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EVALUATION OF THE MECHANICAL PROPERTIES OF ELECTROSLAG REFINED IRON ALLOYS

by

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Carnegie-Mellon Institute of Research

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16. Abstract

Four electroslag remelted iron-base alloys, namely Nitronic 40 (21Cr-6N-9Mn), HY-130, 9Ni-4Co, and D-6 were prepared and evaluated in the form of 15.2 mm thick plates. Smooth-bar tensile tests, double-edge sharp notch fracture toughness tests and Charpy V-notch impact tests were conducted on appropriate heat treated specimens of the four steel plates at 22°C, -50°C, -100°C, -150°C, and -196°C. Similar material characterization, including metallographic evaluation studies on air-melt and vacuum arc melt grades of same four alloy steels were conducted for comparative purposes. A cost analysis of manufacturing plates of air-melt, electroslag remelt and vacuum arc remelt grades was performed. The results of both material characterization and cost analyses have pointed out certain special benefits of electroslag processing iron-base alloys.

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FOREWORD

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Mechanical testing work of this program was performed by Westmoreland Mechanical Testing and Research, Inc., under the supervision of Dr. T. Hengstenberg and Mr. D. Rossi.

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SUMMARY

. Four electroslag remelted (ESR) iron-base alloys, namely, Nitronic 40 (21Cr-6Ni-9Mn), HY-130, 9Ni-4Co, and D-6 were prepared as small size ingots, which were forged into slabs and subsequently rolled into 15.2 mm thick plates. These alloy plate materials, heat treated in appropriate manner, were characterized through determination of smooth bar tensile, double-edge sharp-notch feature toughness, Charpy impact strength properties at 22°C, -50°C, -100°C, -150°C, and -196°C, and evaluation of their microstructural cleanliness. For comparative purposes similar studies were conducted on air-melt and vacuum arc remelt (VAR) grades of the same four alloys. A material manufacturing cost analysis of the three grades of four alloys was performed.

The highlights of this study are that the ESR grade of each experimental alloy steel with few exceptions displayed highest toughness characteristics in the presence of sharp cracks and under conditions of slow rates of loading. The vacuum arc remelted grade was next in standing to the ESR grade followed by the air-melt grade. The smooth bar tensile test results indicated that the air-melt, ESR, and VAR grades of Nitronic 40 and HY-130 alloy steels achieved higher than specification minimum tensile properties; the air-melt and VAR grades of 9Ni-4Co alloy steel also developed the specification minimum tensile strength, but the ESR grade showed lower tensile properties. The D-6 alloy steel also indicated lower tensile properties in the ESR grade at several low test temperatures.

ESR and VAR melting did not significantly influence the Charpy V-notch impact characteristics of Nitronic 40, 9Ni-4Co, and D-6 alloy steels, but ESR melting did lead to marked improvements in the impact properties of HY-130 alloy steel.

The material characterization and manufacturing cost comparison data for the three grades of four iron-base alloys provided in this report help clarify some of the important benefits of ESR processing.

1.0 INTRODUCTION

The objectives of this program are to characterize the mechanical properties of electroslag refined iron-base alloys and to provide comparative mechanical property characterization and manufacturing cost data of the same iron-base alloys produced by conventional air melting and vacuum arc remelting techniques.

The iron-base alloys evaluated in this program include:

(a) Nitronic 40 (21Cr-6Ni-9Mn),

(b) HY-130,

(c) 9Ni-4Co,

(d) D-6 alloy steels.

The mechanical property characterization program conducted was limited to:

(1) smooth tensile tests,

(2) sharp-notch tensile tests,

(3) Charpy impact tests conducted at five different temperatures: namely, room temperature (22°C) minus 500°C, minus 100°C, minus 150°C and at minus 196°C (in liquid nitrogen).

Specimens for all aforementioned tests were extracted from 15.2mm thick plates of each alloy made from air melt, electroslag remelted and vacuum arc remelted ingot or billet stock. No heat treatment was given to the Nitronic 40 test specimens. The specimens of HY-130, 9Ni-4Co and D-6 steels were heat treated in the normal manner specified for each alloy steel.

2.0 EXPERIMENTAL MATERIALS PREPARATION

2.1 Background

For many years, specialty steel and alloys manufacturers have been conscious of the shortcomings of the conventional methods of ingot casting. Undesirable characteristics of conventionally cast ingots include:

(a) axial unsoundness

(b) segregation

(c) coarse crystal structure

(d) high non-metallic inclusion content

(e) higher gas content and porosity.

