AUTHOR: W. F. BROWN, JR.

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

1 GENERAL

This steel was designed specifically for use at cryogenic temperatures. Heat treatments have been developed which produce Charpy-V, impact energies well in excess of 25 ft lb at -320 F. Room temperature tensile strength varies from about 90 to 120 ksi depending on the carbon content and the heat treatment. Unless special attention is given to reducing the content of tramp elements temper embrittlement may be encountered during slow cooling or prolonged heating in the temperature range 500 to 1000 F.

Welding practices have been developed using high-nickel electrodes that produce welds having cryogenic impact values in excess of those of the parent metal. Recently efforts have been made to develop ferritic electrodes which are capable of producing welds with high cryogenic impact values but at a lower cost than characteristic of those made with the high-nickel electrodes.

The steel is widely used in various cryogenic storage vessels with the major application being in transportation and storage of liquified natural gas and other liquid gases. ASME Code permits the use in these applications without stress relief. In the aerospace field, applications include structural members and compressor disks of low temperature (high Reynolds number) wind tunnels.

1.01 <u>Commercial Designation</u>
9 Ni Steel

1.02 <u>Alternate Designations</u>

1.03 <u>Specifications</u>
Table 1.03

1.04 <u>Composition</u>
Table 1.04

1.05 <u>Heat Treatment</u>
General. The commercial heat treatments have
1.051 been developed to provide an optimum combination of room temperature tensile strength and toughness at cryogenic temperatures. When quenched from above the Ae_3 in section sizes less than about 2 inches, the alloy is fully martensitic with a small amount of retained austenite. Reheating at temperatures above about 900 F will result in the formation of austenite which is retained after cooling from the tempering temperature. The amount of retained austenite is time-temperature dependent (see Fig. 1.055). At a given tempering temperature the amount of retained austenite passes through a maximum with increasing tempering time and this maximum shifts to lower times as the tempering temperature is increased. Tempering temperatures above about 1000 F are necessary to produce significant amounts of austenite in practical time periods. The stability of the austenite at cryogenic temperatures depends on the alloy composition and the temperature at which the austenite is formed. Lower tempering temperatures tend to produce more stable austenites but require longer times to produce a given amount. Generally, the commercially heat treated alloy will contain from 4 to 10 percent austenite.

The alloy's high toughness at cryogenic temperatures is associated with the presence of retained austenite as can be seen by comparing Fig. 1.055 with 1.056 and by reference to Fig. 1.0513. The minimum in the -320 F impact energy for material tempered at 950 and 1000 F is associated with an embrittlement reaction discussed later (see 1.09). Tempering at temperatures above 1000 F followed by cooling to -320 F will result in some of the retained austenite transforming to martensite. This is illustrated in Fig. 1.055 which shows the reduction in austenite content for samples cooled to -320 F after tempering. Since this transformation will also occur during cryogenic service, tempering temperatures in excess of 1100 F are not generally used.

Various mechanisms have been suggested to explain the beneficial effect of the retained austenite on the cryogenic toughness. The most likely mechanisms are the scavenging of detrimental impurities from solid solution thereby increasing the toughness of the martensite and/or crack blunting at the martensite-austenite boundaries through crack branching (16) (28).

If cooling above the Ae_3 is sufficiently slow, bainites will be produced and these structures will have reduced yield strengths and toughnesses compared with the martensitic structure (see Fig. 1.057). Large amounts of bainite are found in heavy sections which have been air cooled from the austenitizing temperature (e.g., Table 1.0514).

From the foregoing it is evident that considerable variation in mechanical properties could be encountered due to variations in composition within specification limits, as well as variations in tempering treatments and cooling rates from above the Ae_3 (e.g., Table 1.058). However, with proper care in heat treatment there is no difficulty in meeting the current specifications for tensile strengths and -320 F Charpy-V impact energies in plate less than 1 inch thick (e.g., see Table 3.012) and even very heavy sections can be produced with excellent cryogenic toughness by using special melting practices (e.g., see Tables 1.0922 and 1.0923).

1.052 Quench and temper. Austenitize 1450 to 1500 F, 1 hour per inch but not less than ¼ hour, W.Q. + 1050 to 1125 F, 1 hour per inch but not less than ¼ hour, W.Q. or A.C. at minimum rate of 300 F per hour (14) (15) (30) (31).

	Fe
0.13 max	C
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0.9	Mn
0.15-0.30	Si

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1.053 Double normalize and temper. 1625 to 1675 F, 1 hour per inch but not less than ¼ hour, A.C. + 1425 to 1475 F, 1 hour per inch but not less than ¼ hour, A.C. + 1050 to 1125 F, 1 hour per inch but not less than ¼ hour, W.Q. or A.C. at minimum rate of 300 F per hour (13) (15) (30) (31).

1.054 Stress relief. 1025 to 1085 F, 2 hour for thicknesses up to 1 inch + 1 hour per inch for greater thicknesses, cool at a minimum rate of 300 F per hour (15) see also 1.09.

1.055 Effect of tempering temperature and time on austenite retention at R.T. and -320 F. Fig. 1.055.

1.056 Impact energy at -320 F as a function of tempering time for several tempering temperatures. Fig. 1.056.

1.057 Tensile and impact properties at cryogenic temperatures as a function of percent bainite. Fig. 1.057.

1.058 Variation in mechanical properties of commercially heat treated plate. Table 1.058.

1.059 Tensile and -320 F impact properties of a double quenched and tempered 5 inch thick slab before and after stress relief. Table 1.059.

1.0510 Effect of cold work and subsequent stress relief on -320 F Charpy-V impact energy of plate, Table 1.0510.

1.0511 Effect of grain refining heat treatment on cryogenic tensile and impact properties of plate. Table 1.0511.

1.0512 Effect of low test temperatures on impact energy of plate tempered for various times. Fig. 1.0512.

1.0513 Charpy-V and drop weight tear impact energies at -320 F as a function of percent austenite. Fig. 1.0513.

1.0514 Effect of cooling rates from austenitizing and from the tempering temperature on formation of bainite. Table 1.0514.

1.06 Hardness

1.061 Effect of test temperature on hardness of quenched and tempered plate. Fig. 1.061.

1.062 End quench hardenability. Fig. 1.062.

1.07 Forms and Conditions Available. Sheet, plate, forgings, tubing, seamless pipe in hot formed or heat treated conditions.

1.08 Melting and Casting Practice

1.081 General. The melting and casting practice is designed to minimize inclusion content and to reduce the content of tramp elements. Electric furnace or converter air melting is generally employed with a double slag process. DH vacuum or vacuum stream degassing is used to reduce the hydrogen and oxygen content. DH vacuum degassed ingots are sometimes bottom poured with the metal stream being protected by an inert gas. Continuous casting is employed in some United States steel plants.

1.09 Special Considerations

1.091 Embrittlement. The metallurgical changes occurring in this steel during heat treatment are complex and can have a profound effect on the toughness. The optimum structure appears to consist of a low carbon martensite with about 5 to 10 percent retained austenite. Variations from this structure which contribute to embrittlement are associated with over or under tempering and excessively slow cooling rates from the austenitizing or tempering (or stress relieving) temperature. Over tempering can result in a decreased austenite stability and the consequent formation of untempered martensite. Under tempering can result in temper embrittlement. These deleterious effects can be overcome by proper control of the tempering process. However, the damaging effects of excessively slow cooling rates may be difficult to avoid if the section sizes are sufficiently large.

1.0911 Effects of Cooling Rates. Problems arise from two sources: (1) mixed structures which are produced by too slowly cooling from the austenitizing temperature and (2) temper embrittlement which can be encountered by too long a dwell time in the range between 500 and 1000 F. It is possible to encounter both phenomena during a given heat treat cycle. Fortunately, recent advances in composition and processing control can minimize the temper embrittlement.

Appreciable amounts of bainite (mixed structures) will be produced in sections over about 3 inches thick even though the alloy is quenched. These structures have reduced toughness at cryogenic temperature as compared with the tempered martensites (see Fig. 1.057). The effect of cooling rates from the austenitizing temperature are illustrated in Table 1.0914 which gives results for tests on two heavy sections oil quenched or air cooled from the austenitizing temperature. Note that substantial losses in impact energy at -320 F are associated with air cooling.

Temper embrittlement in this steel is a time-temperature dependent phenomenon with the largest effects being noted between about 700 and 900 F (see Figs. 1.0915, 1.0916, and 1.0917). The effect of very slow cooling from a normal tempering temperature is shown in Table 1.0919. The temper embrittlement is reversible and the toughness may be recovered by retempering at a temperature above about 1050 F (Table 1.0920) but such recovery treatments are not possible if the original embrittlement was associated with heavy sections.

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

When heat treating sufficiently thick sections, the effects of temper embrittlement are superimposed on those associated with mixed structures. For example, Table 1.0921 gives results for simulated cooling rates of a plate 27.5 inches thick subjected to water quenching or air cooling from both the austenitizing and tempering temperature. Note that low impact values at -320 F characterize both cooling conditions but that the room temperature tensile strength is not subtantially changed. Apparently very little information is available concerning the influence of temper embrittlement on valid K_{Ic} values of this alloy. Data obtained from tests on a large forged billet (see Table 3.03722) indicate that substantial reductions in plane strain fracture toughness can accompany stress relief of very heavy sections.

From the foregoing it is evident that stress relief may pose a problem if the cooling rates are sufficiently slow. It is for this reason that ASTM A522 specifies a relatively rapid cooling rate (300 F per hour minimum) from the stress relief temperature. The effect of cooling rate will depend on the alloy composition.

1.0912 Effects of Alloy Composition: Temper brittleness is associated with grain boundary segregation of certain tramp elements. The worst of these are P, Sb, Sn, and As. The effect of these elements can be altered to some extent by modification of the composition. For example, Cr and Si appear to strengthen the embrittling effect of P while the addition of Mo in minor amounts appears to reduce the embrittling effect of the tramp elements. (17) (18) (19).

Special studies and composition control have been employed (20) (21) to minimize temper embrittlement associated with slow cooling from the stress relief temperature. The beneficial effects of reduced Si and increased Mo contents are illustrated in Table 1.0922 for small vacuum melted heats containing low residuals. The improvements are obtained with no sacrifice in tensile strength. Tests of specimens cut from a very large forged cylinder, Table 1.0923, containing very low content of tramp elements, show only a small loss in Charpy-V impact energy associated with very slow cooling (18 F per hour) from the stress relief temperature. In addition, plane strain fracture toughness tests on specimens cut from a very large stress relieved forged disk (see Table 3.03723) show high K_{Ic} values at both the rim and disk bore.

On the basis of the above results it appears that by suitable composition control temper embrittlement can be practically eliminated during stress relief of heavy sections.

1.0913 Other Factors Influencing Toughness. As might be expected impact energy at cryogenic temperatures decreases with an increase in inclusion content (see Fig. 1.0927) and the transverse impact energy (see Fig. 1.0928) decreases with an increase in the cross rolling ratio. Hot or cold worked material should be completely heat treated rather than simply tempered, in order to develop good toughness at cryogenic temperatures (see Table 1.0929).

1.0914 Effect of section size and cooling rate from the austenitizing temperature on the room temperature tensile strength and the -320 F Charpy impact energy of forgings. Table 1.0914.

1.0915 Effect of tempering temperature on hardness and -320 F impact energy of bar. Fig. 1.0915.

1.0916 Iso-embrittlement diagram for plate. Fig. 1.0916.

1.0917 Effect of retempering time and temperature on -320 F impact energy of bar. Fig. 1.0917.

1.0918 Effect of test temperature on impact energy of bar after retempering at 600 F and 800 F. Fig. 1.0918.

1.0919 Influence of cooling rate from tempering temperature on the room temperature tensile strength and the -320 F impact energy of cast bar. Table 1.0919.

1.0920 Impact results illustrating the reversibility of temper embrittlement. Table 1.0920.

1.0921 Effect of cooling rate from austenitizing and tempering temperature on the room temperatrue tensile strength and the -320 F impact energy of a 2-inch thick plate cooled at a rate to simulate that of a 27.5-inch thick plate. Table 1.0921.

1.0922 Average values of room temperature tensile strength and -320 F impact properties of specimens from two heats illustrating the influence of composition on temper embrittlement. Table 1.0922.

1.0923 Influence of stress relief heat treatments on the average values of tensile strength and -320 F impact energy of specimens from a quenched and tempered, thick-walled cylinder. Table 1.0923.

1.0924 Effect of test temperature and stress relief on low temperature impact energy of a large forged billet. Table 1.0924.

1.0925 Tensile properties of a very large quenched and tempered and stress relieved disk forgings. Table 1.0925.

1.0926 Charpy-V impact energies at cryogenic temperatures for a very large quenched and tempered and stress relieved disk forging. Table 1.0926.

1.0927 Transverse impact energy at -320 F as function of inclusions. Fig. 1.0927.

1.0928 Influence of cross rolling ratio on transverse impact energy of plate. Fig. 1.0928.

1.0929 Effect of several heat treatments on the tensile and impact properties of hot worked and cold worked pipe. Table 1.0929.

2 PHYSICAL PROPERTIES AND ENVIRONMENTAL EFFECTS

2.01 Thermal Properties

2.011 Melting range. 2700 to 2900 F.

2.012 Phase changes (see Fig. 2.01211).

2.0121 Time-temperature-transformation diagrams.

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

2.01211 Isothermal transformation diagram. Fig. 2.01211.
2.013 Thermal conductivity. Fig. 2.013.
2.014 Thermal expansion.
2.0141 Coefficient of linear thermal expansion. Fig. 2.0141.
2.015 Specific heat. Table 2.015.
2.016 Thermal diffusivity.

2.02 Other Physical Properties
2.021 Density, 0.28 lb/in^3
2.022 Electrical properties.
2.023 Magnetic properties.
2.0231 Magnetic properties of double normalized alloy. Table 2.0231.

2.03 Chemical Environments
2.031 Corrosion. The corrosion rate of fully descaled U-bend and panel specimens exposed for periods up to 3.8 years at Harbor Island, in warm sea water (constant immersion depth) was 0.004 inch per year. At the 800 ft station at Kure Beach, N.C. the average corrosion rate after two years of exposure was 0.003 inch per year. U-bend specimens gave no indications of stress corrosion. In general the corrosion behavior is similar to other low alloy steels (3).

2.04 Nuclear Environments

3 MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties
3.011 Specified mechanical properties for various product forms. Table 3.011.
3.012 Producers tensile and -320 F Charpy-V impact properties obtained by tests on many 3/8-inch thick plates. Table 3.012.

3.02 Mechanical Properties at Room Temperature. (see 3.03)
3.021 Tension, stress-strain diagrams–tension properties.
3.022 Compression, stress-strain–compression properties.
3.023 Impact.
3.024 Bending.
3.025 Torsion and shear.
3.026 Bearing.
3.027 Stress concentration.
3.0271 Notch properties.
3.0272 Fracture toughness.
3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures
3.031 Tension, stress-strain diagrams–tension properties.
3.0311 Effect of elevated temperatures on tensile properties of quenched and tempered and of double normalized plate. Fig. 3.0311.
3.0312 Range of tensile strengths for double normalized and tempered plate of various thicknesses, Fig. 3.0312.
3.0313 Range of tensile strengths for quenched and tempered plate of various thicknesses. Fig. 3.0313.
3.0314 Effect of low test temperatures on tensile properties of double normalized and of quenched and tempered plate. Fig. 3.0314.
3.0315 Effect of low test temperatures on the tensile properties of quenched and tempered plate. Fig. 3.0315.
3.0316 Effect of low test temperatures on the tensile properties of quenched and tempered 1½ inch plate. Fig. 3.0316.
3.032 Compression-stress/strain diagrams–compression properties.
3.033 Impact.
3.0331 Effect of low test temperatures on the Charpy keyhole impact energy of double normalized and tempered 0.5 inch plate. Fig. 3.0331.
3.0332 Effect of low test temperatures on the Charpy-keyhole impact energy of quenched and tempered 0.5-inch plate. Fig. 3.0332.
3.0333 Effect of low test temperatures on ¾ width Charpy-V energy for double normalized and for tempered and quenched 3/8-inch plate. Fig. 3.0333.
3.0334 Effect of low test temperatures on the Charpy-V impact energy of double normalized 0.5-inch plate. Fig. 3.0334.
3.0335 Effect of low test temperatures on Charpy-V impact energy of quenched and tempered 0.5-inch plate. Fig. 3.0335.
3.0336 Effect of low test temperatures on Charpy-V impact energies of three thicknesses of double normalized and tempered plate. Fig. 3.0336.
3.0337 Effect of low test temperatures on Charpy-V impact energies of three thicknesses of quenched and tempered plate. Fig. 3.0337.
3.0338 Effect of low test temperatures on the Charpy-V impact energies of plate from a 100-ton, air-melt heat. Fig. 3.0338.
3.0339 Drop-Weight-Tear and Charpy-V energies at -320 F for double normalized and for quenched and tempered plates of two thicknesses. Table 3.0339.
3.035 Torsion and shear.
3.036 Bearing.
3.037 Stress concentration.
3.0371 Notch properties.
3.0372 Fracture toughness.
3.03721 Plane strain fracture toughness of plate at cryogenic temperatures. Table 3.03721.
3.0722 Effect of test temperature and stress relief on room temperature and -320 F tensile properties and plane strain fracture toughness of a large forged billet. Table 3.03722.
3.03723 Tensile properties and plane strain fracture toughness of a very large, quenched and tempered and stress relieved disk forging. Table 3.03723.
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.05 Fatigue Properties
3.051 Conventional fatigue properties.
3.0511 S-N Curves for double normalized and tempered, 0.75-inch diameter bar at room and cryogenic temperatures. Fig. 3.0511.

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

3.0512 S-N Curves for 0.75-inch, quenched and tempered plate. Fig. 3.0512.

3.0513 Rotating-beam fatigue strength for 0.25-inch, quenched and tempered plate at -270 F. Table 3.0513.

3.0514 S-N Curves for smooth and cracked specimens from quenched and tempered plate tested at room temperature and -320 F. Fig. 3.0514.

3.0515 Plastic strain range vs cycles to failure for quenched and tempered plate. Fig. 3.0515.

3.052 Fatigue crack propagation.

3.0521 Fatigue crack propagation rates at room temperature for double normalized and tempered, 1.3-inch plate. Fig. 3.0521.

3.0522 Fatigue crack propagation rate scatterband for quenched and tempered, 0.34-inch plate at room temperature. Fig. 3.0522.

3.0523 Fatigue crack propagation rate scatterband for quenched and tempered, 0.34-inch plate at -260 F. Fig. 3.0523.

3.0524 Fatigue crack propagation rates at room and cryogenic temperatures for quenched and tempered 1.25-inch plate. Fig. 3.0524.

3.06 Elastic Properties

3.061 Poisson's ratio.

3.062 Modulus of elasticity.

3.0621 Static modulus at room temperature and -320 F. Table 3.0621.

4 FABRICATION

4.01 Forming

4.011 General. There are no difficult problems with the hot or cold forming of this alloy and with few exceptions practices commonly employed for other low alloy steels should be satisfactory.

