 N/ mm^2

Elongation
(2 in. or 50 mm), min, % 30.0

Heat Treatment

Annealing–ASTM A 658

The following procedure for heat treatment is recommended in the above mentioned standard:

Heat to 1450 ± 50 ºF (790 ± 28 ºC); hold at this temperature ½ hour per inch (25 mm) of thickness, but not less than 15 minutes; cool in still air. Typical hardnesses after several alternate annealing treatments are shown in Table I.

TABLE I

Annealing of 36 Per Cent Nickel-Iron Alloy

Temperature ºF	Temperature ºC	Cooling Medium	Hardness Rockwell B
1200	650	Air	87-88
1500	815	Air	77-78
1800	980	Air	70-71
1900	1040	Air	66-68

Stability Anneal

The following three-stage heat treatment was developed[1] to achieve the optimum combination of low expansion coefficient and high dimensional stability:

1. Heat to 1525 ºF (830 ºC), hold ½ hour per inch (25 mm) of thickness, water quench.

2. Reheat to 600 ºF (315 ºC), hold 1 hour per inch (25 mm) of thickness, air cool.
3. Reheat to 205 ºF (96 ºC), hold 48 hours, air cool.

Mechanical Properties

Tensile Properties and Hardness

Typical room temperature mechanical properties of annealed and cold worked 36 per cent nickel-iron alloy are shown in Table II.[2] The effect of temperature on the tensile properties of plate and forged bars in the annealed condition are shown in Figures 1 and 2.

36 per cent nickel-iron alloy is not notch-sensitive: the ratio of notched tensile strength to unnotched tensile strength is on the order of 1.10 at room temperature as well as at -320 ºF (-196 ºC).[3]

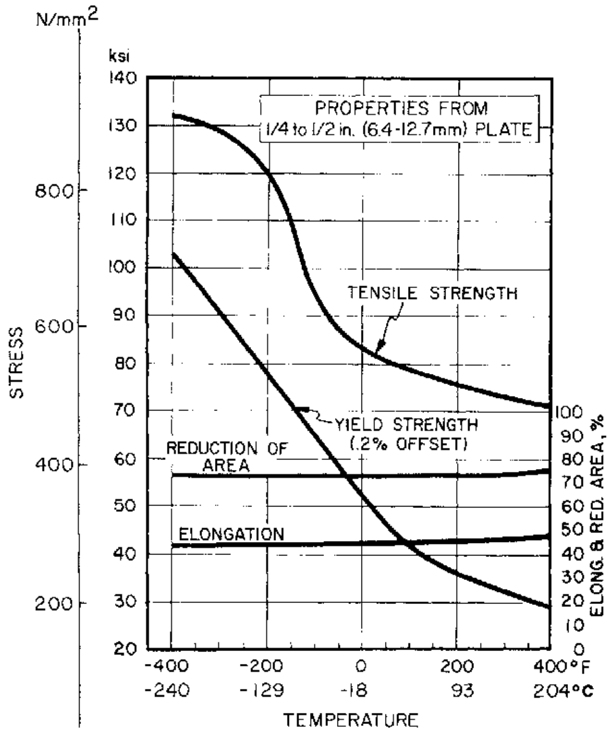

Figure 1. Effect of temperature on the typical tensile properties of annealed 36% Ni-Fe alloy.