All of these characteristics affect mechanical properties, especially, fracture toughness and crack propagation resistance. Conventionally cast ingots require heavy reductions during mechanical working combined with long and expensive heat treatments so as to develop the structures which will provide the required minimum mechanical properties.

To alleviate the aforementioned problems, to improve product yield and enhance reliability of alloy steels intended for critical applications, consumable electrode remelting processes are often applied. Two methods widely used for this purpose are: (1) Vacuum arc remelting (VAR) and (2) Electroslag remelting (ESR).

In VAR, the metal is remelted under reduced pressure in a direct current (D.C.) arc between the electrode and a pool of metal in a water cooled copper mold.

In ESR, remelting of the consumable electrode is accomplished at atmospheric pressure in a superheated molten slag bath which also protects the molten metal from atmospheric contamination. The melting and solidification of the ingot is conducted in a water cooled mold. The passage of electricity through the slag generates adequate heat to melt the end of electrode immersed in the slag layer and refining of the metal takes place as a result of slag-metal reactions.

In ESR and VAR, progressive melting and solidification of small amounts of metal, in a given time span, produce an ingot of high internal soundness, uniformity of chemical composition, minimized inclusions and higher yield of useful metal compared to the conventionally chill-cast ingots.

2.2 Conventional Manufacturing Method For Alloy Steels

Alloy steels of the type evaluated in this program are presently made in electric arc furnaces. However, these alloy steels, for special reasons, can also be made in air or vacuum induction furnaces and other types of primary melting furnaces.

Electric arc furnaces used today range in capacity from several tons up to 200 tons. In normal practice, the higher alloy steels are seldom made in electric arc furnaces larger than 100 tons. Some of the more important advantages of electric arc furnaces are:

1. Practically all grades of alloy steels can be made.
2. Electric heat using carbon or graphite electrodes is economical, and relatively clean.
3. Temperature of the slag and melt can be controlled within the required limits.
4. Efficiency of recovery of most alloying elements from various charge materials is reasonably good.

The disadvantages of electric-arc furnace relates to high cost of the installation, operating labor, power, electrodes, refractories and relatively high gas content in the metal.

2.3 Electric Arc Furnace Operation

The electric arc furnace can melt various types of charge materials. The charge for a specific type of alloy steel heat generally consists of about 40% heavy scrap, 40% medium scrap and the balance, light scrap. Ferro-alloys, alloying oxide pellets and virgin alloys which are not easily oxidized are usually charged prior to melt down of the entire charge of a heat.

Melt down is accomplished with excess carbon in the bath to avoid oxidation of the light scrap. During melt down, it is essential to form a molten metal pool as quickly as possible to protect the furnace bottom.

Ore or oxygen is used after melt down to reduce the carbon content. Oxidation occurs in varying degrees both during melt down and carbon removal period. This is also the period when phosphorus, silicon, manganese, carbon, chromium and some sulfur are oxidized. The oxidation practice varies with alloy grades melted; thus the low carbon grades require a relatively high degree of oxidation and the high carbon grades, minor amount of oxidation. The removal of carbon is promoted by raising the bath temperature which also increases the fluidity of the metal and slag bath thus facilitating the removal of inclusions. Blowing oxygen through a lance into the bath helps to attain these results faster.

Electric furnace steel may be made using single slag, double slags or essentially non-reactive slag. In the single slag practice, the initial slag is converted to a reducing slag by furnace additions. In double slagging practice, the initial oxidizing slag is removed from the bath and is replaced with a reducing slag. The latter is the most common industry practice of making alloy steels needed for critical applications. The non-reactive (neutral) slagging practice is used primarily when the charged metallics in the electric arc furnace will yield the desired steel composition without refinement.

Alloy steels containing large amounts of chromium and very low carbon content are often made by a duplexing technique. This consists of melting down the charge in the electric arc furnace and transferring the molten metal to a reactor vessel and blowing down the carbon to perform the deoxidation reactions using an argon-oxygen or similar gas mixture in conjunction with a refining slag. Argon-oxygen deoxidation results in savings of easily oxidizable alloying elements, such as chromium or manganese, produces clean molten metal and to an extent obviates the need for vacuum processing of molten metal.