4.012 Forging. Starting 2250 F, finishing 1600 F.

4.013 Rolling. Relatively high soaking temperatures and substantial amounts of cross rolling result in improved impact proeprties (see Fig. 4.014). Air cooling following rolling tends to avoid the precipitation of AlN and MnS along austenite grain boundaries. Soaking temperatures below about 2012 F tend to produce a nickel enriched scale at the metal surface that is associated with grain boundary oxidation. In some cases slabs are covered on the face and back with thin steel sheets to reduce surface oxidation during rolling (35).

4.014 Effect of rolling ratio and soaking temperature on room temperature Charpy-V energy. Fig. 4.014.

4.02 Machining and Grinding.

4.03 Joining

4.031 Welding. General comments: Welding is generally done on stock in the fully heat treated condition. In so far as the steel is concerned, the only special precaution necessary is the avoidance of induced magnetism which can result in arc instability using DC processes. Remnant fields should be below 50 Oersted or AC electrodes (see Table 4.0315) should be used. Welding research and development has concentrated on those problems associated with the fabrication of large cryogenic storage vessels both for use in sea shipment of liquified gases and for ground storage. In production of these vessels post weld heat treatments are generally not possible nor have they been proven necessary (e.g., Table 4.03136). Weldments are required to have room temperature strengths, tensile and yield, close to those of the parent metal combined with very high toughness at cryogenic temperatures. The general practice is to use relatively low-carbon, high-nickel electrodes and filler wires (see Table 4.0315 and 4.0316). In some compositions the Ni content is reduced and the Mo or Cr content increased.

These high Ni wires and electrodes are expensive and considerable care is necessary in both the design of the weld joint and in control of the weld process to avoid hot cracking. Attempts have been made to use austenitic stainless steel electrodes but thin layers of hard martensite were formed at the fusion line which resulted in clevage fractures at the weld metal boundary (41). More recently considerable effort has been directed to the development of relatively low cost ferritic fillers. However, as yet no substantial production has been undertaken with these compositions.

Various welding processes are used in the fabrication of 9Ni Steel structures (e.g., Table 4.0317). Submerged metal arc (SMA) welding is generally used on the vertical joints and overhead. Automatic gas tungsten arc (GTA) welding in the vertical position is under development and has been used in the production of LNG (Liquified Natural Gas) storage tanks (37). Subarc and GMA welding is frequently used in the horizontal position. An excellent review of welding practices published in 1973 (27) gives valuable information concerning the various techniques and precautions that characterize the successful welding of 9Ni Steel. The following sections will not duplicate this detailed information but will concentrate on the mechanical properties of weld metal and weldments.

4.0311 Submerged Metal Arc Welding: This process when used with the high nickel electrodes is capable of producing very high -320 F Charpy-V values in the weld metal, in the fusion zone and in the heat affected zone (HAZ) (see Tables 4.0318 to 4.03111). Tensile ultimate and yield strengths for SMA deposited weld metal are generally lower than those of the parent metal with the largest difference being observed in the yield strength (compare Table 4.03112 with Tables 3.011 and 2.012). Special electrode compositions have been developed to produce a weld metal with room temperature tensile and yield strength matching that of the parent metal (e.g., Table 4.03113). However, such high strength weld metal will have lower -320 F Charpy-V energies than that produced by the more commonly used electrodes (e.g., compare Tables 4.0319 and 4.03110). Stress relief does

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

not reduce the Charpy values of the commonly used high nickel weld metals (see Tables 4.03110 and 4.03111). The influence of stress relief on the HAZ is more difficult to define due to the non-uniform properties within this zone and the varability that exists from one weldment to another. This variation introduces considerable scatter into the Charpy data. However, on the basis of averages there appears to be no substantial reduction in -320 F Charpy energies in the HAZ associated with stress relief (see Tables 4.0318 to 4.0311). Room temperature tensile properties of SMA high nickel weld metal do not appear to be influenced by stress relief (see Tables 4.03113 and 4.03114).

The results of wide center-crack plate tests on high nickel SMA weldments reveal crack strengths at -320 F in the HAZ well below those of the parent metal (see Figs. 4.03115 and 4.03116). Crack propagation tests on wide panels with cracks in the high nickel weld metal or in the fusion zone reveal da/dN values to be essentially equal to those of the parent metal at ΔK values above about 50 ksi $\sqrt{\text{inch}}$. However, at lower values of ΔK the crack propagation rates of the weld metal and the fusion zone appear to be lower than those of the parent metal (compare Figs. 4.03117 and 4.03118 with 3.0523). At -260 F the crack propagation rates in the fusion zone appear to be somewhat lower than at room temperature (see Fig. 4.03118).

Attempts have been made to develop ferritic electrodes (11 percent Ni) for the SMA process. However, the weld metal Charpy impact energies at -320 F have been considerably below those produced by the high nickel electrodes (see Table 4.03120) and at present no commercial applications appear to exist for the SMA process with ferritic electrodes.

4.0312 Gas Metal Arc Welding. Two modifications of this process, pulsed spray and short arc are adapted to automation and can be used in the vertical and overhead positions (37). With low carbon high nickel fillers, the -320 F weld metal Charpy-V and tensile properties of GMA welds are essentially the same as produced by the SMA process using similar high nickel electrodes (see Table 4.03121).

Investigation of ferritic fillers for the GMA process have defined an optimum nickel content in the wire of about 11 percent (see Fig. 4.03124). Using ferritic wire with the spray or short arc process, weld metal -320 F Charpy-V values in excess of 45 ft lbs were obtained in the vertical position and in excess of 65 ft.-lbs. were obtained in the horizontal position (see Fig. 4.03125). However, GMA welding using ferritic fillers has not been used in commercial production but rather emphasis has shifted to development of the more flexible GTA process (36).

4.0313 Gas Tungsten Arc Welding. The GTA process permits control of heat input and wire feed rates over a wide range. In addition, elements such as boron which can not be transferred in a metal arc can be added to GTA filler wire and the GTA process is adapted to reheating of final weld passes or to smoothing weld toes. Recently a highly automated GTA apparatus has been developed which permits welding in the vertical and overhead positions (37).

Using high nickel fillers based on the Hastalloy composition, very high -320 F Charpy-V energies characterize weld metal deposited by the automatic GTA technique (see Table 4.03126). Room temperature tensile properties are essentially equal to those produced by other processes using the high nickel wires or electrodes.

Because of the inherent flexibility of the GTA process, considerable attention has been given to its use with ferritic fillers (36) (37) (38). Using a low carbon ferritic filler containing about 11 percent Ni, Charpy-V values in excess of 60 ft lbs can be obtained at -320 F for weld metal providing the oxygen and nitrogen content of the weld metal is below about 50 ppm (see Fig. 4.03127). It appears that boron additions up to about 0.002 percent are necessary to control intergranular fracture at cryogenic temperatures (38). The Charpy-V energies in ferritic GTA weld metal and in the parent plate HAZ decrease rapidly with heat inputs above about 100 kJ/inch (see Figure 4.03128). A decrease in the weld metal tensile strength properties is also observed with increasing heat input (see Fig. 4.03129). The impact energies of the weld metal and the HAZ obtained with ferritic fillers will be a function of the amount of weld metal deposited on each pass. Small amounts deposited at relatively low heat inputs result in the best properties due to the auto-tempering of the previously deposited metal. To assist in this process, remelting of the finishing passes may be employed (see Tables 4.03130 and 4.03131). Using this reheating process high -320 F Charpy energies are obtained in the weld metal throughout the plate thickness (see Table 4.03132) and in the fusion zone and HAZ (see Table 4.03133). It is not clear from the published information to what extent reheating would be necessary during commercial welding nor how this process could be controlled effectively in the field. Presumably it would be increasingly necessary as the parent plate thickness decreased. While laboratory tests indicate considerable promise for use of ferritic fillers in the GTA, process no commercial applications have been reported.

4.0314 Sub-arc Welding. Automatic sub-arc welding is frequently used in the horizontal seams of large cryogenic fluid storage tanks. With the use of nickel filler wire with basic fluxes high deposition rates are possible that result in welds having -320 F Charpy-V impact energies essen-

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

tially equal to those produced by the SMA process. The room temperature tensile strength and the cryogenic impact energy will depend on the filler wire composition with the higher carbon contents giving lower impact values but higher tensile strengths. Typical results using a 0.12 C high nickel filler are shown in Table 4.03135. Attempts to use ferritic fillers (11 percent Ni) with the submerged arc process employing a flux cored wire have resulted in -320 F Charpy-V impact energies less than about 30 ft lb for the weld metal (26). Apparently there is presently no intensive development of ferritic fillers for the sub-arc process.

4.0315 Typical compositions of welding wire for coated electrodes. Table 4.0315.

4.0316 Typical compositions of welding wire for filler metal. Table 4.0316.

4.0317 Examples of electrodes used in various welding processes for fabrication of LNG tanks of 9Ni Steel. Table 4.0317.

4.0318 Charpy-V impact energies at room and -320 F at several positions with respect to the weld in SMA welded double normalized and tempered plate. Table 4.0318.

4.0319 Impact energies at -320 F at various locations in an SMA Weldment. Table 4.0319.

4.03110 Impact energies at -320 F at various locations in an SMA butt welded plate before and after stress relief. Table 4.03110.

4.03111 Effect of stress relief on -320 F Charpy impact values of SMA weld metal. Table 4.03111.

4.03112 Examples of weld processes, electrodes and fillers used in the United States along with typical mechanical properties of weld metal. Table 4.03112.

4.03113 Tensile properties of SMA weldments made on pieces cut from a large ring forging. Table 3.03113.

4.03114 Room temperature tensile properties of SMA weld metal in manually welded double normalized and tempered plate. Table 4.03114.

4.03115 Effect of low test temperatures on crack strength of the HAZ in a manual weldment of quenched and tempered plate. Fig. 4.03115.

4.03116 Effect of low test temperatures on crack strength of parent and of weld metal in a manual weldment of quenched and tempered plate. Fig. 4.03116.

4.03117 Fatigue crack propagation rates at room temperature for quenched and tempered SMA welded plate. Fig. 4.03117.

4.03118 Fatigue crack propagation rates at room temperature and -260 F for quenched and tempered SMA welded plate. Fig. 4.03118.

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4.03120 Shielded metal arc weld metal properties for a high and low nickel-coated electrode composition. Table 4.03120.

4.03121 Impact energies for SMA and GMA welds made in 0.5-inch plate and not stress relieved. Table 4.03121.

4.03122 Impact energies at -270 F for pulsed GMA and SMA welded plate. Table 4.03122.

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4.03124 Impact energy of GMA weld metal at -320 F as function of nickel content of wire. Fig. 4.03124.

4.03125 Effect of low temperatures on impact energy of 11 percent Ni GMA weld metal. Fig. 4.03125.

4.03126 Room temperature tensile properties and -320 F impact energy of automatic GTA weld metal for various welding positions. Table 4.03126.

4.03127 Effect of nitrogen or oxygen content on -320 F impact energy of ferritic weld metal deposited by automatic GTA process. Fig. 4.03127.

4.03128 Effect of heat input on -320 F impact energy of weld metal and HAZ produced by automatic GTA process using a ferritic filler. Fig. 4.03128.

4.03129 Effect of heat input on tensile properties of ferritic weld metal produced by automatic GTA process. Fig. 4.03129.

4.03130 Effect of surface reheat on -320 F Charpy-V impact energies of GTA weldments made with a ferritic filler. Table 4.03130.

4.03131 Low temperature tensile and impact properties of ferritic weld metal deposited by automatic GTA. Table 4.03131.

4.03132 Impact energy at -320 F for ferritic weld metal deposited by automatic GTA as function of notch distance from plate surface. Fig. 4.0313.

4.03133 Impact energy at -320 F for ferritic weld metal deposited by automatic GTA as function of distance from weld center. Fig. 4.03133.

4.03134 Welding conditions with ferritic filler and resulting weld metal -320 F Charpy impact values. Table 4.03134.

4.03135 Example of sub-arc welding conditions and resulting weld properties. Table 4.03135.

4.03136 Results of cryogenic burst tests on as-welded test cylinders. Table 4.03136.

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Fe	
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

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	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni			
Form	Plate	Forgings	Tubing	Pipe
ASTM	A353-74 A553-74	A522-76	A334-77	A333-77
ASME	SA 353 SA 553	SA 522	SA 334	SA 333
SAE-ASTM Unified Number	K81340	K81340	K81340	K81340

TABLE 1.03. SPECIFICATIONS

Alloy	Fe-9Ni			
Form	Plate		Forgings Tubing Pipe	
Source	(13)(14)		(15) (30) (31)	
Composition, percent	Min	Max	Min	Max
Carbon	--	0.13	--	0.13
Manganese	--	0.90	--	0.90
Phosphorous	--	0.035	--	0.040
Sulphur	--	0.040	--	0.040
Silicon	0.15	0.30	0.15	0.30
Nickel	8.50	9.50	8.50	9.50

TABLE 1.04. CHEMICAL COMPOSITION BY HEAT ANALYSIS (13)(14)(15)(30)(31)

Alloy	Fe-9Ni			
Form	0.38 to 3-inch Plate(a)			
Condition	Double Normalized and Tempered		Quenched and Tempered	
Test Temp, F	RT	-320	RT	-320 F
No. of Tests	16	10	58	26
F_{tu}, ksi				
Average	111	171	112	162
Std Dev	6.9	5.9	4.1	10.1
F_{ty}, ksi				
Average	93	135	103	130
Std Dev	8.4	10.5	6.1	17.9
No. of Tests	--	7	--	15
Charpy-V, ft lb (at -320 F)				
Average	--	39	--	50
Std Dev	--	5.6	--	17.5

(a) The data base was insufficient to distinguish an effect of thickness.

TABLE 1.058. VARIATION IN MECHANICAL PROPERTIES OF COMMERCIALLY HEAT TREATED PLATE [(25), TABLES 12 AND 14]

Alloy	Fe-9Ni							
Form	5-inch Slab							
Condition	1553 F, 2 hr, WQ + 1481 F, 2 hr, WQ + 1103 F, 2 hr, AC							
Stress Relieve	No				1050 F, 15 hr, AC			
Location	¼ Thick		Center		¼ Thick		Center	
Direction	L	T	L	T	L	T	L	T
F_{tu}, ksi	100	100	–	–	96	95	–	–
F_{ty}, ksi	89	89	–	–	87	86	–	–
Charpy-V, ft lb (at -320 F)	71	55	55	58	42	49	47	46

TABLE 1.059. TENSILE AND -320 F IMPACT PROPERTIES OF A DOUBLE QUENCHED AND TEMPERED 5-INCH THICK SLAB BEFORE AND AFTER STRESS RELIEF (6)

Alloy	Fe-9Ni											
Form	½-inch Plate											
Condition	1475 F, ½ hr, WQ + 1100 F, 2 hr, WQ						1650 F, ½ hr, AC + 1450 F, ½ hr, AC + 1100 F, 2 hr, WQ					
Stress Relief after Plastic Strain	1050 F 2 hr, AC			None			1050 F 2 hr, AC			None		
Plastic Strain, percent	0	5	10	0	5	10	0	5	10	0	5	10
Charpy-V, ft lb (at -320 F)	–	42	40	33	21	18	–	39	40	32	12	10

TABLE 1.0510. EFFECT OF COLD WORK AND SUBSEQUENT STRESS RELIEF ON CHARPY-V IMPACT ENERGY OF PLATE [(3), FIGURE 9]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni							
Form	0.94-inch Plate							
Condition	1625 F, 1 hr, WQ + 1454, 1 hr, WQ + 1067 F, 1 hr, WQ(a)		1625 F, 2 hr, WQ + 1346 F, 1 hr, WQ + 1202 F, 1 hr, WQ + 1346 F, 1 hr, WQ + 1202 F, 1 hr, WQ + Temper 1 hr(b) at					
			1022 F, WQ		1067 F, WQ		1112 F, WQ	
Test Temp, F	-320	-452	-321	-452	-320	-452	-320	-452
F_{tu}, ksi	163	204	–	–	163	223	–	–
F_{ty}, ksi	145	189	–	–	146	191	–	–
e, percent	34	25	–	–	–	–	–	–
RA, percent	72	65	–	–	–	–	–	–
Charpy-V, ft lb	125	75	137	128	–	–	107	106

(a) Grain size ~ 10μm. (b) Grain size after tempering ~ 1-4μm.

TABLE 1.0511. EFFECT OF GRAIN REFINING HEAT TREATMENT ON CRYOGENIC TENSILE AND IMPACT PROPERTIES OF PLATE [(29), P. 1830]

Alloy	Fe-9Ni				
Form	1.2-inch Plate				
Condition	1475 F, 1 hr, Cool at Rates A, B, C, D, or E Between 1292 and 572 F + 1075 F, 1 hr, Cool at Rates A, B, C, D, or E Between 1292 and 572 F				
Cooling Rate(a)	A	B	C	D	E
Plate Thickness For Equivalent Cooling Rate in					
Air, inches	0.08	0.67	0.91	1.4	11(b)
Water, inches	1.2	4.3	5.5	7.0	–
Bainite, percent	0	10	25	60	95

(a) Rates in F/min between 1292 and 572 F: A = 882, B = 94, C = 67, D = 41, E = 4.5.
(b) Cooled in Vermiculite.

TABLE 1.0514. EFFECT OF COOLING RATES FROM AUSTENITIZING AND FROM TEMPERING TEMPERATURES ON FORMATION OF BAINITE [(5), TABLE 5]

Alloy	Fe-9Ni			
Composition	0.11 C, 0.21 Si, 0.59 Mn,, 0.007 S, 0.013 P			
Section Size	4¾-inch Sq Billet		9-inch Dia Forging	
Heat Treatment(a)	1454 F, AC + 1063 F, AC	1454 F, OQ + 1063 F, AC	1454 F, AC + 1058 F, AC	1454 F, OQ + 1058 F, AC
RT F_{tu}, ksi(b)	98	98(c)	120	110
RT F_{ty}, ksi(b)	72	88(c)	74	88
Charpy-V, ft lb(b) (at -320 F)	30	62	5	22

(a) Austenitizing was preceded by 1652 F normalize with quench medium as for austenitize.
(b) All tests represent center positions in the billets or forgings except as indicated.
(c) Mid radius position.