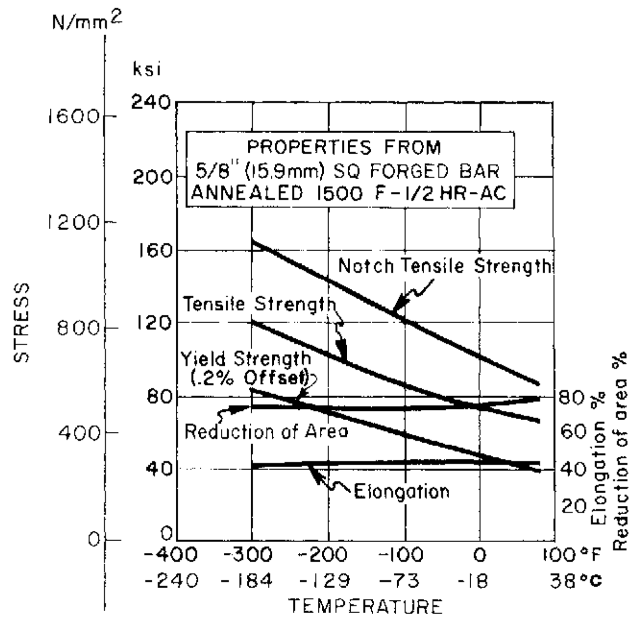

Figure 2. Effect of temperature on the tensile properties of forged 36% Ni-Fe alloy in the annealed condition.

TABLE II

Typical Mechanical Properties of 36 Per Cent Nickel-Iron Alloy

	Annealed	**Cold Worked 15%**	**Cold Worked 25%**	**Cold Worked 30%**
Tensile Strength, psi	71,400	93,000	100,000	106,000
N/mm^2	(492)	(641)	(690)	(731)
Yield Strength (0.2% Offset), psi	40,000	65,000	89,500	95,000
N / mm^2	(276)	(448)	(617)	(655)
Elongation (2 in. or 50 mm), %	41	14	9	8
Reduction of Area, %	72	64	62	59
Brinell Hardness	131	187	207	217

Stability of Properties on Exposure to Low Temperatures for Long Times

The mechanical properties of 36 per cent nickel-iron alloy are not affected by exposure to low temperatures for long periods of time. Exposure for times up to several thousand hours at –320 ºF (–196 ºC) with and without applied stress have not altered its mechanical properties, even in the case of notch-sensitivity.

Impact Properties

The effect of temperature on the Charpy impact values of annealed and cold worked 36 per cent nickel-iron alloy is shown in Figure 3.

Fatigue Properties

The room temperature fatigue strength at 10^8 cycles of polished rotating-beam R. R. Moore specimens of annealed 36 per cent nickel-iron alloy is approximately 40,000 psi (276 N/mm^2). Figure 4 shows axial fatigue properties of cold rolled 0.040 inch (1.0 mm) thick sheet at room temperature and at –100 ºF (–73 ºC). Typical fatigue endurance limits at 10^7 cycles for sheet specimens tested in alternating plane bending at constant strain amplitude are 27,000-31,000 psi (186-214 N/mm^2) at room temperature and 39,000-41,000 psi (269-283 N/mm^2) at –320 ºF (–196 ºC).[3]

Welding

For pressure vessel construction, 36 per cent nickel-iron alloy falls into Group P-10g, Table Q-11.1, Section IX of the ASME Code governing welding procedure qualification. The ASME tensile requirement for the weld metal is 65,000 psi (448 N/mm^2) minimum. Welds of matching strength to the base plate have been achieved using appropriate filler metals such as modified 36 per cent nickel-iron filler metal, INCONEL* Filler Metal 92 and HASTELLOY** alloy W.

The 36 per cent nickel-iron alloy can be readily welded. However, where matching thermal and mechanical properties are required, either TIG (tungsten inert gas) or the short-circuiting modification of MIG (metal inert gas) welding processes should be used. The shielding gas normally used is argon, although helium-argon mixtures may be used. In general, welding procedures and precautions are not much more stringent than those exercised for high quality welds in the AISI 300 series stainless steels. A commercially available filler metal of modified 36 per cent nickel-iron alloy closely matching the base metal in expansion properties has been developed.[4] This composition in per cent is listed below:

Modified 36 per cent Nickel-Iron Alloy Filler Metal

Nickel	36.0
Carbon	0.1
Manganese	3.0
Silicon	0.1 max
Titanium	1.0
Sulfur*	.01 max
Phosphorus*	.02 max
Iron	Bal

* Total percentage of P plus S not to exceed 0.025%.