The Nitronic 40 (21Cr-6Ni-9Mn) steel evaluated in this program was manufactured using the duplexing process involving electric arc furnace melting followed by argon-oxygen deoxidation and refining. The ingots were, however, cast in conventional chill molds.

The present industrial practice of manufacturing alloy steels, such as, D6 and 9Ni-4Co, is by electric arc furnace melting and casting of the heat into electrode molds, followed by vacuum arc or electroslag remelting of these electrodes into ingots of various sizes. The billets and other finished products are then made by mechanical working of VAR or ESR ingots. Because of this manufacturing practice air melt grade D6 and 9Ni-4Co alloy steels are not normally produced. HY130 is produced by air-melting. However, a majority of heats are cast as slab ingots which are directly rolled into plates. Hence, round bars suitable for VAR and ESR melting are not normally available.

2.4 Induction Melting of HY130, 9Ni-4Co and D6 Alloy Steels

Primary melting of HY130, 9Ni-4Co and D6 alloy steels to prepare the air melt grade plate stock required in this program, was done by air-induction melting alloy charge materials of reasonably high purity. Melts were made in a 363 kg. magnesia lined crucible. The molten metal of the required chemical composition was cast into a single

228.6 mm round cornered square (RCS) tapering to 177.8 mm RCS x 863.6 mm long ingot mold. A ceramic hot top was used on each ingot to reduce the ingot center cavity. Drillings were taken from each ingot and its chemical analysis was verified. An ultrasonic inspection was performed starting at the bottom of each ingot. Then, an ultrasonically sound segment in each ingot was marked and a portion weighing 68 to 79.4 kg. was directly forged into a 127 mm thick and 254 mm wide slab. The balance of each ingot, including the hot top was forged into approximately 165 mm round billet.

One half of the length of each air induction melted forged billet was remelted into an ESR ingot. The second half of each billet was descaled and subsequently remelted into VAR ingot.

The Nitronic 40 material was purchased initially as an 8 inch RCS billet weighing approximately 499 kg. A 91 kg. section of this billet was forged into slab representing the air melt grade. The remainder of the billet was forged into 178 mm round and 152 mm round electrodes, respectively, for ESR and VAR melting.

2.5 Electroslag Remelting Process

The essential features of the electroslag remelting process are shown schematically in Figure 1. ESR melting is conducted at atmospheric pressure under a molten slag cover which excludes air from the molten metal. Electrical connections, usually line frequency alternating current (AC), are made to the electrode and the water cooled base plate which supports the mold and the remelted solidified ingot. The heat required for melting of the electrode is generated in the slag layer by Joule (I^2R) heating due to the passage of high amperage current.

The power source, usually includes a transformer for stepping down the line voltage to the operating voltage in the range 30V to 110V and a saturable reactor to limit the current to a required maximum. By adding a DC control circuit to the reactor system, a stepless power control is achieved during ESR.

The slag during ESR of alloy steels is generally maintained at a specified constant temperature in the range 1750°C to 1950°C. Drops of metal fall from the electrode through the slag, as shown in Figure 1 (Stage A through Stage C) into the molten metal pool. Stable melting is maintained by controlling the power input and the electrode feed rate into the molten slag.

The ingot solidification characteristics are influenced largely by the size, shape and superheat of the molten metal pool. The ESR ingot grows through progressive solidification of the molten metal.

The ESR ingot is encased in a thin shell of solidified slag. This thin slag skin around the ESR ingot reduces lateral heat flow between the ingot and the mold wall. The presence of this slag skin as a sleeve around the ingot, results in more pronounced directional solidification than achieved in VAR. The slag skin promotes the formation of smooth surface on ESR ingots. These ingots require a minimum of dressing or more often, no dressing at all prior to hot working into mill products. ESR ingots, therefore, provide higher product yield than chill cast and VAR ingots.

The relative simplicity of the ESR system permits melting of two or more electrodes either in tandem, or in series, in order to produce ingots of larger weight, size and shape than by VAR. Square and slab shaped ingots produced by ESR can be directly processed into finished mill shapes which not only reduces the number of mechanical working steps but also results in lower manufacturing costs and higher product yield.