TABLE 1.0914. EFFECT OF SECTION SIZE AND COOLING RATE FROM THE AUSTENITIZING TEMPERATURE ON THE ROOM TEMPERATURE TENSILE STRENGTH AND THE -320 F CHARPY IMPACT ENERGY OF FORGINGS [(2), TABLE 7]

Alloy	Fe-9Ni	
Composition	0.10 C, 0.40 Si, 0.50 Mn, 0.008 S, 0.006 P, 0.010 Sn, 0.003 Sb, 0.035 As	
Form	Cast 5/8-inch Bar From 28 lb Heats	
Heat Treatment	1652 F, AC + 1050 F, 4 hr, WQ	1562 F, AC + 1050 F, 4 hr, Cool 18 F/hr
RT F_{tu}, ksi	114	114
RT F_{ty}, ksi	103	103
Charpy-V, ft lb (at -320 F)	50	8

TABLE 1.0919. INFLUENCE OF COOLING RATE FROM THE TEMPERING TEMPERA TURE ON THE ROOM TEMPERATURE TENSILE STRENGTH AND THE -320 F IMPACT ENERGY OF CAST BAR [(2), FIGURES 7, 8, 9, AND TABLE 8]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

Alloy	Fe-9Ni					
Form	¾-inch Bar					
Condition	1450 F, ½ hr, WQ + 1050 F, 20 hr, WQ + A, B or C					
	A = 800 F, 6 days, WQ		B = A + 1050 F, 2 hr, WQ		C = B + A	
Test Temp, F	RT	-320 F	RT	-320 F	RT	-320 F
Charpy-V, ft lb	127	23	141	60	132	23

TABLE 1.0920. IMPACT RESULTS ILLUSTRATING THE REVERSIBILITY OF TEMPER EMBRITTLEMENT [(16), P. 143]

Alloy	Fe-9Ni			
Composition	0.09 C, 0.42 Mn, 0.012 S, 0.012 P, 0.25 Si, 0.01 Mo, 0.02 Cr			
Form	2-inch Plate			
Heat Treatment	1650 F, 2 hr, FC + 1100 F, 2 hr, FC FC at Rate to Simulate Cooling of a WQ, 27½-inch Thick Plate		1650 F, 2 hr, FC + 1100 F, 2 hr, FC FC at Rate to Simulate Cooling of a AC, 27½-inch Thick Plate	
Specimen Position in 27½-inch Plate	Mid Thickness	¼ Thickness	Mid Thickness	¼ Thickness
RT F_{tu}, ksi	118	115	115	118
RT F_{ty}, ksi	94	90	81	84
Charpy-V, ft lb (at -320 F)	13	14	4	9

TABLE 1.0921. EFFECT OF COOLING RATE FROM THE AUSTENITIZING AND TEMPERING TEMPERATURE ON THE ROOM TEMPERATURE TENSILE STRENGTH AND THE -320 F IMPACT ENERGY OF A 2-INCH THICK PLATE COOLED AT A RATE TO SIMULATE THAT OF A 27½-INCH THICK PLATE (7)

Alloy	Fe-9Ni					
Composition	0.10 C, 0.27 Si, 0.01 Mo, 0.14 Cr(a)			0.10 C, 0.14 Si, 0.15 Mo, 0.16 Cr(b)		
Heat Treatment(c)	Quench and Temper	Stress Relieved	Very Slow Cool	Quench and Temper	Stress Relieved	Very Slow Cool
RT F_{tu}, ksi	114	110	–	115	114	–
RT F_{ty}, ksi	82	85	–	101	101	–
Charpy-V, ft lb (at -320 F)	52	18	7	68	66	53
Lateral Expansion, mils	29	9	3	43	47	34

(a) Heat V-8 residuals: 0.012 P, 0.005 S, 0.010 As, 0.019 Sn, 0.0031 Sb.
(b) Heat V-3 residuals: 0.010 P, 0.006 S, 0.008 As, 0.021 Sn, 0.0025 Sb.
(c) Quench and temper: 1472 F, 3 hrs, cool 36 F/min. + 1061 F, 8 hrs, WQ.
Stress relieved: Quench and temper + 1049 F, 15 hrs, cool 299 F/hr.
Very slow cool: Quench and temper + 1049 F, 1 hr, cool 18 F/hr.

TABLE 1.0922. AVERAGE VALUES OF ROOM TEMPERATURE TENSILE STRENGTH AND -320 F IMPACT PROPERTIES OF SPECIMENS FROM TWO HEATS ILLUSTRATING THE INFLUENCE OF COMPOSITION ON TEMPER EMBRITTLEMENT [(21), SECTION 3, TABLES 1, 3, 4, 5, 6 AND 7]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

Alloy	Fe-9Ni					
Composition	0.08 C, 0.18 Si, 0.54 Mn, 0.005 S, 0.005 P, 0.02 Mo, 0.006 As, 0.008 Sn, 0.0013 Sb					
Form	50-inches OD x 31.5-inches ID x 28-inches High Forged Cylinder					
Specimen Location	4½ inches From Quenched End at Mid Thickness (½T)					
Heat Treatment	Quench and Temper(a)		Stress Relieved(b)		Very Slow Cool(c)	
Test Direction	Tangential	Axial	Tangential	Axial	Tangential	Axial
RT F_{tu}, ksi	99	–	99	–	99	–
RT F_{tu}, ksi	78	–	77	–	79	–
Charpy-V, ft lb (at -320 F)	58	50	52	47	43	44
Lateral Expansion, mils	37	33	33	29	29	32

(a) Quench and Temper: 1492 F, 9 hr, WQ + 1076 F, 8 hr, WQ.
(b) Stress Relieved: Quench and Temper + 1058 F, 8 hr, cool 299 F/hr.
(c) Very Slow Cool: Quench and Temper + 1058 F, 16 hr, cool 18 F/hr.

TABLE 1.0923. INFLUENCE OF STRESS RELIEF HEAT TREATMENTS ON THE AVERAGE VALUES OF TENSILE STRENGTH AND -320 F IMPACT ENERGY OF SPECIMENS FROM A QUENCHED AND TEMPERED THICK WALLED CYLINDER [(21), SECTION 2, TABLES 1 AND 2]

Alloy	Fe-9Ni							
Form	9 x 20 x 34-inches, Forged Billet(a) (e)							
Condition	1650 F, 9 hr, WQ + 1475 F, 9 hr, WQ + 1080 F, 9 hr, WQ + Stress Relief							
Test Temp, F	-150				-320			
Test Direction(f)	LT		TL		LT		TL	
Stress Relief(b)	Yes	No	Yes	No	Yes	No	Yes	No
Charpy-V, ft lb(c) (at -320 F)	95	67	–	–	50	49	–	30

(a) Composition: 0.11 C, 0.59 Mn, 0.010 S, 0.009 P, 0.26 Si, 8.58 Ni, 0.28 Cr, 0.08 Mo, 0.10 Cu.
(b) Stress Relief: 1055 F, 20 hr, cool 300 F max/hr.
(c) Specimens at center of 9-inch dimension.
(e) RT $F_{tu}(L)$ = 124 ksi, RT $F_{tu}(T)$ = 121, RT $F_{tu}(L)$ = 118 ksi after stress relief.
(f) See ASTM E399-78.

TABLE 1.0924. EFFECT OF TEST TEMPERATURE AND STRESS RELIEF ON LOW TEMPERATURE IMPACT ENERGY OF A LARGE FORGED BILLET(22)

Alloy	Fe-9Ni			
Form	11-inches Thick x 162-inches dia Forged Disk(a) Electric Furnace Air Melt, Al Deoxidation in Ladel, Vacuum Stream Degassed			
Condition	1652 F, 16 hrs, AC + 1112 F, 16 hr, AC + 1472 F, 12 hr, WQ + 1076 F, 18 hr, AC + 1022 F, 15 hr, AC + 842 F, 4 hrs, Cool 54 F/hr, to RT			
Specimen Position in Reference to Disk Faces	Surface		Center	
Specimen Radial Position	Rim	Bore	Rim	Bore
Test Direction	Radial	Radial	Tangential	Tangential
F_{tu}, ksi	116	118	115	117
F_{ty}, ksi	104	106	104	105
e (2-inches), percent	26	27	27	27
RA, percent	78	69	75	73

(a) Composition: 0.12 C, 0.15 Si, 0.64 Mn, 0.006 P, 0.010 S, 9.17 Ni, 0.20 Mo, 0.013 Al, 0.10 Cr, 0.05 Cu, 0.007 Sn, 0.0015 Sb, 0.0073 N, 11 ppm H, 15 ppm O.

TABLE 1.0925. TENSILE PROPERTIES OF VERY LARGE QUENCHED AND TEMPERED AND STRESS RELIEVED DISK FORGING (32)

Alloy	Fe-9Ni			
Form	11-inches Thick x 162-inches Dia Disks(a)			
Condition	See Table 1.0925			
Specimen Position Respect to Disk Faces	Surface		Center	
Specimen Radial Position	Rim	Bore	Rim	Bore
Notch Orientation(b)	RC	RC	CR	CR
Charpy-V, ft lb				
at -275 F	93	95	–	–
at -320 F	79	78	85	82

(a) For Composition see Table 1.0925. (b) See ASTM E399-78.

TABLE 1.0926. CHARPY-V IMPACT ENERGIES AT CRYOGENIC TEMPERATURES FOR A VERY LARGE QUENCHED AND TEMPERED AND STRESS RELIEVED DISK FORGING (32)

Fe	
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni					
Form	Hot Worked Pipe 6¾-inches ID x 2 23/32-inches Wall Thickness			Cold Worked Pipe 6-inches ID x 3/8-inch Wall Thickness		
Condition	Double Normalize(a) + Temper	Quench(b) + Temper	As Rec'd(c) + Temper	Double Normalize + Temper	Quench + Temper	As Rec'd + Temper
F_{tu}, ksi	100	101	–	103	105	98
F_{ty}, ksi	84	93	–	90	88	92
e, percent	34	33	–	36	36	34
RA, %	76	79	–	80	80	79
Charpy-V, ft lb						
RT	155	166	131	133	142	122
-320 F	51	135	9	71	59	38

(a) 1650 F, AC + 1450 F, AC + 1060 F, 2 hr, AC. (b) 1450 F, WQ + 1060 F, 2 hr, WQ.
(c) As received + 1060 F, 2 hr, AC.

TABLE 1.0929. EFFECT OF SEVERAL HEAT TREATMENTS ON THE TENSILE AND IMPACT PROPERTIES OF HOT WORKED AND COLD WORKED PIPE [(2), TABLE 3]

Alloy	Fe-9Ni			
Condition	1650 F, AC + 1450 F, AC + 1100 F, AC			
Temp, F	-320 to 80	80 to 700	80 to 1000	700 to 1000
Mean Btu/lb/F	0.0878	0.119	0.131	0.156

TABLE 2.015. SPECIFIC HEAT [(3), TABLE 12]

Alloy	Fe-9Ni			
Form	Plate	Forgings	Tubing	Pipe
Source	(13)(14)	(15)	(30)	(31)
F_{tu}, ksi	100-120	100 (min)	100 (min)	100 (min)
F_{ty}, ksi	85 (min)	75 (min)	75 (min)	75 (min)
e (2-inches), %	20 (min)	––	(b)	(b)
RA, percent	––	45 (min)	––	––
Charpy-V, ft lb(a) (at -320 F)				
L	25 (min)	––	––	––
T	20 (min)	––	––	––

(a) Average of three tests with not more than one value below the minimum and no value < 20 ft lb.

(b) See ASTM A334 (tubing) or ASTM A333 (pipe) for elongation minimum values for various specimen types and wall thicknesses.

TABLE 3.011. SPECIFIED MECHANICAL PROPERTIES FOR VARIOUS PRODUCT FORMS

Alloy	Fe-9Ni
Condition	1650 F, AC + 1450 F, AC + 1100 F, AC
Temp, F	Saturation Induction - Gauss at 16,700 Oersteds
-320	21,360
-148	20,830
32	20,300
68	20,210
212	19,850
316	19,250
572	18,500
752	17,570
932	16,290

TABLE 2.0231. MAGNETIC PROPERTIES OF DOUBLE NORMALIZED ALLOY [(3), TABLE 13]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni			
Form	3/8-inch Plate			
Condition	1475 F, ½ hr, WQ + 1100 F, 2 hr, WQ		1650 F, ½ hr, AC + 1450 F, ½ hr, AC + 1100 F, 2 hr, WQ	
	9 Plates		6 Plates	
	Avg	Std Dev	Avg	Std Dev
F_{tu}, ksi	108.9	2.7	105.4	3.5
F_{ty}, ksi	101.8	3.4	83.4	1.8
Charpy-V, ft lb (at -320 F)	30.6	2.5	29.1	3.1

TABLE 3.012. PRODUCERS TENSILE AND -320 F CHARPY-V IMPACT PROPERTIES OBTAINED BY TESTS ON MANY 3/8-INCH PLATES [(11), P. 13]

Alloy	Fe-9Ni							
Form	Plate							
Condition	Double Normalize and Temper per ASTM A553				Quench and Temper per ASTM A353			
Thickness, inches	0.63		0.75		0.63		0.75	
RT F_{tu}, ksi	111	115	113	118	112	117	111	119
RT F_{ty}, ksi	91	94	83	104	103	110	94	115
Drop Weight, ft lb (at -320 F)	1379	800	649	800	2094	991	2334	2534
Charpy-V, ft lb (at -320 F)	36	39	33	27	50	29	54	35

TABLE 3.0339. DROP WEIGHT TEAR AND CHARPY-V ENERGIES AT -320 F FOR DOUBLE NORMALIZED AND FOR QUENCHED AND TEMPERED PLATES OF TWO THICKNESSES [(25), TABLE 13]

Alloy	Fe-9Ni			
Form	3-inch Plate(a)		1¼-inch Plate(b)	
Condition	As Rolled		1455 F, 1½ hr, WQ 1119 F, 1¼ hr, AC	
Test Temp, F	-170	-320	-320	-423
F_{ty}, ksi	–	–	149	174
K_{Ic}, ksi-inch½	45	63	153(c)	83

(a) Ref 4 (b) Ref 12, Table 4 (c) Converted from J_{Ic}

TABLE 3.03721. PLANE STRAIN FRACTURE TOUGHNESS OF PLATE AT CRYOGENIC TEMPERATURES (4) (12)

Alloy	Fe-9Ni			
Form	9 x 20 x 34-inches Forged Billet(a)			
Direction(b)	SL			
Condition(c)	A		B	C
Test Temp, F	RT	-320	-320	-320
F_{tu}, ksi	124	177	178	178
F_{ty}, ksi	118	163	161	149
RA, percent	50	15	14	24
K_{Ic}, ksi-inch½	–	91	85	132
Charpy-V, ft lb	–	22	–	–

(a) For Composition see Table 1.0911.
(b) See ASTM E399-78.
(c) Condition A - 1650 F, 9 hr, AC + 1050 F, 9 hr, AC + 1470 F, 9 hr, WQ + 1050 F, 9 hr, AC + Stress Relief 1025 F, 9 hr, AC to 800 F, 4 hr, FC 18 F/hr.
Condition B - Condition A + 1050 F, 3 hr, FC 150 F/hr, specimen blanks heat treated.
Condition C - Condition A + 1050 F, 3 hr, WQ, specimen blanks heat treated.

TABLE 3.03722. EFFECT OF TEST TEMPERATURE AND STRESS RELIEF ON ROOM TEMPERATURE AND -320 F TENSILE PROPERTIES AND PLANE STRAIN FRACTURE TOUGHNESS OF A LARGE FORGED BILLET (33)

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

Alloy	Fe-9Ni		
Form	11-inches Thick x 162-inches Dia Forged Disk		
Condition	See Table 1.0925 For Condition and Composition		
Specimen Position With Respect to Disk Faces	Center		
Specimen Radial Position	Rim		Bore
Test Direction(b)	RL	LR	RL
F_{tu}, ksi (RT)	116	115	114
F_{ty}, ksi (RT)	105	105	102
RA, percent (RT)	72	73	66
F_{tu}, ksi (-320 F)	178	178	179
F_{ty}, ksi (-320 F)	146	147	141
RA, percent (-320 F)	54	42	60
K_{Ic}, ksi-inch$^{1/2}$(a) (-320 F)	193	193	182

(a) Converted from J_{Ic} (E at -320 F = 29000 ksi) (b) See ASTM E399-78

TABLE 3.03723. TENSILE PROPERTIES AND PLANE STRAIN FRACTURE TOUGHNESS OF A VERY LARGE QUENCHED AND TEMPERED AND STRESS RELIEVED DISK FORGING (33)

Alloy	Fe-9Ni			
Form	¼-inch Plate From Air Melt 100 Ton Heat			
Condition(a)	1475 F, ¼ hr, WQ + 1120 F, ½ hr, AC			
Method	Rotating Beam R = 1 F = 10,000 rpm			
	Fatigue Strength at -270 F, ksi at Cycles			
	10^4	10^5	10^6	10^7
Stress Conc.				
K_t = 1	–	(135)	100	98
K_t = 2.7	(110)(b)	65	48	40

(a) -270 F, F_{tu} = 152 ksi.
(b) Numbers in ( ) extrapolated.

TABLE 3.0513. ROTATING BEAM FATIGUE STRENGTH AT -270 F FOR ¼-INCH QUENCHED AND TEMPERED PLATE [(8), FIGURE 6]

Alloy	Fe-9Ni	
Form	11-inches Thick x 162-inches Dia Forged Disk	
Condition	See Table 1.0912	
Temp	RT	-320 F
E, 1000 ksi	29.5	28.6

TABLE 3.0621. STATIC ELASTIC MODULUS AT ROOM TEMPERATURE AND -320 F (33)

Alloy	Fe-9Ni						
Form	Welding Wire - Coated Electrodes						
Designation	Inco Weld A	Inco(c) Weld B	Inco 182	Nyloid-2(c)	Cryotherm 60	ERNo Cv-6	Inco(a) 113
Element, percent							
C	0.03	0.10	0.05	0.08	0.17	0.12	0.05
Ni	70.0	70.0	67.0	65.0	51	66(b)	62.5
Cr	15.0	15.0	14.0	13.0	10	5	21.5
Mo	15.0	2.0	–	6.0	2.5	24	9.0
Mn	2.0	2.0	7.8	3.0	2.7	1.0	1.0
Fe	9.0	9.0	7.5	Bal	Bal	5.5	2.5
Cb + Ta	1.8	2.5	1.8	1.2	1.3	–	2.8
Ti	–	–	0.4	–	–	–	–
S	0.008	0.008	0.008	–	–	0.03	0.01
Cu	0.006	0.06	0.1	–	–	–	0.2
Si	0.3	0.3	0.5	–	–	1.0	0.4
W	–	–	–	1.2	–	–	–
V	–	–	–	–	–	–	0.60

(a) Supercedes Inco 112. (b) Includes 2.5% Co. (c) For use with AC.