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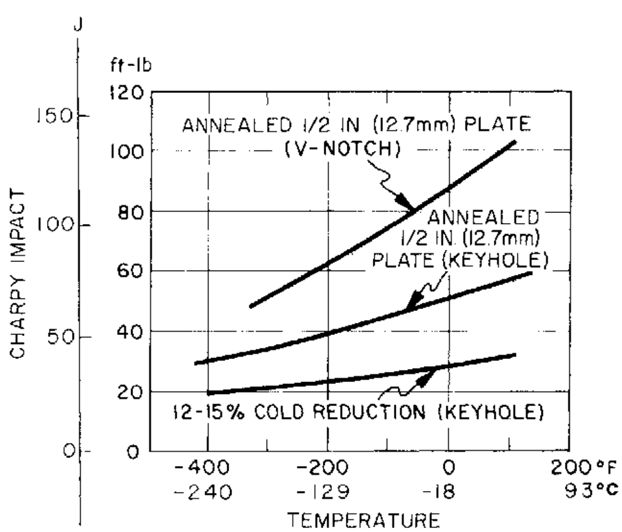

Figure 3. Effect of test temperature on Charpy Impact Values for 36% Ni-Fe alloy.

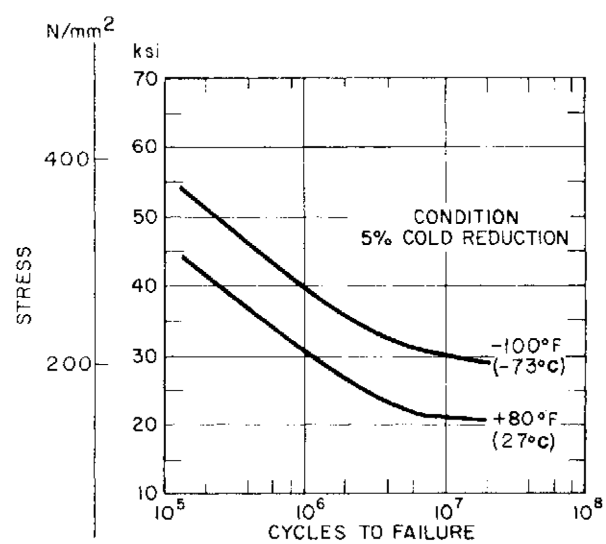

Figure 4. Axial fatigue characteristics of smooth 0.040 in. (1.0 mm) 36% Ni-Fe alloy sheet at 80 ºF (27 ºC) and -100 ºF (-73 ºC).

Typical mechanical properties of TIG welds at three test temperatures are shown in Table 111.[5] The data reported were determined on ¼ inch (6.4 mm) plate but similar properties are achieved readily in sheet thickness welds and in heavier plate weldments. Welding of 36 per cent nickel-iron alloy pipe using the inert gas processes is covered in NASA Specification 75M09470.

36 per cent nickel-iron alloy is readily resistance welded. Welding variables are essentially the same as those used for annealed austenitic stainless steels. Spot welds meeting all requirements of MIL-W-6858 have been made in matching and dissimilar sheet thickness combinations from 1/16 to ¼ inch (1.6-6.4 mm).[6]

Where thermal expansion considerations permit, 36 per cent nickel-iron alloy can be joined readily to itself as well to a variety of iron and nickel-base alloys using such general purpose filler metals as INCONEL Filler Metal 92 and HASTELLOY alloy W. Typical properties are shown in Table IV.[5]

Corrosion

General corrosion rates of 36 per cent nickel-iron alloy are below one mil per year (.025 mm/yr) for both industrial and marine atmospheric exposures. (Table V). The 36 per cent nickel-iron alloy has shown some susceptibility to stress-corrosion cracking in tests when exposed to sea water or marine atmospheres. Data obtained from multiple U-bend specimen exposures are summarized in Table V. Rapid cracking has been reported in acid chloride environments of pH 2 and at elevated temperatures.