2.5.1 Metal Refining in ESR

Typical ESR slags have electrical conductivities in the range 1 to 15 ohm $^{-1}$ cm^{-1} at 2000°C. Calcium fluoride, CaF_2, is the principal constituent of most ESR slags and typical slags for remelting alloy steels contain fair amounts of alumina, (Al_2O_3), lime (CaO), and sometimes small amounts of magnesia (MgO), silica (SiO_2). Nearly all the slags in the system CaF_2-Al_2O_3-CaO used for ESR have liquidus temperatures below 1450°C. The presence of alumina in the slag increases the resistivity which leads to greater electrical efficiency. Electrical power—required to remelt alloy steel electrodes in ESR is in the range 1000 to 1300 KWH per ton.

The presence of alumina improves the formability of slag to impart a good surface to the ingot and also leads to good sulfur removal. The addition of basic oxides, such as CaO and MgO further improves the chemical reactivity of the slag. The slag-metal reactions in ESR are essentially the same as in conventional steel making. Oxygen and sulfur contents are both reduced in ESR ingots in normal practice using simple slags, such as $70CaF_2$, $30Al_2O_3$. The presence of silica and iron oxide creates instability in ESR slags which leads to loss of alloying elements such as aluminum, titanium, silicon, manganese, vanadium, chromium, in that order. Hydrogen cannot be removed during ESR. Hence the electrodes and slags used should not cause hydrogen level in ESR ingot to rise above 2 ppm.

2.6 Vacuum Arc Remelting Process

Vacuum arc remelting of alloy steel in normal industry practice is done under pressure ranging from 10 mm to 10^{-3} mm of mercury. A diagrammatic representation of a typical vacuum arc remelting system is given in Figure 2. The electrode is welded on to a stub which is held by a ram. Within the vacuum chamber the ram carries the electrode clamp. One lead of the power source is connected to the electrode clamp and the second lead is connected to the crucible.

Melting is commenced by striking an arc between the electrode and the base pad after evacuating the mold to the desired pressure level. Once a molten pool of metal has formed, the current is increased gradually to establish the desired melt rate of the electrode and ingot solidification. At the end of the melting process the arc current is reduced in several stages to produce hot-topping effect and thus minimize the axial cavity in the ingot.

Since the ingot is progressively solidified, few equiaxed crystals are observed in VAR ingots. However, as the ingot grows longer less heat is lost through the base and the structure becomes less ideal. When the ingot length is about three times its diameter the columnar crystals change direction, becoming less vertical. At a length of about five times the diameter, side-cooling seems to predominate and lengths greater than this are not favored because of the adverse effect on macrostructure. The present practical size limit of VAR ingot seems to be around 1524 mm. Because of the absence of an equiaxed axial region in VAR ingots, banding is markedly reduced and inclusions which remain after remelting are uniformly dispersed throughout the ingot. This results in significant improvement in the transverse ductility in VAR material as compared to air melted and chill cast counterpart material.

Surface dressing of both electrode and VAR ingots is necessary at some stage of mill processing in order to produce high quality finished products. This results in somewhat lower product yield than via ESR.

VAR ingot surface is both rough and chemically inhomogeneous. The roughness is caused mainly by the "corona" effect caused by the splashing of metal droplets by the arc on to the cold walls of the mold immediately above the advancing ingot. The inhomogeneity is caused by the condensation of volatile elements, such as manganese on the inner surface of the mold.

In VAR, as the droplets of metal form in the arc they are subjected to low pressure, instantaneously to very high temperatures, and are then cooled rapidly by the molten metal pool to normal steel making temperatures. The low pressures are undoubtedly responsible for the low hydrogen content of VAR steel -- below 1 ppm. Vacuum arc remelting has no effect upon sulfur and phosphorus contents; however, high vapor pressure trace elements are partially removed. A major advantage of VAR is that it reduces the inclusion content of alloy steels. However, with few exceptions, some nitrides, oxides and sulfides are too stable to be thermally disassociated and hence they tend to remain in VAR ingots. Oxygen dissolved in the air-cast electrodes is significantly reduced by VAR.

3.0 EXPERIMENTAL MATERIALS PROCESSING

The experimental materials purchased at the beginning of the program effort included (a) Nitronic 40 (21Cr-6Ni-9Mn) alloy steel in the form of a 203 mm square billet weighing 499 kg., (b) HY-130 alloy steel, (c) 9Ni-4Co alloy steel and (d) D-6 alloy steel. The latter three alloy steels were air-induction melted and chill cast as 228.6 m square tapering to 177.8 mm square ingots, each weighing around 330 kg with the hot top.