TABLE 4.0315. TYPICAL COMPOSITIONS OF WELDING WIRE FOR COATED ELECTRODES [(27), TABLE 5; (34), P. 59]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni				
Form	Welding Wire - Filler Metal				
Designation	Inconel 92	Inconel 82	Inconel 625	Chromenar	ERNo Cv-3
Element, percent					
C	0.03	0.02	0.05	0.04	0.10
Ni	71.0	72.0	61.0	67.0	67.0
Cr	16.4	20.0	21.5	–	20.0
Mo	–	–	9.0	–	–
Mn	2.3	3.0	0.2	3.0	3.0
Fe	6.6	1.0	2.5	1.0	3.0
Cb + Ta	–	2.5	3.6	2.5	2.5
Ti	3.2	0.6	0.2	0.5	0.75
S	0.007	0.007	0.008	–	0.015
Cu	0.04	0.04	–	–	0.50
Si	0.1	0.2	0.2	–	0.50
Al	–	–	0.2	–	–

TABLE 4.0316. TYPICAL COMPOSITIONS OF WELDING WIRE FOR FILLER METAL [(27), TABLE 6; (34), P. 58 AND 59]

Alloy	Fe-9Ni			
Welding Process	SMA	Subarc	GMA	GTA
Electrodes and/or Fluxes	See Table 4.0311	Wires: AWS ERNiCr-3, Inco 92, Inco 82	Inco 625, Inco 92, Inco 82	NGS 709W[a]
	Hastelloy C	Fluxes: Inco 4, Lincoln 880, Nittetsu-10		

(a) 0.025 C, 0.16 Si, 0.23 Mn, 14.6 Cr, 13.7 Mo, 2.8 W, 5.6 Fe, Bal Ni.

TABLE 4.0317. EXAMPLES OF ELECTRODES USED IN VARIOUS WELDING PROCESSES FOR FABRICATION OF LNG TANKS OF 9NI STEEL

Alloy	Fe-9Ni									
Form	1.02-inch Plate									
Condition	Double Normalized and Tempered per ASTM A353-722 + Weld									
Welding Conditions	SMA, 0.16-inch Dia Electrode[a], 120-130 Amps, 27 V, 5.9-inches/min, 34,300 J/inch									
Stress Relief	None					1058 F, 1 hr, AC				
Specimen Location	A	B	C	D	E	A	B	C	D	E
Charpy-V, ft lb[b]										
RT	79	65	123	101	108	79	65	123	101	108
-320 F	78	65	80	40	42	75	65	80	40	30

(a) For composition of electrode see Table 4.0319.
(b) See Table 4.03114 for weld tensile strengths.

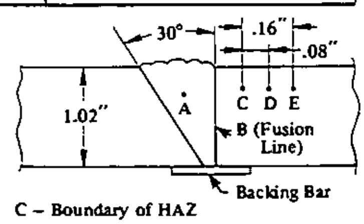


TABLE 4.0318. CHARPY-V IMPACT ENERGIES AT ROOM AND -320 F AT SEVERAL POSITIONS WITH RESPECT TO THE WELD IN SMA WELDED DOUBLE NORMALIZED AND TEMPERED PLATE [(26), P. 47, 48, 50-54]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

Alloy	Fe-9Ni									
Form	1.97-inch Plate									
Condition	Quenched and Tempered per ASTM 553-72a + Weld									
Welding Conditions	SMA, 0.16-inch Dia Electrode(a), 140 Amps, 25 V, 5.9-inches/min 35,600 J/inch									
Stress Relief	None					1058 F, 2 hr, AC				
Specimen Location(b)	A	B	C	D	E	A	B	C	D	E
Charpy-V, ft lb(c)										
RT	65	51	170	126	130	65	66	170	126	130
-320 F	60	51	66	52	46	70	61	79	64	46

(a) 0.04 C, 0.35 Si, 1.76 Mn, 0.004 P, 0.004 S, 71 Ni, 15.8 Cr, 0.87 Mo, 2.29 Cb (Essentially Inco Weld A).
(b) For specimen location see Table 4.0318.
(c) For weld tensile strengths see Table 4.03114.

TABLE 4.0319. IMPACT ENERGIES AT -320 F AT VARIOUS LOCATIONS IN AN SMA WELDMENT [(26), P. 60-64]

Alloy	Fe-9Ni						
Form	See Table 4.03113						
Composition	See Table 4.03113						
Welding Conditions	High Strength Electrode (See Table 4.03113)						
Specimen(a) Location	Weld Metal	Fusion Line	HAZ Center	HAZ Boundary	Distance From HAZ Boundary 0.08-inch	0.20-inch	Base Metal
Charpy-V, ft lb (at -320 F)							
As Welded	40	39	70	53	43	45	45
After Stress Relief(b)	40	30	56	56	47	40	34

(a) Notch at ¾ thickness position. (b) Stress relief, 1058 F, 16 hrs.

TABLE 4.03110. IMPACT ENERGIES AT -320 F AT VARIOUS LOCATIONS IN A SMA BUTT WELDED PLATE BEFORE AND AFTER STRESS RELIEF [(39), TABLE 8]

Alloy	Fe-9Ni							
Form	0.98-inch Plate							
Conditions	Quenched and Tempered Per ASTM 553-72a 3 SMA Weld + SR							
Welding Condition	Double V SMA Weld(a), 150 Amps, 25 V, 5.5 inches/min, 41,000 J/inch Interpass Temp < 212 F							
Test Location	Weld Metal				HAZ			
Stress Relief 1 hr, AC	None	1000	1058	1112	None	1000	1058	1112
F_{tu}, ksi(b)	107	106	103	106	–	–	–	–
Charpy-V, ft lb (at -320 F)	65	65	65	65	72	76	79	90

(a) Electrode Composition: 0.03 C, 70 Ni, 15 Cr, 2 Mo, 9 Mn, 3 W, 0.03 Fe.
(b) Tensile strength of transverse weld joint.

TABLE 4.03111. EFFECT OF STRESS RELIEF ON -320 F CHARPY IMPACT VALUES OF SMA WELD METAL [(26), P. 112]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni				
Form	Weld Metal				
Weld Process	SMA DC	SMA AC	Subarc		GMA
Filler Wire or Electrode	Inco 113 ACRO Alloy Ni-9 Nylord-2	Inco Weld B	Inco 82 Inco 92	Lincoln Flux 880	Inco 625 Inco 92 Inco 82 ERNiCr-3
F_{tu}, ksi	100	108	98		100-120
F_{ty}, ksi	60	68	55		65-80
Charpy-V, ft lb (at -320 F)	47	44	80		50-100

TABLE 4.03112. EXAMPLES OF WELD PROCESSES, ELECTRODES AND FILLERS USED IN THE UNITED STATES ALONG WITH TYPICAL MECHANICAL PROPERTIES OF WELD METAL (3) (27)

Alloy	Fe-9Ni			
Form	1.18-inch Plate Cut Tangentially From Mid Thickness of 50-inch OD x 31.5 ID x 28-inch High Forged Cylinder			
Composition	See Table 1.0923 (Parent Metal)			
Welding Conditions	42 Pass SMA Butt Welds With Inconel Electrode 112, 100-130 A Direct Current, Reverse Polarity, 25-26 V, 7 to 7.5 inches/min			
Specimen	Transverse Butt Weld[a] As Welded	Weld + 1058 F, 16 hr	All Weld Metal As Deposited	Parent[b] Metal
F_{tu}, ksi	102	100	111	102
F_{ty}, ksi	72	74	80	78
e(2-inch), %	31	38	38	33
RA, percent	71	70	--	72

(a) All specimens failed in base metal. (b) Quenched and tempered per ASTM 553-72a.

TABLE 4.03113. TENSILE PROPERTIES OF SMA WELDMENTS MADE ON PIECES CUT FROM A LARGE RING FORGING [(39), TABLE 5]

Alloy	Fe-9Ni			
Form	Plate			
Condition	Double Normalized and Tempered per ASTM A353-72a + Weld		Quenched and Tempered per ASTM A553-72a + Weld	
Thickness, inches	1.02		1.97	
Welding Conditions	60° Double V, SMA Butt Weld 0.16-inch Dia Electrode[c] 120-130 Amps 27 V 5.91 inches/min 34,300 J/inch		60° Double V, SMA Butt Weld 0.16-inch Dia Electrode[c] 130 Amps 24 V 5.91 inches/min 31,800 J/inch	
Stress Relief	None[a]	1058 F, 1 hr, AC	None[b]	1058 F, 1 hr, AC
F_{tu}, ksi	101	103	102	100
F_{ty}, ksi	87	91	92	94

(a) Parent Metal F_{tu} = 106 ksi, F_{ty} = 90 ksi. (b) Parent Metal F_{tu} = 107 ksi, F_{ty} = 98 ksi.
(c) For composition see Table 4.0319.

TABLE 4.03114. ROOM TEMPERATURE TENSILE PROPERTIES OF SMA WELD METAL IN MANUALLY WELDED DOUBLE NORMALIZED AND TEMPERED PLATE [(26), P. 45-46]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni	
Form	Plate	
Condition	Quench and Temper per ASTM 553-72a + Weld	
Thickness, inches	0.63	0.98
Weld Type	Manual SMA	Manual SMA
Electrode(a)	Hastalloy C	Hastalloy C
Current, Amps	600	650
Voltage	35	35
Speed, inch/min	16.5	15.4
Heat Input, J/inch	76,200	88,900

(a) Composition: 0.08 C, 1.0 Si, 1.0 Mn, 15 Cr, 16 Mo, 3.75 W, 5.5 Fe, 0.35 V + remainder of Ni + Co.

TABLE 4.03119. WELDING CONDITIONS FOR TEST RESULTS REPRESENTED IN FIGURES 4.03115 TO 4.03118 [(26), P. 68]

Alloy	Fe-9Ni	
Form	0.55-inch Plate	
Condition	Plate Condition Not Specified + SMA V Groove Weld	
Welding Condition	To Specification JIS Z 3211	
Weld Electrode	N-9-70(a)	N-9-12(b)
F_{tu}, ksi	96	85
F_{ty}, ksi	56	61
Charpy-V, ft lb		
at RT	116	104
at -320 F	51	30

(a) 0.04 C, 0.35 Si, 1.76 Mn, 0.004 P, 0.004 S, 15.8 Cr, 71 Ni, 0.87 Mo.
(b) 0.12 C, 0.34 Si, 7.04 Mn, 0.024 P, 0.008 S, 16.33 Cr, 11.46 Ni, 0.06 Mo.

TABLE 4.03120. SHIELDED METAL ARC WELD METAL PROPERTIES FOR A HIGH AND LOW NICKEL COATED ELECTRODE COMPOSITION [(26), P. 118]

Alloy	Fe-9Ni			
Form	½-inch Plate			
Condition	1650 F, ½ hr, AC + 1450 F, ½ hr, AC + 1050 F, 2 hr, AC + Weld			
Welding(a)	SMA(b)		GMA(c)	
Notch Location	Weld	HAZ	Weld Metal	HAZ
Charpy-V, ft lb				
at RT	68-80	119-127	104-114	76-104
at -320 F	60-71	68-82	96-101	43-60

(a) Welding Conditions: 80° V, Cu backing bar, no preheat or post heat, Interpass < 200 F; SMA - 3/16-inch dia Inco-weld A, 140-150 amp rev polarity, 5 passes + root seal; GMA - 1/16-inch dia Inconel filler 92, 300-310 amp reverse polarity, 75 ft^3/hr Argon, 4 passes + root seal.
(b) RT Transverse Tensile: F_{tu} = 97 ksi, F_{ty} = 63 ksi, e = 19 percent.
(c) RT Transverse Tensile: F_{tu} = 101 ksi, F_{ty} = 66 ksi, e = 17 percent.

TABLE 4.03121. IMPACT ENERGIES FOR SMA AND GMA WELDS MADE IN ½-INCH PLATE AND NOT STRESS RELIEVED [(24), TABLE 9]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni									
Form	¼-inch Plate From Air Melt 100 Ton Heat									
Condition(d)	1475 F, ¼ hr, WQ + 1120 F, ½ hr, AC + Single V Weld									
Weld(b)(c)	Pulsed GMA Filler Inconel 92, 75% He + 25% A 4 to 6 Passes, Interpass 150 F max, 8.2 to 12.5 inches/min, 9.6 to 20.4 KJ/inch					SMA - Inco Weld B 3 to 4 Passes, Interpass 150 F max, 2.8 to 5.0 inches/min, 23.6 to 44.4 KJ/inch				
Specimen Location	Weld Metal	Fusion Line	Fusion Line + 1 mm	Fusion Line + 3 mm	Fusion Line + 5 mm	Weld Metal	Fusion Line	Fusion Line + 1 mm	Fusion Line + 3 mm	Fusion Line + 5 mm
Charpy-V, ft lb(a) at -270 F	34	31	26	30	54	19	22	22	29	37

(a) 2/3 specimen size for pulsed GMA, ½ specimen size for SMA notch plane parallel to weld direction and normal to plate surface.
(b) Welded in rolling direction.
(c) Weld Tensile Properties: Pulsed GMA, RT F_{tu} = 103 ksi, -320 F F_{tu} = 128 ksi; SMA RT F_{tu} = 104 ksi, -320 F F_{tu} = 133 ksi.
(d) For plate properties see Figure 3.031.

TABLE 4.03122. IMPACT ENERGIES AT -270 F FOR PULSED GMA AND SMA WELDED PLATE [(8), TABLES 2 AND 3]

Alloy	Fe-9Ni						
Form	¼-inch Plate From Air Melt 100 Ton Heat						
Condition	1475 F, ¼ hr, WQ + 1120 F, ½ hr, AC						
Method	Rotating Beam R = -1, F = 10,000 rpm						
	Test Temp, F	Stress Conc	Fatigue Strength, ksi at cycles 10^4	10^5	10^6	10^7	10^8
Base Metal	-320	$K_t = 2.7$	(95)(b)	65	42	30	27
Pulsed GMA(a) Weld	-320	$K_t = 2.7$	(85)	58	42	35	34
SMA Weld(a)	-320	$K_t = 2.7$	(85)	58	42	35	34
Base Metal	-270	$K_t = 1$	–	(135)	100	100	–

(a) For welding conditions and tensile properties see Table 4.03122.
(b) Numbers in ( ) extrapolated.

TABLE 4.03123. ROTATING BEAM FATIGUE STRENGTH AT CRYOGENIC TEMPERATURES FOR BASE METAL, GMA AND SMA WELDS [(8), FIGURES 6 AND 7]

Alloy	Fe-9Ni				
Form	Weld Metal in 0.9-inch Plate				
Weld Process	Automatic GTA Filler Composition 0.025 C, 0.16 Si, 0.23 Mn, 14.6 Cr, 13.7 Mn, 2.8 W, 5.6 Fe, < 50 ppm O_2, Bal Ni				
Weld Position	Flat	45° Vertical	Vertical	45° Overhead	Overhead
F_{tu}, ksi	100	99	102	101	100
F_{ty}, ksi	60	56	60	60	60
e, percent	38	38	36	44	37
Charpy-V, ft lb at -320 F	86	82	81	87	102

TABLE 4.03126. ROOM TEMPERATURE TENSILE PROPERTIES AND -320 F IMPACT ENERGY OF AUTOMATIC GTA WELD METAL FOR VARIOUS WELDING POSITIONS [(37), TABLE 2]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

Alloy	Fe-9Ni													
Form	0.47-inch Plate													
Wire Composition	0.04 C, 0.01 Si, 0.39 Mn, 11 Ni													
Specimen Location	GTA Weld Metal							Fusion Zone						
Weld Heat Input, KJ/inch	43		66			84		43		66			84	
Surface Reheat, KJ/inch	0	25	0	25	43	0	25	0	25	0	25	43	0	25
Charpy-V, ft lb (at -320 F)	56	59	39	52	60	30	48	52	81	22	41	66	22	44

TABLE 4.03130. EFFECT OF SURFACE REHEAT ON -320 F CHARPY-V IMPACT ENERGIES OF GTA WELDMENTS MADE WITH A FERRITIC FILLER (36)

Alloy	Fe-9Ni			
Form	Ferritic Weld Metal Deposited by Automatic GTA			
Composition	0.034 C, 0.36 Mn, 0.03 Si, 0.003 P, 0.005 S, 11.22 Ni, 0.36 Co 0.018 Al, 0.008 Ti, 0.001 B, 5 ppm N			
Welding Conditions	Verticle, 230-280 A, 10.5-11.5 V, 1.7-2.4 inches/min 84 KJ - 119 KJ/inch, Shield Argon, Interpass < 300 F GTA Surface Remelt (See Below)			
Test Temp, F	32	-148	-302	-320
F_{tu}, ksi(a)	120	137	148	169
F_{ty}, ksi	106	119	132	153
e, percent	22	22	24	25
RA, percent				
Charpy-V, ft lb(a)	166	155	140	111

(a) Specimens at plate center.

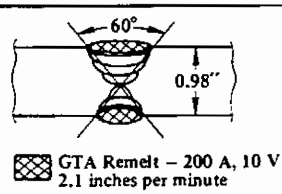


TABLE 4.03131. LOW TEMPERATURE TENSILE AND IMPACT PROPERTIES OF FERRITIC WELD METAL DEPOSITED BY AUTOMATIC GTA [(38), TABLE 4 AND FIGURE 25]

Alloy	Fe-9Ni			
Form	0.71-inch Plate			
Wire Compositions	0.04 C, 0.01 Si, 0.39 Mn, 11 Ni			
Welding Conditions	Semi-Automatic GTA, 230 Amps, 1.6 to 3.5 inches/min			
Argon Flow Rate, ft^3/min	0.35	0.44	0.53	1.06
O_2 in Weld, ppm	31	27	33	30
Charpy-V, ft lb at -320 F	57	122	127	100

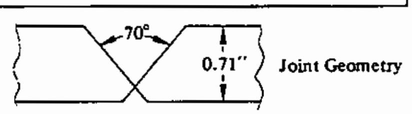


TABLE 4.03134. WELDING CONDITIONS WITH FERRITIC FILLER AND RESULTING WELD METAL -320 F CHARPY IMPACT VALUES [(36), TABLE 1]

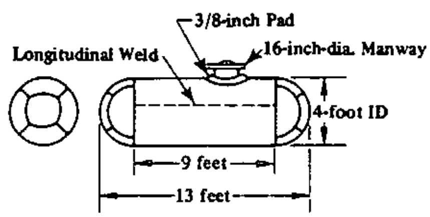
	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

Alloy	Fe-9Ni	
Form	0.39 to 0.59-inch Plate	
Condition	Automatic Subarc Weld	
Welding Conditions	ERNiCr-3[(a)] Filler With Basic Flux, 240-270 A, 28-30 V, Speed 10 inches/min to 28 inches/min, Interpass Temp < 100 F, 7 Passes/Joint	
Location	Weld Metal	HAZ
F_{tu}, ksi	101	–
Charpy-V, ft lb (at -320 F)	72	50

(a) See Table 4.0316.

TABLE 4.03135. EXAMPLE OF SUBARC WELDING CONDITIONS AND RESULTING WELD PROPERTIES (40)



Alloy	Fe-9Ni			
Form	Welded Test Vessel 3/8-inch Wall			
Condition[(a)]	Double Normalize + Temper F_{tu} = 105 ksi		Quench and Temper F_{tu} = 109 ksi	
	As Welded[(b)]	SR[(c)]	As Welded[(b)]	SR[(c)]
Burst Temp, F	-310	-320	-302	-311
Burst Stress, ksi	136	93	133	130

(a) For material heat treatment see Table 3.021.
(b) SMA Type 310 stainless steel coated electrodes.
(c) Stress relief 1050 F, 2 hr, cool 300 F/hr to 600 F, AC.