The alloy is also subject to deep pitting on boldly exposed surfaces in flowing sea water at two feet per second (0.6 m/sec). (Table V).

Physical Properties

The thermal expansion properties in the annealed condition are shown in Table VI.[7] Figure 5 illustrates the thermal contraction of annealed and cold worked 36 per cent nickel-iron alloy between room temperatures and –423 ºF (–253 ºC). Cold work usually reduces thermal expansion while composition variations usually raise expansion values.

The effect of temperature upon the modulus of elasticity, modulus of rigidity and thermal conductivity of 36 per cent nickel-iron alloy are shown respectively in Figures 6, 7 and 8.

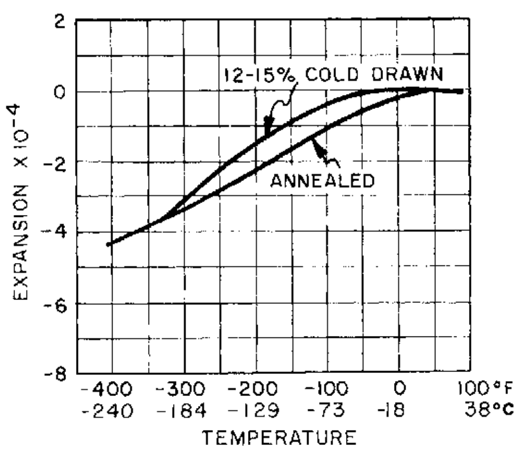

Figure 5. Thermal contraction of cold drawn and annealed 36% Ni-Fe alloy from 70 ºF (21 ºC).

TABLE III
Mechanical Properties of TIG Welded 36 Per Cent Nickel-Iron Alloy[a]

Condition	Test Temperature ºF	Test Temperature ºC	Tensile Strength psi	Tensile Strength N/mm²	Yield Strength (0.2% Offset) psi	Yield Strength (0.2% Offset) N/mm²	Elongation (1 in. or 25 mm) %	Charpy V-Notch Impact[b] ft-lb	Charpy V-Notch Impact[b] J
As	70	21	70,200	484	44,600	308	26.0-30.0	46	62
Welded	–320	–196	120,800	833	88,800	612	23.0	–	–
	–423	–253	126,100	869	110,100	759	17.0-20.0	19	26
Welded and	70	21	72,000	496	43,600	301	25.0-30.0	56	76
Annealed	–320	–196	122,400	844	89,300	616	22.0	–	–
at 1450 ºF	–423	–253	129,800	895	105,500	727	20.0-20.5	24	32

a Plate ¼ inch (6.4 mm) thick using modified 36% nickel-iron alloy filler metal.
b Subsize impact specimen.

TABLE IV

Butt Weld Mechanical Properties of TIG Welded Dissimilar Metals

Mechanical Properties at Indicated Test Temperatures[a]

36 Ni-Fe Welded to:	Filler wire[b]	+70 ºF (21 ºC) TS[c] ksi	TS[c] N/mm²	.2% YS ksi	.2% YS N/mm²	Elong. (2 in. or 50 mm), %	CVN[d] ft-1b	CVN[d] J
36 Ni-Fe	92	79	545	61	421	27	77	104
AISI 304	92	75	517 1	42	290	32	55	75
	W	76	524 1	43	297	28	–	–
AISI 304L	92	76	524 1	41	283	33	54	73
	W	75	517 0	38	262	45	–	–
AISI 316	92	75	517 1	43	297	26	40	54
	W	76	524 1	43	297	30	–	–
AISI 321	92	75	517 1	44	303	27	45	61
	W	76	524 1	45	310	25	–	–
AISI 347	92	76	524 1	44	303	24	38	52
	W	76	524 1	45	310	25	–	–
AISI 1020	92	68	469 0	46	317	18	35	48
	W	68	469 0	46	317	20	–	–