The division of all four alloy steels into air melt slabs an electrodes suitable for electroslag and vacuum arc remelting was done in such a way as to produce at least 68 kg. of plate material of the three grades of each alloy. Table I provides data of initial weight o material procured, the weights of air melt slabs, ESR ingots, VAR ingo and the weights of plates produced of each alloy.

3.1 Conversion of Air Melted Grade Experimental Steel into Plate

Forging of air melted ingots or billet into 127 mm thick by 254 mm wide slabs was done because of the maximum opening of only 171 mm available in the plate rolling mill. All slabs were surfac ground prior to rolling into plates. The air-melted slabs were soaked at 1150 ± 10°C for four hours and directly rolled in seven or eight roll passes into 152 mm (0.6 inch) thick plates. After the fourth pass, each plate was flame cut into two halves and the rolling complet with only one time heating of the slab. All plates were cooled to roo temperature on a steel roller rack. The plates were flat and even the two ends of each plate were sound. No sonic flaws were detected in any of the rolled plates representing the air melted alloys.

3.2 ESR and VAR Electrode Preparation

Electrodes for ESR were prepared from Nitronic 40 billet and air-induction melted and cast ingots of HY-130, 9Ni-4Co and D-6 alloy steels. All alloy electrodes except the Nitronic 40 alloy were rough forged as 165 mm round bars. The Nitronic 40 electrode for ESR was forged as a 178 mm round bar and for VAR, as a 152 mm diameter bar. The 165 mm diameter electrode was the ideal size for ESR melting into 241 mm diameter mold and the machined 152 mm electrode into 203 mm diameter VAR ingot mold. The smaller electrode to mold ratio used in ESR, as compared in VAR, provides for more intense refining action. Since the Nitronic 40 alloy had low sulfur initially, no additional refining during ESR was necessary and therefore, a larger diameter electrode was used to reduce forging costs. A larger mold fill ratio during ESR increases production rate and reduces electrical energy and overall costs.

3.3 ESR Melting

Details of the ESR process used are given in Tables II through V, respectively for Nitronic 40, HY-130, 9Ni-4Co and D-6 alloy steels.

Two ESR ingots of Nitronic 40 were prepared. The purpose was to investigate the ability of the ESR process to maintain the nitrogen in the Nitronic 40 alloy using an acid slag with air or an inert (argon) atmosphere over the slag.

The forged electrodes were directly used for ESR without removal of the scale formed during heating prior to forging and during the stress relief operation after forging. The scale formed on the forged electrode was light in the case of Nitronic 40 and HY-130 but moderately heavy (thick) in D-6 and very heavy in the 9Ni-4Co alloy.

All ESR melts were initiated by charging molten slag in the mold. The molten slag in each case was prepared in a water-cooled copper mold using a non-consumable electrode. All ESR melted ingots displayed excellent surface condition from the bottom to top and good hot top condition. The bottom contact pads used in all ESR melts, except the 9Ni-4Co ESR ingot, were made of the same alloy. In the latter case, a mild steel contact pad was used since the 9Ni-4Co alloy electrode was too hard to cut by a power hacksaw.

3.4 VAR Melting

The starting electrodes for VAR melting were approximately 165 mm in diameter which were all surface machined down to 152 mm. diameter bars.

Details of the VAR process used, the weight of electrodes supplied and the ingots returned are provided in Table VI. The electrical parameters used for VAR melting were approximately the same for each of the four experimental alloys. The VAR process was initiated by striking an arc directly on the bottom copper plate attached to the mold. Hence, neither a contact pad or machine chips were used as in older versions of VAR melting practice.

The VAR ingots produced were of good surface condition; although the hot tops in 9Ni-4Co and D-6 alloy ingot were poor, they were reasonably filled in the other two alloy ingots.

3.5 Forging of ESR and VAR Ingots

Prior to forging, the VAR ingots were surface dressed. Then, each ESR and VAR ingot was sonic checked and found to have no internal defects.

All ingots were heated slowly to 982°C and homogenized at this temperature for a period of 4 hours. The homogenized ingots were then transferred to a furnace maintained at 1120 to 1130°C, soaked for one hour and subsequently forged into 127 mm thick by 254 mm wide slabs. The forged slabs were all slow cooled to ambient temperature. The scale remaining on the surfaces of each slab was removed by grinding. This operation produced material loss of the order of 2 to 3 per cent of forged slab weight.