TABLE 4.03136. RESULTS OF CRYOGENIC BURST TESTS ON AS-WELDED TEST CYLINDERS [(1), TABLE 5]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

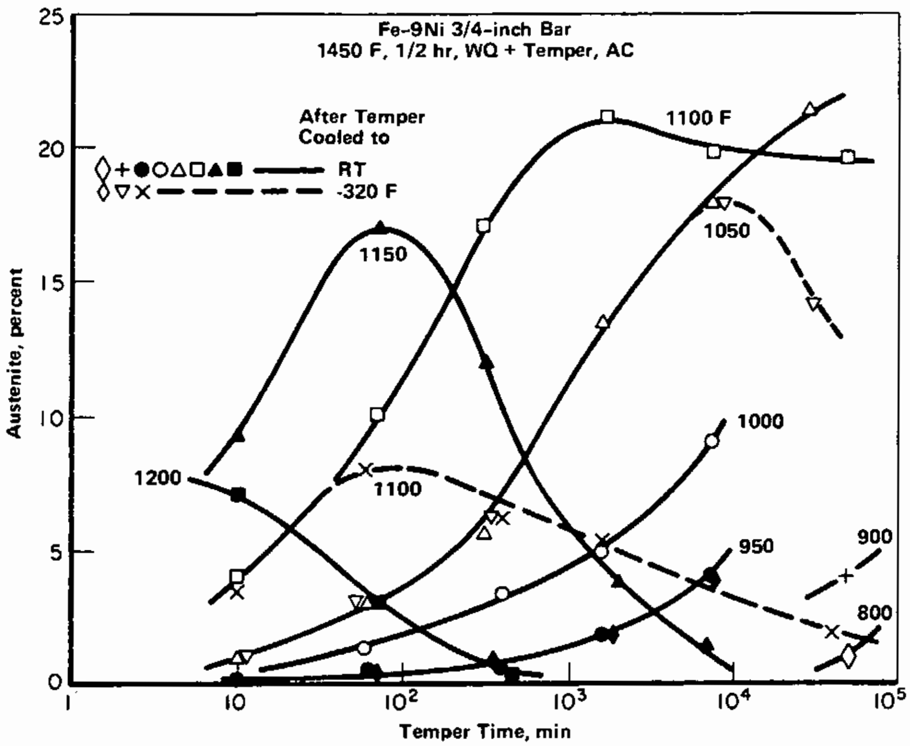


FIGURE 1.055. EFFECT OF TEMPERING TEMPERATURE AND TIME ON AUSTENITE RETENTION AT RT AND -320 F, [(16) FIGURE 3]

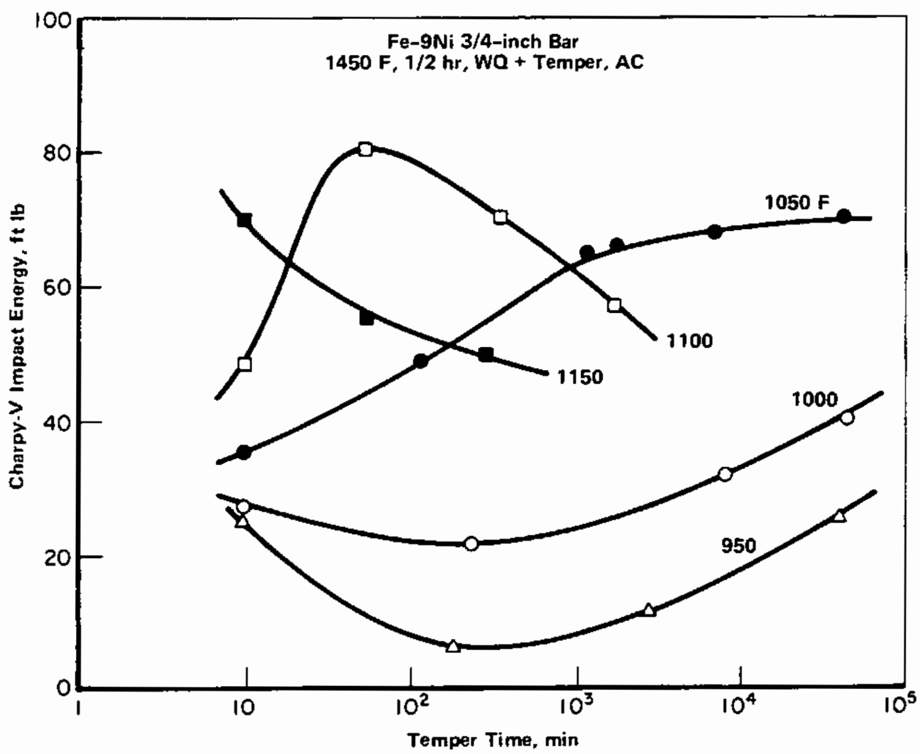


FIGURE 1.056. IMPACT ENERGY AT -320 F AS A FUNCTION OF TEMPERING TIME FOR SEVERAL TEMPERING TEMPERATURES [(16) FIGURE 6]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

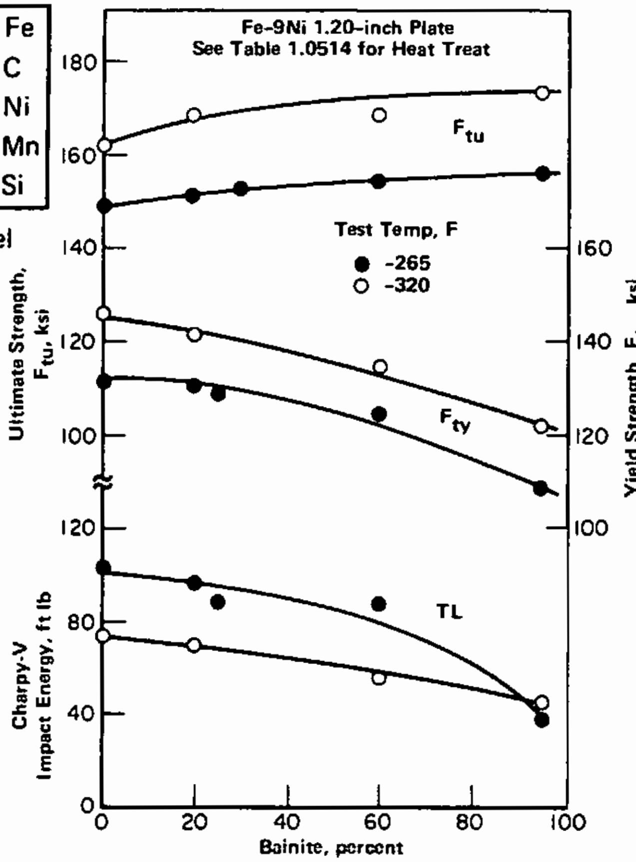


FIGURE 1.057. TENSILE AND IMPACT PROPERTIES AT CRYOGENIC TEMPERATURES AS FUNCTION OF PERCENT BAINITE [(5) TABLE 3]

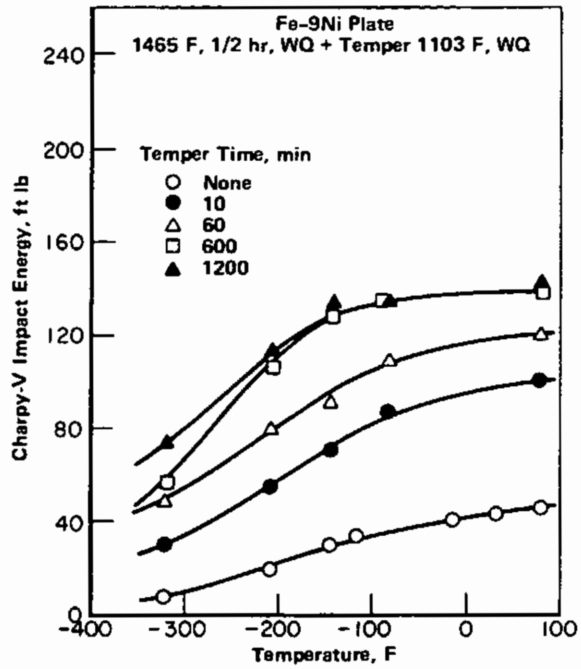


FIGURE 1.0512. EFFECT OF LOW TEST TEMPERATURES ON IMPACT ENERGY OF PLATE TEMPERED FOR VARIOUS TIMES [(28) FIGURE 8]

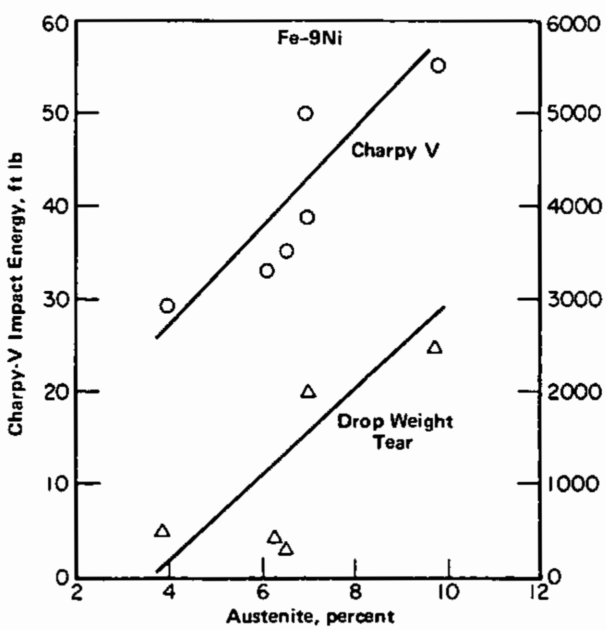


FIGURE 1.0513. CHARPY V AND DROP WEIGHT TEAR IMPACT ENERGIES AT -320 F AS FUNCTION OF PERCENT AUSTENITE [(25) FIGURE 25]

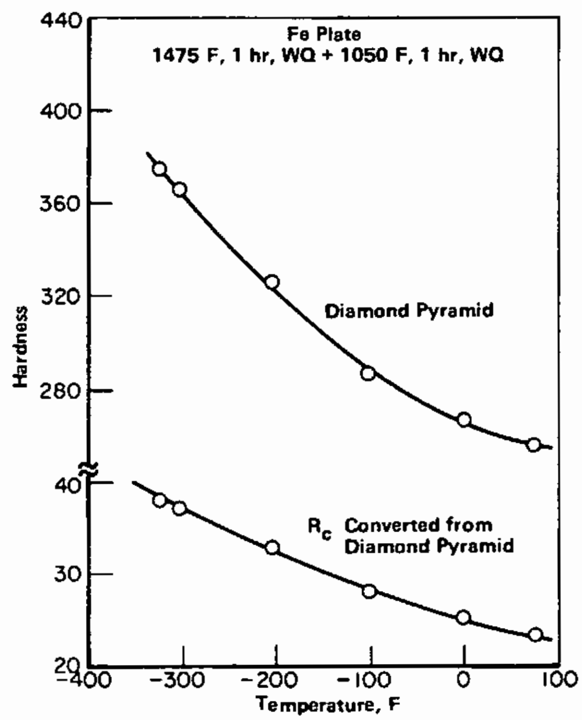


FIGURE 1.061. EFFECT OF TEST TEMPERATURE ON HARDNESS OF QUENCHED AND TEMPERED PLATE [(3) TABLE 5]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

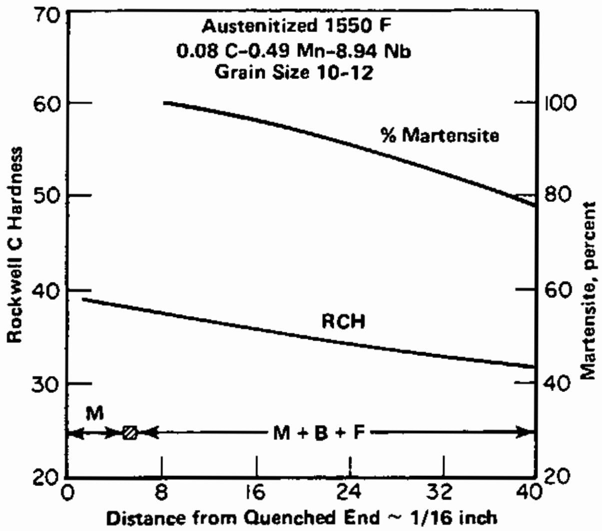


FIGURE 1.062. END QUENCHED HARDENABILITY [(3) FIGURE 4]

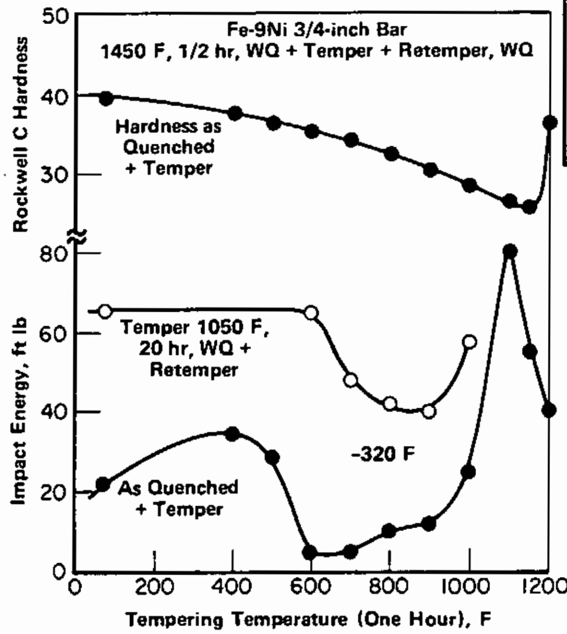


FIGURE 1.0915. EFFECT OF TEMPERING TEMPERATURE ON HARDNESS AND -320 F IMPACT ENERGY OF BAR [(16) FIGURES 5 AND 9]

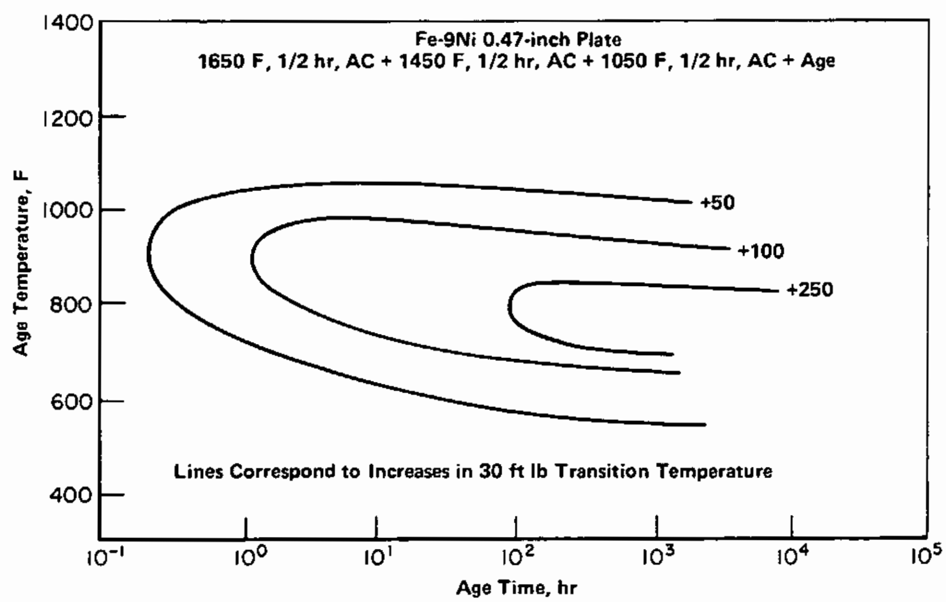


FIGURE 1.0916. ISO-EMBRITTLEMENT DIAGRAM FOR PLATE (4)

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

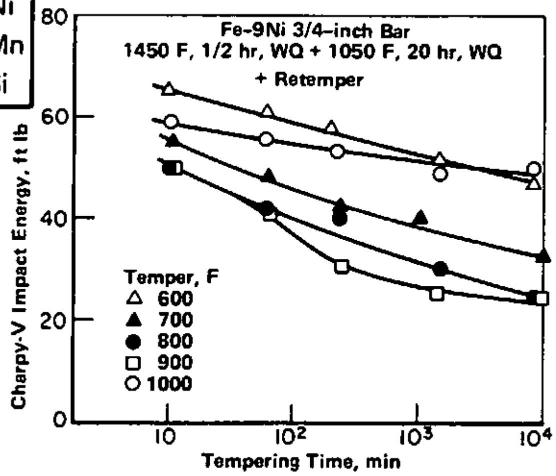


FIGURE 1.0917. EFFECT OF RETEMPERING TIME AND TEMPERATURE ON -320 F IMPACT ENERGY OF BAR [(16) FIGURE 10]

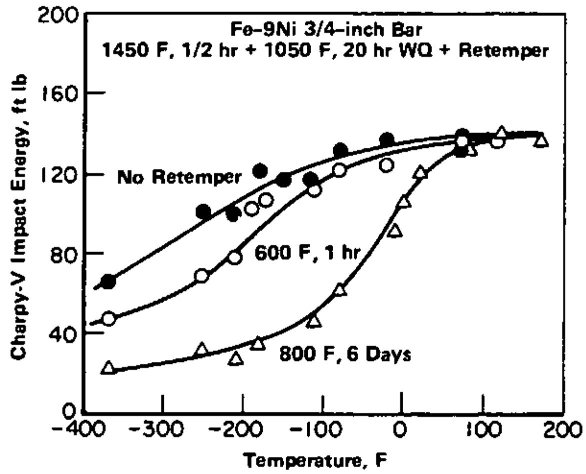


FIGURE 1.0918. EFFECT OF TEST TEMPERATURE ON IMPACT ENERGY OF BAR AFTER RETEMPERING AT 600 F AND 800 F [(16) FIGURE 11]

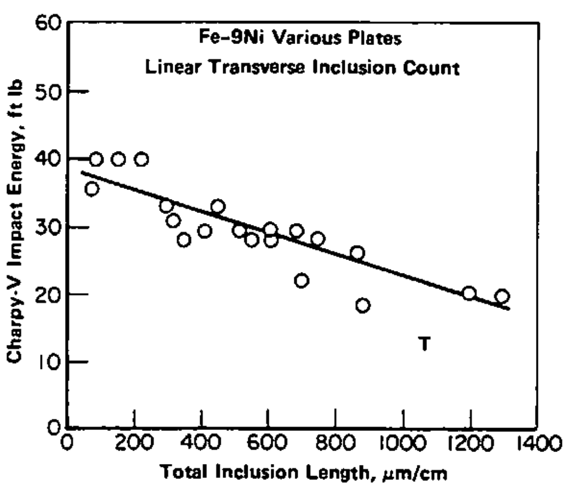


FIGURE 1.0927. TRANSVERSE IMPACT ENERGY AT -320 F AS FUNCTION OF INCLUSIONS [(29) FIGURE 2]