36 Ni-Fe Welded to:	Filler wire[b]	–320 ºF (–196 ºC) TS[c] ksi	TS[c] N/mm²	.2% YS ksi	.2% YS N/mm²	Elong. (2 in. or 50 mm), %	CVN[d] ft–Ib	CVN[d] J
36 Ni-Fe	92	137	945	97	669	35	46	62
AISI 304	92	133	917 W	53	365	21	39	53
	W	129	889 W	50	348	20	–	–
AISI 304L	92	135	931 W	43	297	28	30	41
	W	132	910 W	44	303	26	–	–
AISI 316	92	133	917 W	89	614	20	28	39
	W	132	910 W	79	545	–	–	–
AISI 321	92	138	952 1	53	365	29	29	39
	W	126	869 W	54	372	20	–	–
AISI 347	92	141	972 1	72	496	30	20	27
	W	136	938 W	71	490	25	–	–
AISI 1020	92	131	903 0	95	655	14	19	26
	W	123	848 W	79	545	12	–	–

36 Ni-Fe Welded to:	Filler wire[b]	–423 ºF (–253 ºC) TS[c] ksi	TS[c] N/mm²	.2% YS ksi	.2% YS N/mm²	Elong. (2 in. or 50 mm), %	CVN[d] ft–Ib	CVN[d] J
36 Ni-Fe	92	140	965	109	752	32	46	62
AISI 304	92	136	938 1	63	434	29	36	49
	W	140	965 W	60	414	19	–	–
AISI 304L	92	128	883 W	46	317	22	36	49
	W	138	952 W	49	338	19	–	–
AISI 316	92	145	1000 1	101	696	27	29	39
	W	125	862 W	84	579	17	–	–
AISI 321	92	137	945 1	54	372	26	28	38
	W	136	938 W	59	407	17	–	–
AISI 347	92	144	993 1	80	552	27	21	28
	W	138	952 1	79	545	21	–	–
AISI 1020	92	113	779 0	102	703	2.0	19	26
	W	103	710 0	86	593	5.0	–	–

[a]All materials ¼-inch (6.4 mm) thick plate, annealed prior to welding.
[b]92 signifies INCONEL Filler Metal 92
W signifies HASTELLOY alloy W.

[c]W =Failed in weld metal
1 =Failed in 36 Ni-Fe parent metal
O =Failed in other parent metal

[d]Subsize impact specimen.

Physical Constants

Typical values of indicated physical constants[8] for 36 per cent nickel-iron alloy are shown below:

	English Units	Metric Units
Modulus of Elasticity	20.5×10^6 psi (see Figure 6)	141×10^3 N/mm^2
Modulus of Rigidity (Shear)	8.1×10^6 psi (see Figure 7)	56×10^3 N/mm^2
Poisson's Ratio	0.290	
Density	0.294 lb/cu in.	8.14 g/cu cm
Electrical Resistivity	490 ohm (circ mil/ft)	81.5 microhm-cm
Specific Heat	0.123 Btu/lb/°F (77-212 °F)	0.123 cal/g/°C (25-100 °C)
Thermal Conductivity	93 Btu/hr/sq ft/°F/in. (see Figure 8)	.032 cal/sec/sq cm/°C/cm
Curie Temperature	530 °F	277 °C
Melting Point	2600 °F	1427 °C

TABLE V

General Corrosion Rates

Atmospheric Exposures	Test Duration	Corrosion Rate mils per year	Corrosion Rate mm/yr
Industrial	10 years	0.7	.02
Marine	up to 5 years	0.1-0.3	.003-.008

Localized Corrosion Phenomena

Stress Corrosion

Exposure	Test	Test Duration	Apparent Crack Progression mils per year	Apparent Crack Progression mm/yr
Marine Atmosphere Kure Beach, N.C.	U-Bend	up to 4 years	3-11	.08-0.28

Pitting

Exposure	Result
Immersion in flowing 2 fps (0.6 m/sec) sea water at ambient temperature	Sheet material perforates rapidly: .019 in. (0.5 mm)–within 16 days .060 in. (1.5 mm)–within 49 days

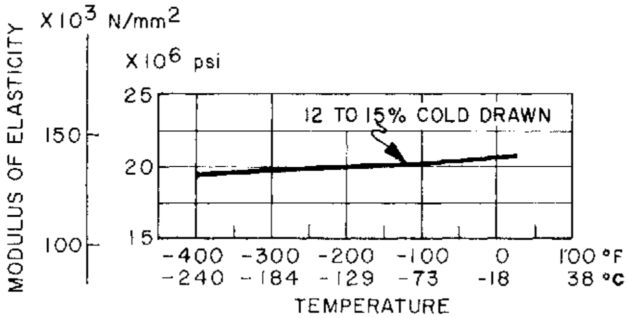

Figure 6. Effect of temperature on the Modulus of Elasticity of 36% Ni-Fe alloy.

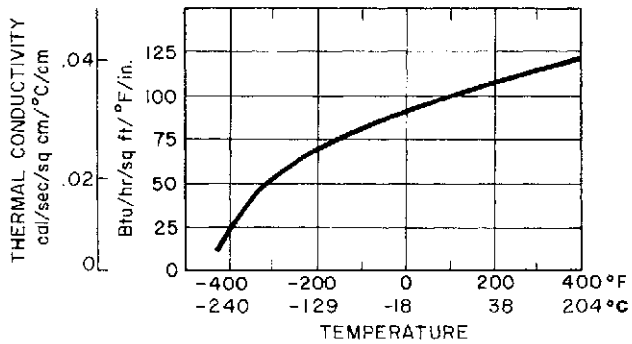

Figure 8. The effect of temperature on the Thermal Conductivity of 36% Ni-Fe alloy.

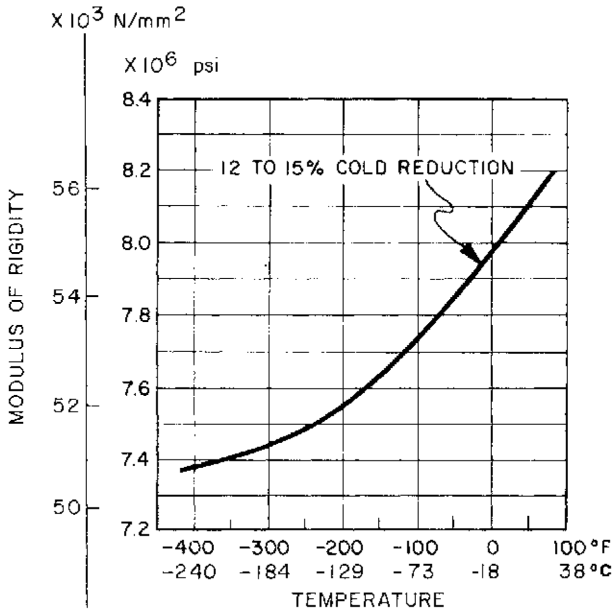

Figure 7. Effect of temperature on the Modulus of Rigidity of 36% Ni-Fe alloy.

TABLE VI

Thermal Expansion Data on 36 Per Cent Nickel-Iron Alloy

Temperature Range		Mean Coefficient of Linear Expansion	
°F	°C	per°F	per°C
-400 to 0	-240 to -18	1.20×10^{-6}	2.16×10^{-6}
-200 to 0	-129 to -18	1.10×10^{-6}	1.98×10^{-6}
0 to 200	- 18 to 93	0.70×10^{-6}	1.26×10^{-6}
200 to 400	93 to 204	1.50×10^{-6}	2.70×10^{-6}
400 to 600	204 to 316	6.40×10^{-6}	11.52×10^{-6}

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