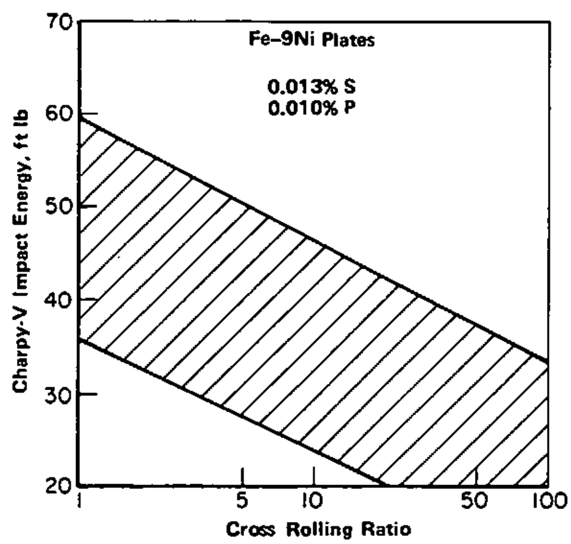


FIGURE 1.0928. INFLUENCE OF CROSS ROLLING RATIO ON TRANSVERSE IMPACT ENERGY OF PLATE [(29) FIGURE 4]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

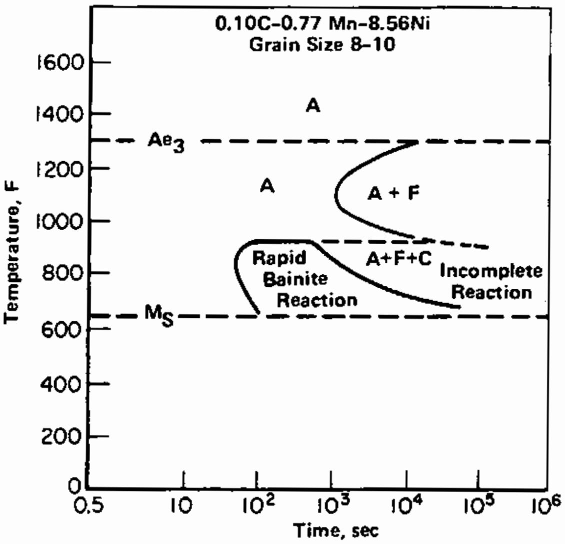


FIGURE 2.01211. ISOTHERMAL TRANSFORMATION DIAGRAM [(3) FIGURE 5]

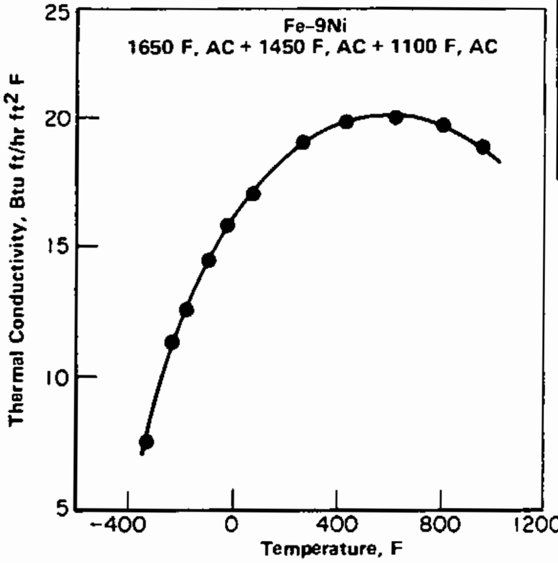


FIGURE 2.013. THERMAL CONDUCTIVITY [(3) TABLE 11]

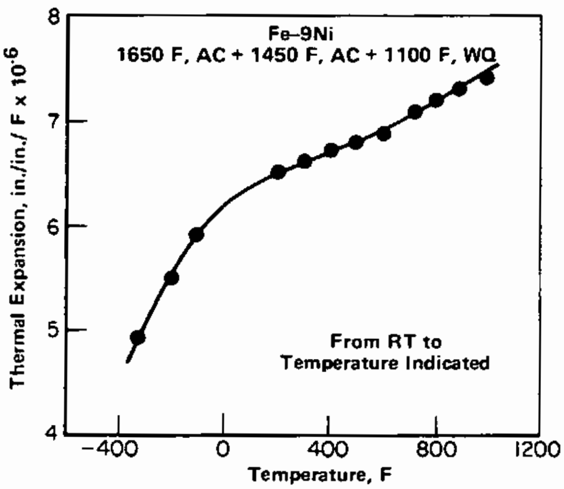


FIGURE 2.0141. COEFFICIENT OF LINEAR THERMAL EXPANSION [(3) TABLE 10]

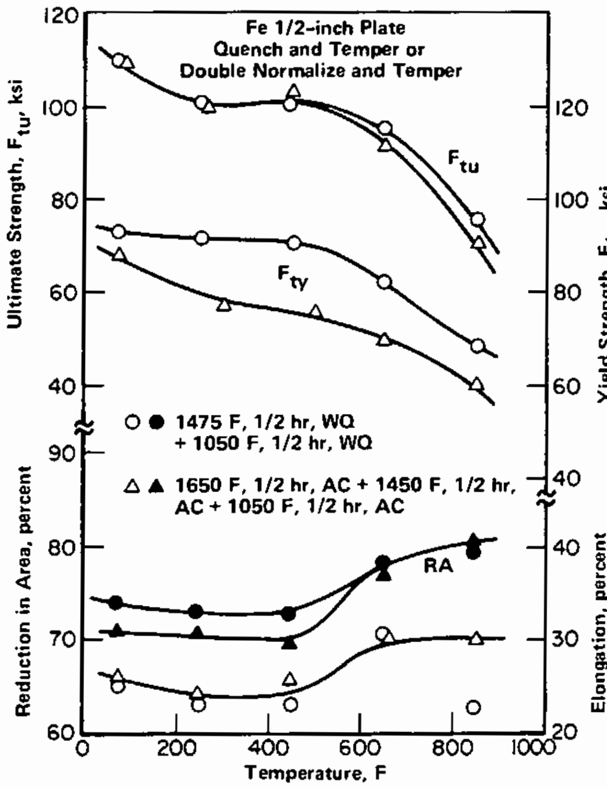


FIGURE 3.0311. EFFECT OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF QUENCHED AND TEMPERED OR DOUBLE NORMALIZED 1/2-INCH PLATE [(3) TABLE 9]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

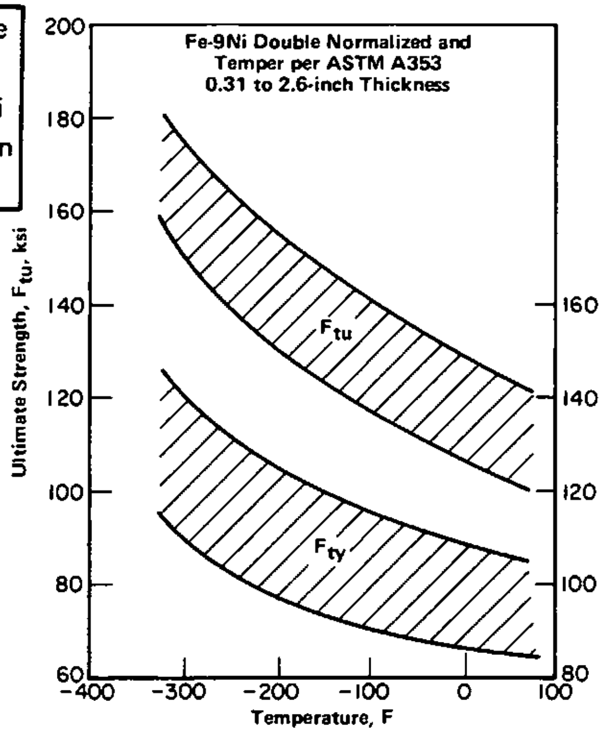


FIGURE 3.0312. RANGES OF TENSILE AND YIELD STRENGTHS FOR DOUBLE NORMALIZED AND TEMPERED PLATE OF VARIOUS THICKNESSES [(25) FIGURE 20]

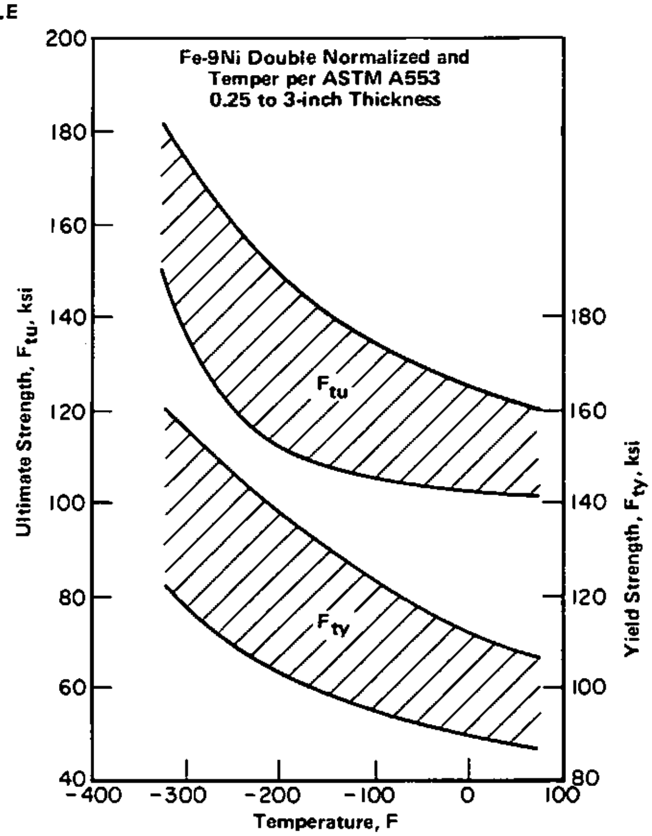


FIGURE 3.0313. RANGES OF TENSILE AND YIELD STRENGTHS FOR QUENCHED AND TEMPERED PLATE OF VARIOUS THICKNESSES [(25) FIGURE 21]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

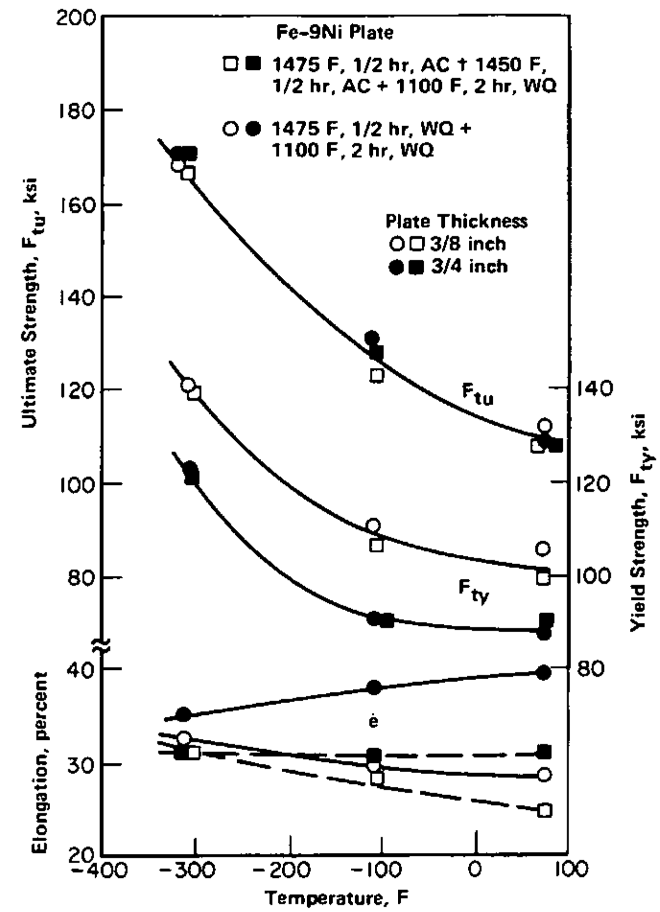


FIGURE 3.0314. EFFECT OF LOW TEST TEMPERATURES ON TENSILE PROPERTIES OF DOUBLE NORMALIZED AND TEMPERED AND QUENCHED AND TEMPERED PLATE [(11) P. 15]

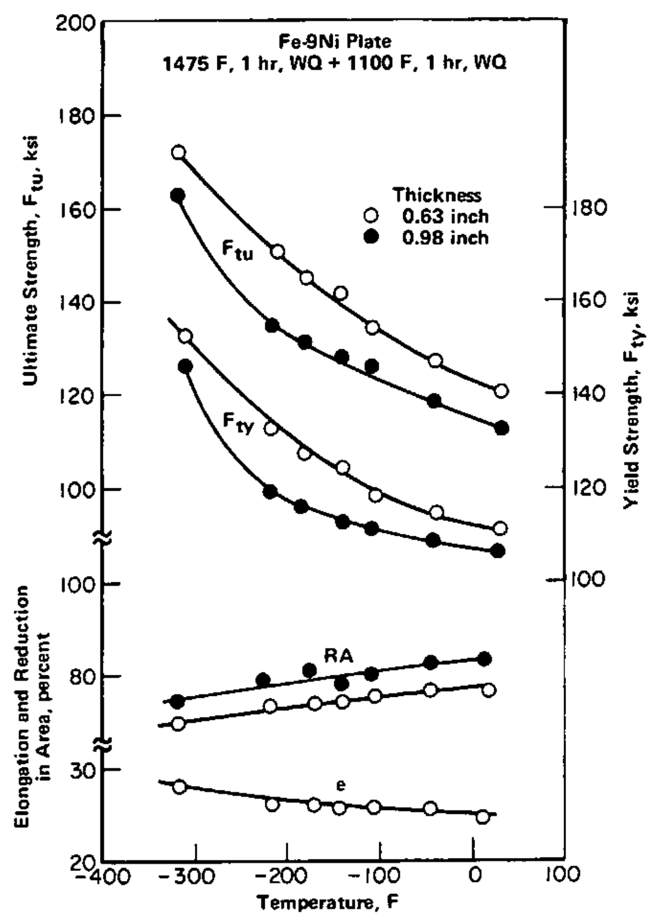


FIGURE 3.0315. EFFECTS OF LOW TEST TEMPERATURES ON THE TENSILE PROPERTIES OF QUENCHED AND TEMPERED PLATE [(26) P. 37]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

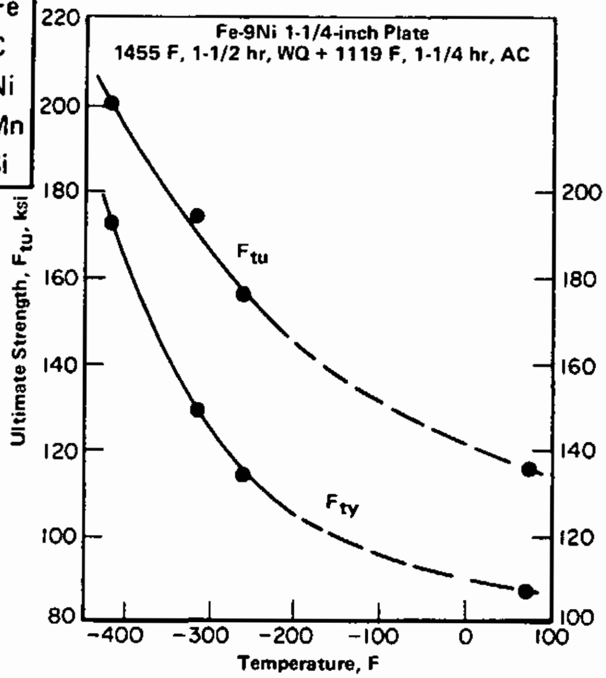


FIGURE 3.0316. EFFECT OF LOW TEST TEMPERATURES ON TENSILE PROPERTIES OF QUENCHED AND TEMPERED 1-1/2 INCH THICK PLATE [(12) TABLE 2]

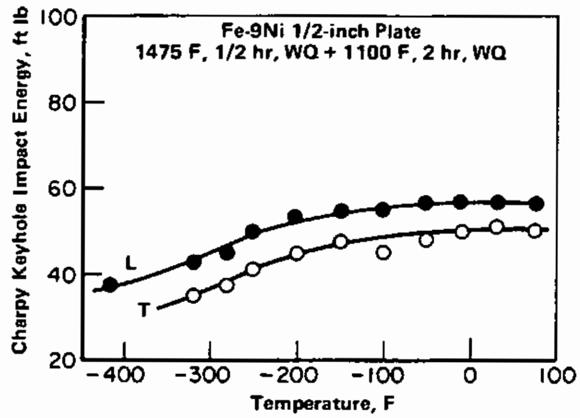


FIGURE 3.0331. EFFECT OF LOW TEST TEMPERATURES ON THE CHARPY KEYHOLE IMPACT ENERGY OF DOUBLE NORMALIZED AND TEMPERED 1/2-INCH PLATE [(11) P. 17]

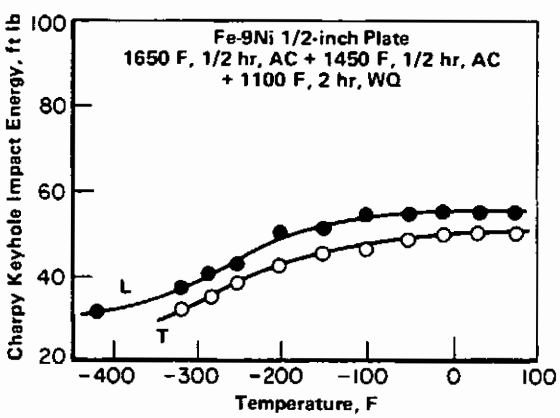


FIGURE 3.0332. EFFECT OF LOW TEST TEMPERATURES ON THE CHARPY KEYHOLE IMPACT ENERGY OF QUENCHED AND TEMPERED 1/2-INCH PLATE [(11) P. 17]

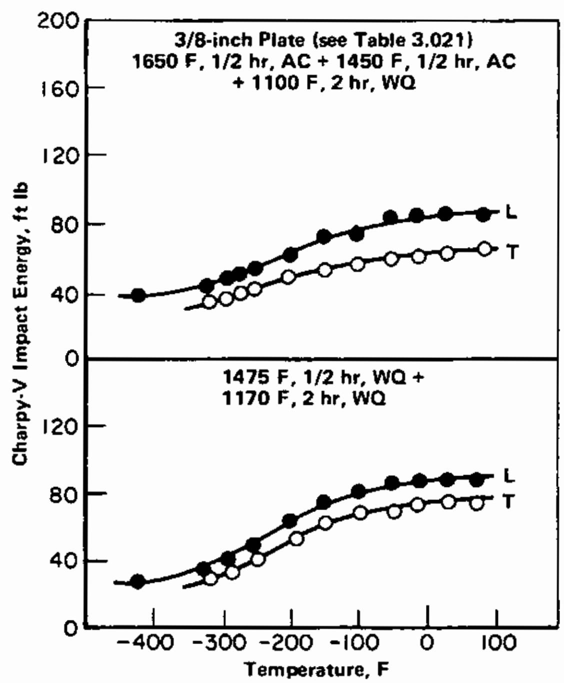


FIGURE 3.0333. EFFECT OF LOW TEST TEMPERATURES ON 3/4 WIDTH CHARPY V ENERGY FOR DOUBLE NORMALIZED AND FOR QUENCHED AND TEMPERED 3/8-INCH PLATE [(1) FIGURE 2]

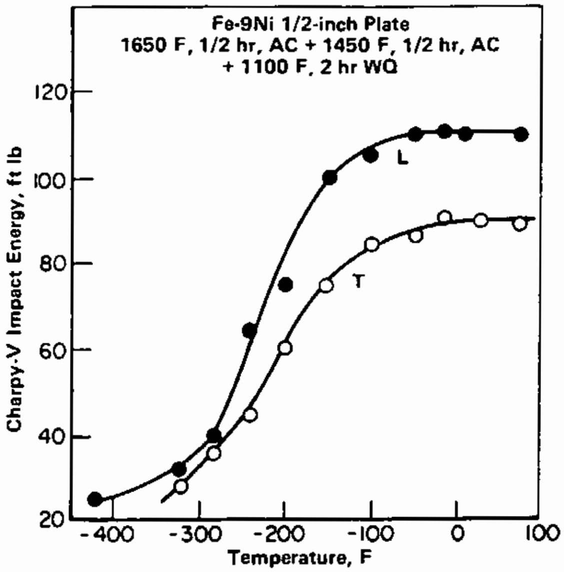


FIGURE 3.0334. EFFECT OF LOW TEST TEMPERATURES ON THE CHARPY V IMPACT ENERGY OF DOUBLE NORMALIZED 1/2 IN. PLATE [(11) P. 16]

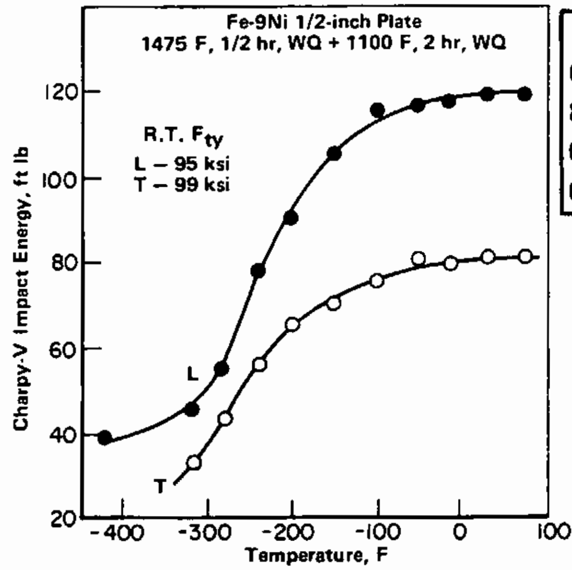


FIGURE 3.0335. EFFECT OF LOW TEST TEMPERATURES ON CHARPY V IMPACT ENERGY OF QUENCHED AND TEMPERED 1/2 IN. PLATE [(11) P. 16]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

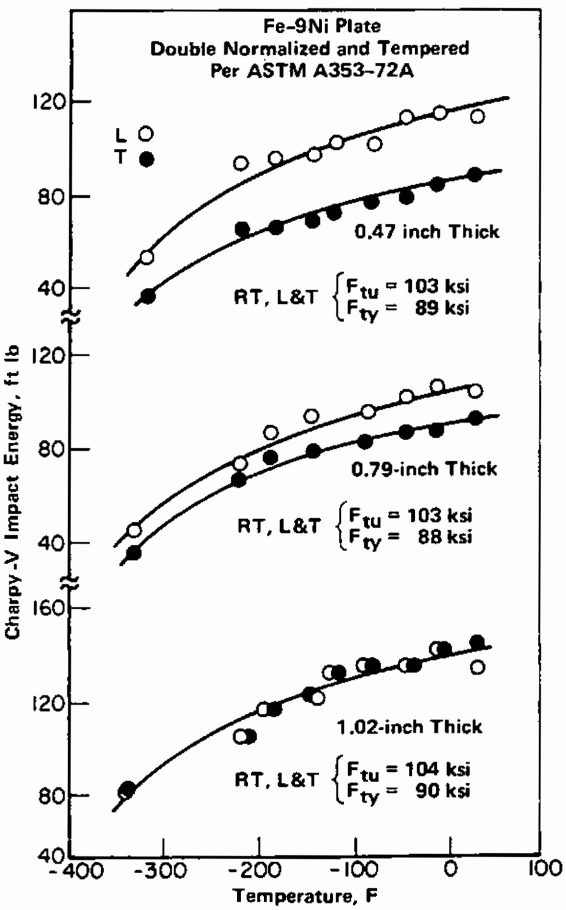


FIGURE 3.0336. EFFECT OF LOW TEST TEMPERATURES ON CHARPY V IMPACT ENERGIES OF THREE THICKNESSES OF DOUBLE NORMALIZED AND TEMPERED PLATE [(26), P. 15-17]

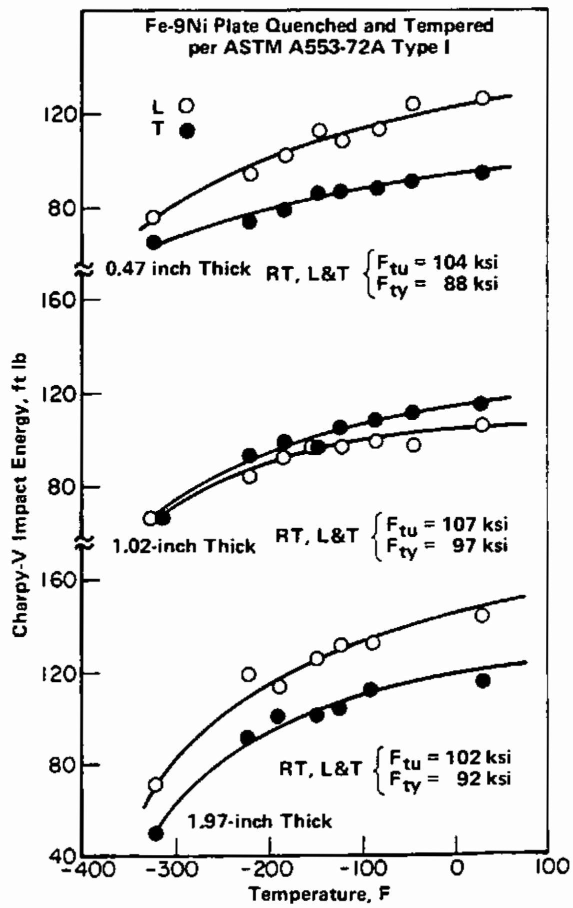


FIGURE 3.0337. EFFECT OF LOW TEST TEMPERATURES ON CHARPY V IMPACT ENERGIES OF THREE THICKNESSES OF QUENCHED AND TEMPERED PLATE [(26), P. 19-22]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

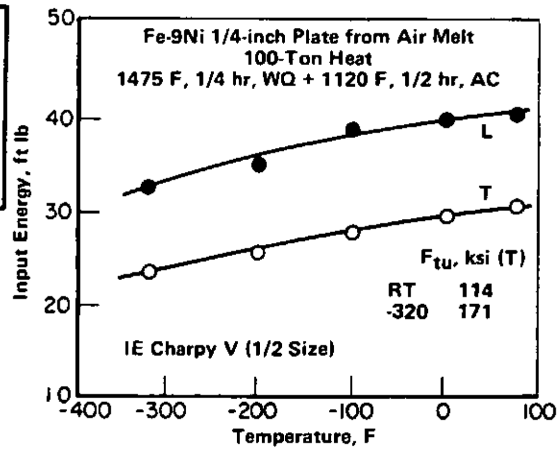


FIGURE 3.0338. EFFECT OF LOW TEST TEMPERATURES ON CHARPY V IMPACT ENERGIES OF PLATE FROM A 100-TON AIR MELT HEAT [(8) TABLE 1]

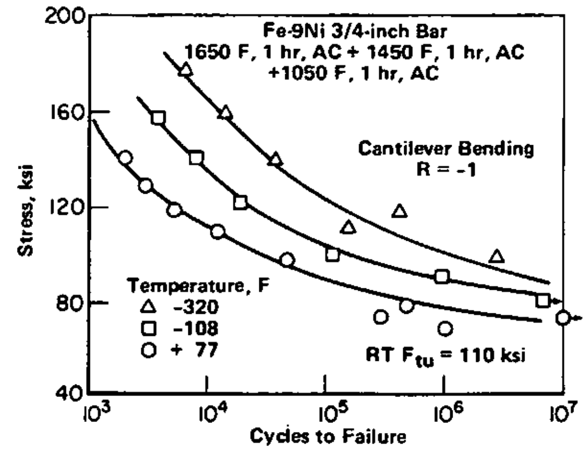


FIGURE 3.0511. S-N CURVES FOR DOUBLE NORMALIZED AND TEMPERED 3/4-INCH-DIA. BAR AT ROOM AND CRYOGENIC TEMPERATURES [(10) FIGURE 17]

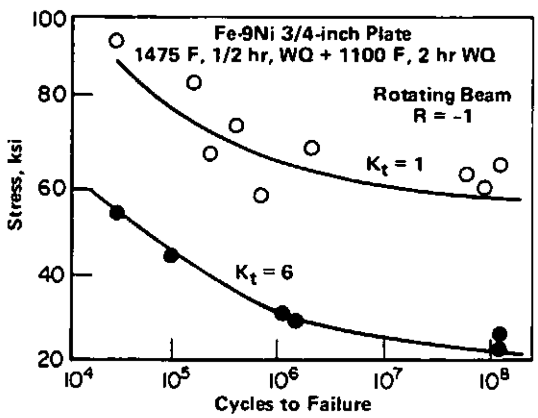


FIGURE 3.0512. S-N CURVES FOR 3/4-INCH QUENCHED AND TEMPERED PLATE [(11) P. 15]

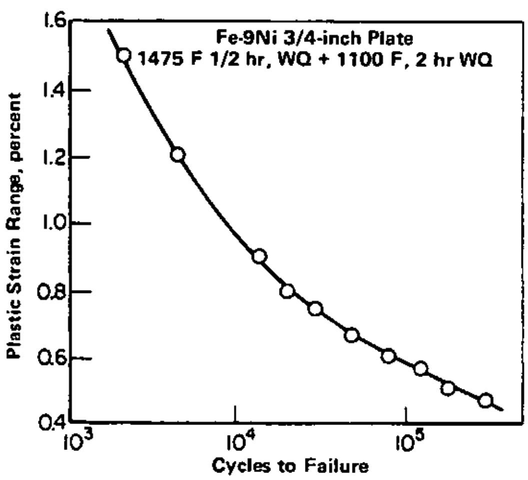


FIGURE 3.0515. PLASTIC STRAIN RANGE VS CYCLES TO FAILURE FOR QUENCHED AND TEMPERED PLATE [(11) P. 15]

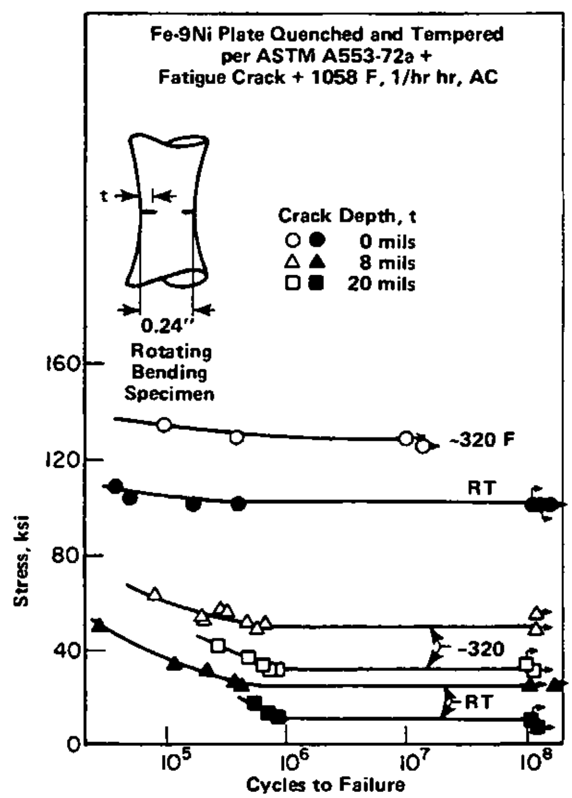


FIGURE 3.0514. S-N CURVES FOR SMOOTH AND CRACKED SPECIMENS FROM QUENCHED AND TEMPERED PLATE TESTED AT RT AND -320 F [(26) P. 91]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

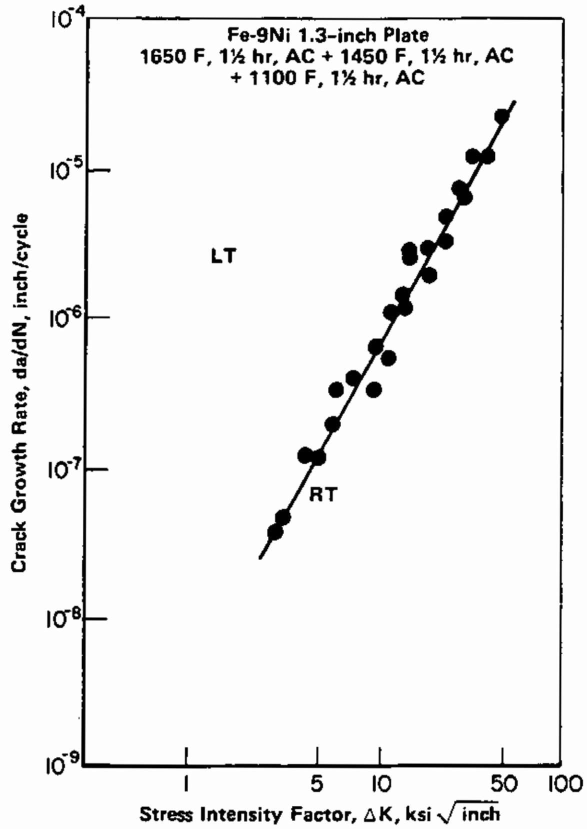


FIGURE 3.0521. FATIGUE CRACK PROPAGATION RATES AT ROOM TEMPERATURE FOR DOUBLE NORMALIZED AND TEMPERED 1.3-INCH PLATE [(9) FIGURE 8]

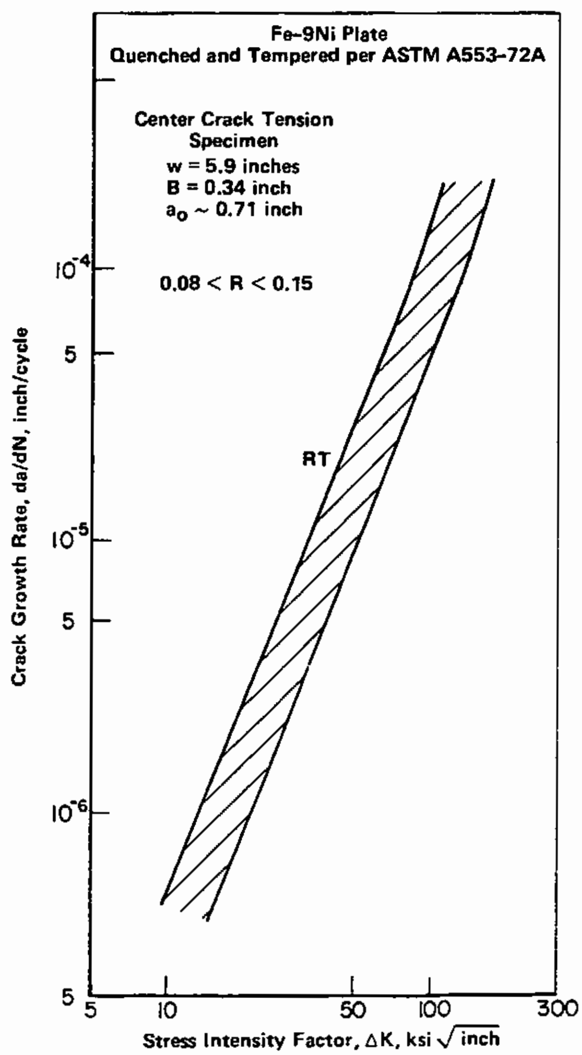


FIGURE 3.0522. FATIGUE CRACK PROPAGATION RATE SCATTERBAND FOR QUENCHED AND TEMPERED 0.34-INCH PLATE AT ROOM TEMPERATURE [(26) P. 83]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

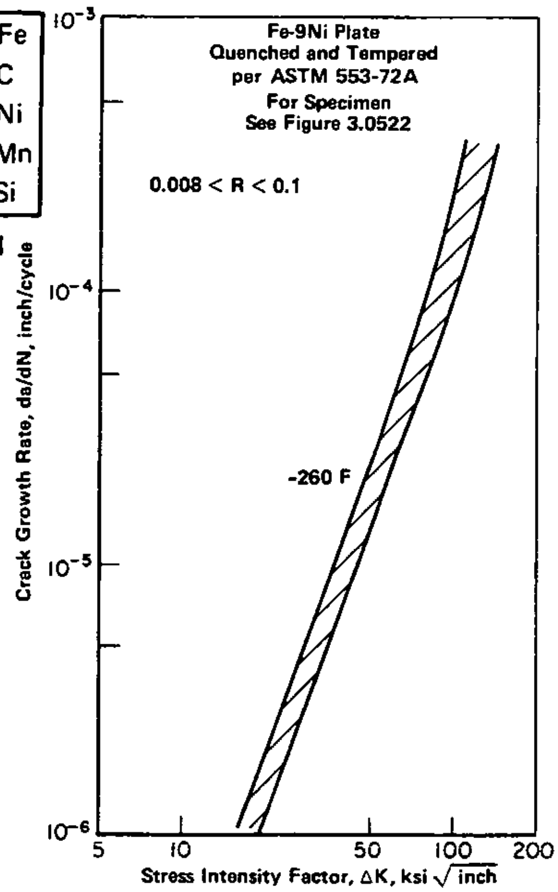


FIGURE 3.0523. FATIGUE CRACK PROPAGATION RATE SCATTERBAND FOR QUENCHED AND TEMPERED 0.34-INCH PLATE AT -260 F [(26) P. 84]

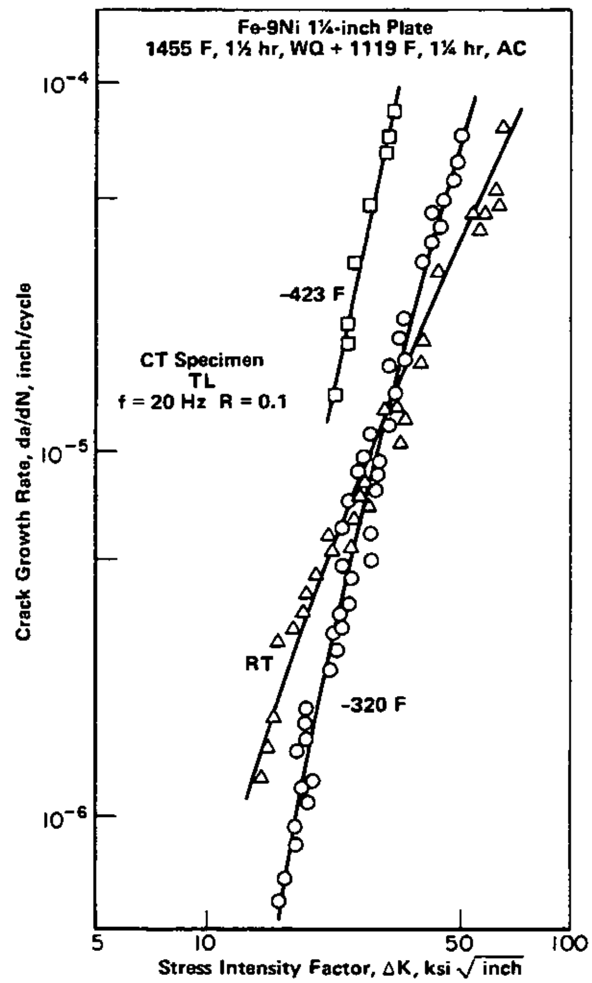


FIGURE 3.0524. FATIGUE CRACK PROPAGATION RATES AT ROOM AND CRYOGENIC TEMPERATURES FOR QUENCHED AND TEMPERED 1-1/4 INCH PLATE [(13) FIG. 9]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

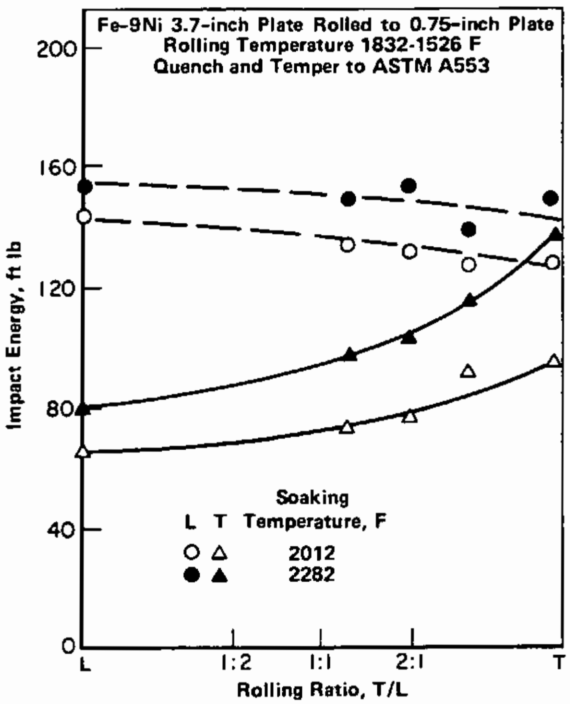


FIGURE 4.014. EFFECT OF ROLLING RATIO AND SOAKING TEMPERATURE ON ROOM TEMPERATURE CHARPY-V ENERGY [(35) FIGURE 5]

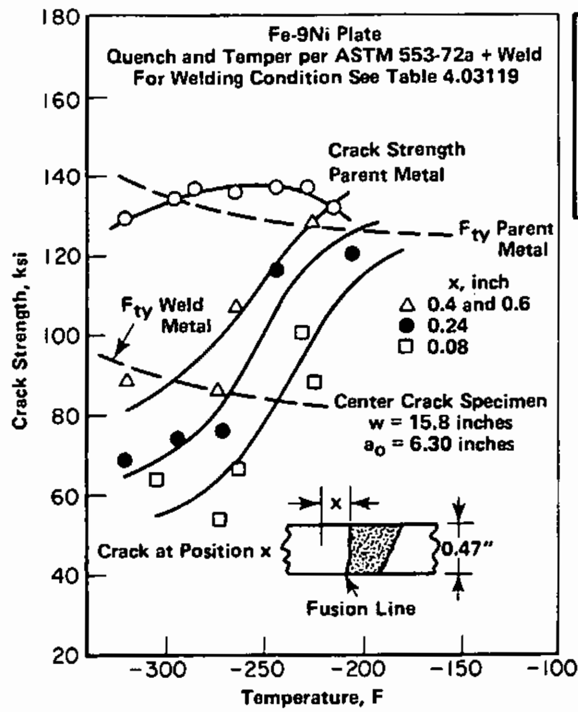


FIGURE 4.03115. EFFECT OF LOW TEST TEMPERATURES ON CRACK STRENGTH OF THE HAZ IN A MANUAL WELDMENT OF QUENCHED AND TEMPERED PLATE [(26) P. 72]

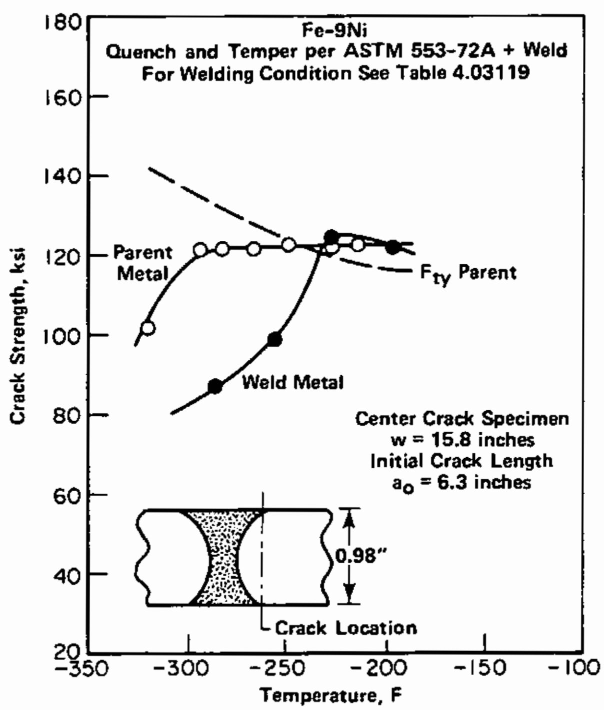


FIGURE 4.03116. EFFECT OF LOW TEST TEMPERATURES ON CRACK STRENGTH OF PARENT AND OF WELD METAL IN A MANUAL WELDMENT OF QUENCHED AND TEMPERED PLATE [(26) P. 73]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

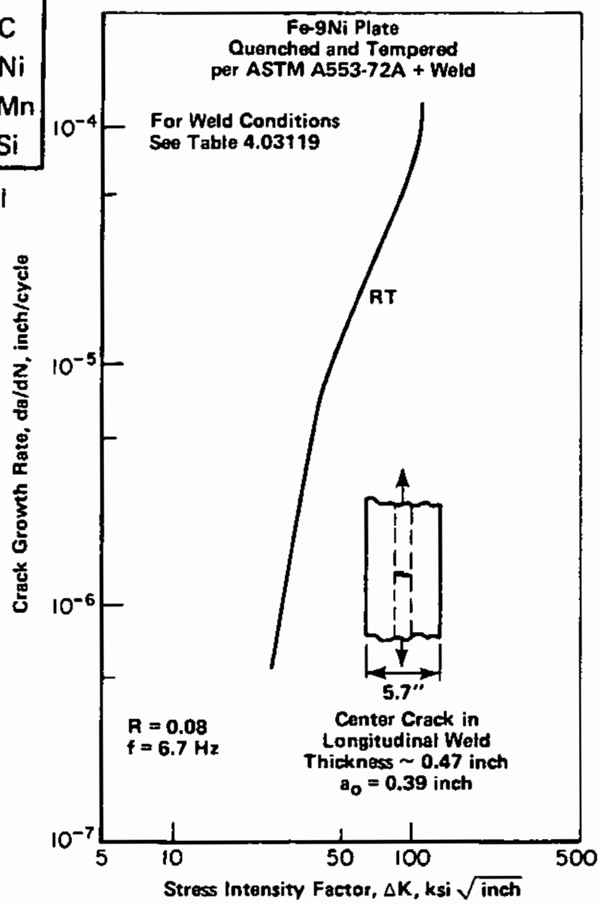


FIGURE 4.03117. FATIGUE CRACK PROPAGATION RATES AT ROOM TEMPERATURE FOR QUENCHED AND TEMPERED SMA WELDED PLATE [(26) P. 86]

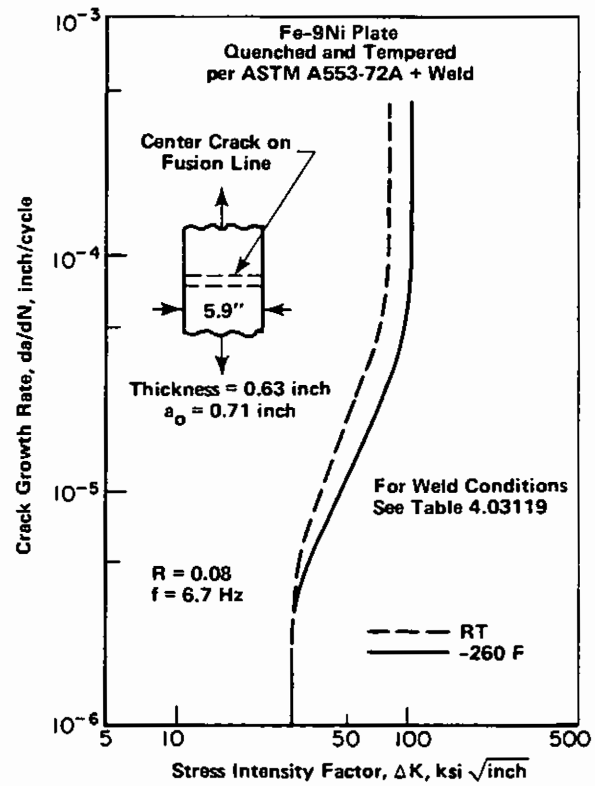


FIGURE 4.03118. FATIGUE CRACK PROPAGATION RATES AT RT AND FOR QUENCHED AND TEMPERED SMA WELDED PLATE [(26) P. 85]

	Fe
0.13 max	C
8.5–9.5	Ni
0.9	Mn
0.15–0.30	Si

9 Ni Steel

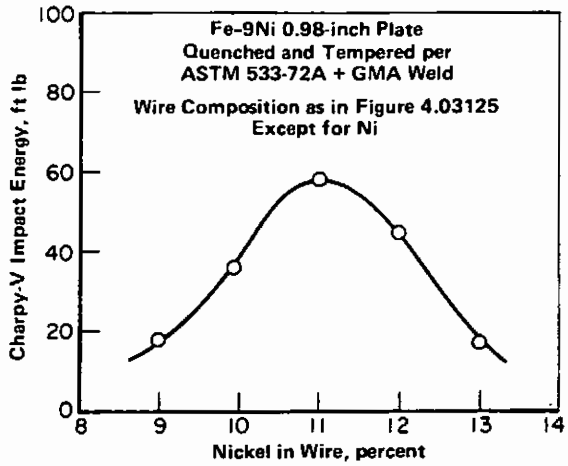


FIGURE 4.03124. IMPACT ENERGY OF GMA WELD METAL AT -320 F FUNCTION OF WIRE Ni CONTENT [(26) P. 129]

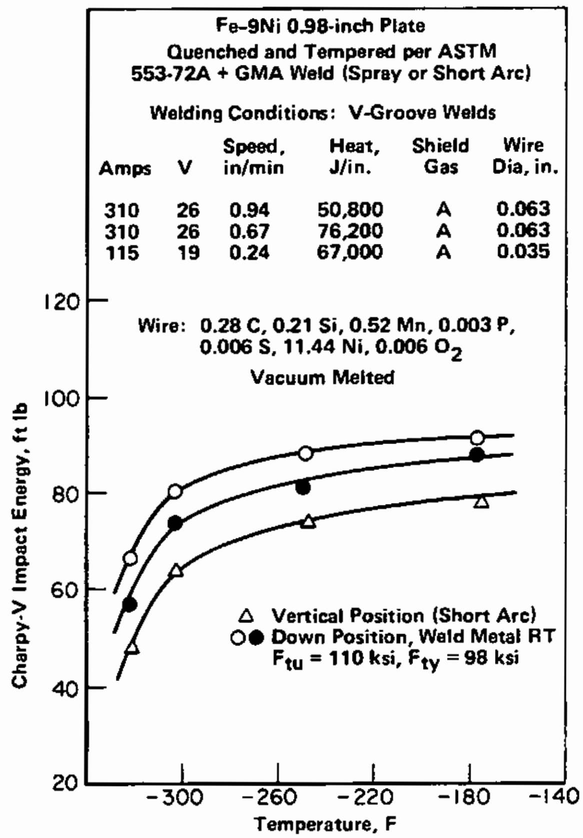


FIGURE 4.03125. EFFECT OF LOW TEMPER- ATURES ON IMPACT ENERGY OF 11 PERCENT Ni GMA WELD METAL [(26) P. 125-127]

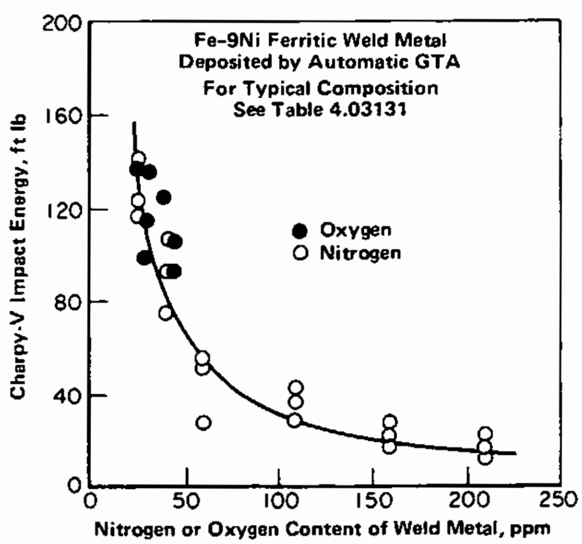


FIGURE 4.03127. EFFECT OF NITROGEN OR OXYGEN CONTENT ON -320 F IMPACT ENERGY OF FERRITIC WELD METAL DEPOSITED BY AUTOMATIC GTA PROCESS [(38) FIGURE 2 AND 3]

	Fe
0.13 max	C
8.5-9.5	Ni
0.9	Mn
0.15-0.30	Si

9 Ni Steel

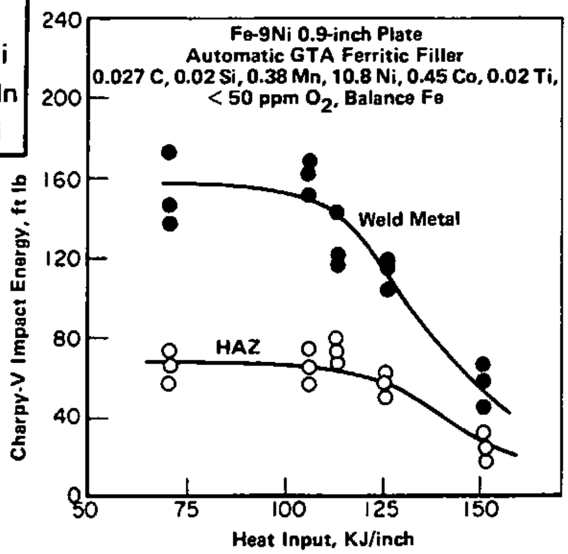


FIGURE 4.03128 EFFECT OF HEAT INPUT ON -320 F IMPACT ENERGY OF WELD METAL AND HAZ PRODUCED BY AUTOMATIC GTA PROCESS USING A FERRITIC FILLER [(37) FIG. 3]

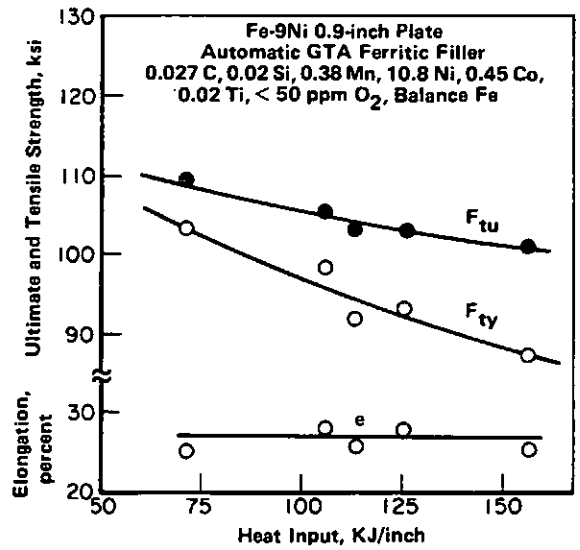


FIGURE 4.03129 EFFECT OF HEAT INPUT ON TENSILE PROPERTIES OF FERRITIC WELD METAL PRODUCED BY AUTOMATIC GTA PROCESS [(37) FIG. 4]

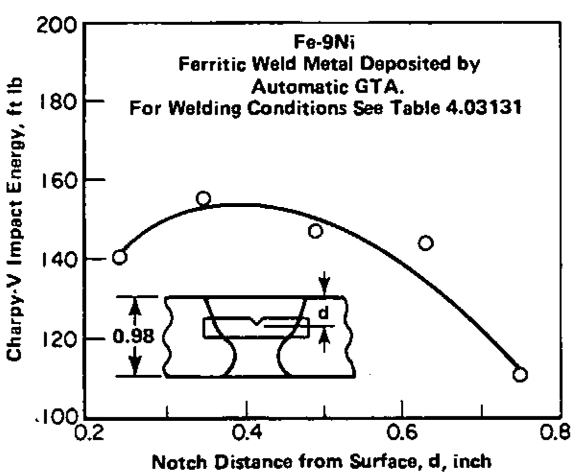


FIGURE 4.03132. IMPACT ENERGY AT -320 F FOR FERRITIC WELD METAL DEPOSITED BY AUTOMATIC GTA AS FUNCTION OF NOTCH DISTANCE FROM PLATE SURFACE [(38) FIG. 26]

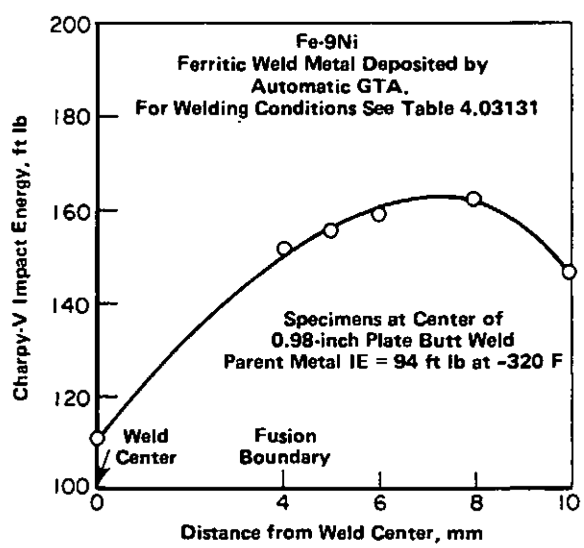


FIGURE 4.03133. IMPACT ENERGY AT -320 F FOR FERRITIC WELD METAL DEPOSITED BY AUTOMATIC GTA AS FUNCTION OF DISTANCE FROM WELD CENTER [(38) FIG. 24]