3.6 Rolling of Plates from ESR and VAR Slabs

ESR and VAR slabs were heated to their respective rolling temperatures of 1121°C and 1149°C and soaked for two hours and then directly rolled into 15.2 mm thick plates without an intermediate reheating operation. After the third rolling pass, each plate was cut into two equal sections and subsequently each section rolled into the finish thickness. The rolled plates were individually cooled on roller racks. The plate rolling was accomplished with minor loss of material due to scale formation.

3.7 Chemical Analyses of Experimental Steel Ingots and Plates

For the sake of presenting the chemical analyses of each experimental alloy steel as affected by the successive processing steps, the chemical analyses results of samples from the air cast ingot, ESR ingot, VAR ingot and the plate product of each grade are assembled in tabular forms. Tables VII through X present such data respectively for Nitronic 40, HY-130, 9Ni-4Co and D-6 alloy steels evaluated in this program.

4.0 CHARACTERIZATION OF EXPERIMENTAL ALLOY STEELS

4.1 Preparation of Various Test Specimens

The rolled plate of each experimental alloy steel was ultrasonically tested and found to have no detectable internal flaws. Three types of mechanical test specimens, namely, tensile test, Charpy vee notch impact test and double edge notch (DEN) fracture toughness test, were prepared from each of the twelve (12) plates representing the four alloy steels and three quality grades of each steel. Test specimen blanks were cut starting from the mid length of each plate and traversing towards the end of the plate as shown in Figure 3. All specimens were oriented longitudinally along the length (rolling direction) of each plate.

4.2 Heat Treatment of Mechanical Test Specimens

All mechanical test specimen coupons were heat treated prior to machining into the required form. Heat treatment was performed in a laboratory size furnace in which the required temperature was controlled within plus or minus 2°C. Specimens were heat treated in groups of ten at a time. The heat treatment given to the mechanical test specimen of each alloy is presented in Table XI.

4.3 Mechanical Test Specimen Machining and Precracking of DEN Specimens

The dimensions and geometry of the three types of mechanical tests, namely tensile, impact and fracture specimens are as shown in Figure 3. The notch in the Charpy impact and DEN fracture test specimens was placed in the RW direction. (Ref. Figure 3).

Precracking of DEN specimen was done in a cantilever type bending machine shown in Figure 4. The specimen having a machined vee notch was held in a clamp rigidly on one side of the notch, and the opposite side of the specimen was clamped in an extension arm. Flexural load was applied on the extension arm using an eccentric bearing mounted on the spindle of a 5H.P, 980 RPM electric motor. The flexural load applied at the root of the machined notch could be varied by adjusting the length of the extension arm from the point of load application and also by varying the depth of offset in the eccentric bearing. The stress required to generate the fatigue crack was maintained well below 25 per cent of the yield stress of each alloy steel in the heat treated condition. Crack extension in the specimen was monitored by sighting a 10X power microscope horizontally at the root of the notch.

The balancing U shaped notch of depth equal to the crack depth in the DEN specimen was inserted by machining rather than by saw cutting. The practices used in this task conformed to ASTM Method of Test E 399-72.

4.4 Mechanical Testing of Specimens

Mechanical tests conducted for characterization of the four experimental alloy steels included the following:

A. Smooth tensile tests -- at least twelve, 6.35 mm diameter specimens tested from each of the 12 plates representing the three grades of 4 alloy steels.

B. Double edge notch precracked fracture tests -- at least fourteen, 25.4 mm wide by 83.8 mm long DEN specimens tested from each of the 12 alloy steel plates.

C. Charpy impact tests -- at least fifteen standard V-notch impact specimens tested from each of the 12 alloy steel plates.

Testing each type of aforementioned specimen was conducted at five different temperatures as noted below:

(a) Room temperature

(b) -50°C

(c) -100°C

(d) -150°C

(e) -196°C (immersed in liquid nitrogen).

4.5 Cryogenic Testing of Mechanical Test Specimens

The cryostat used (Figure 5(a)) for achieving sub-zero temperatures for conducting the tensile and DEN fracture tests was purchased from Cincinnati Cryo-engineering Corporation, a commercial manufacturer of cryostats. This device consists of a two piece box like enclosure as shown in Figure 5(b). The cryostat chamber opens like a book on a vertical hinge. Holes provided at the top and bottom of the cryostat chamber allow for the test specimen grips and the pull rods to be centrally located in the enclosure. A fan mounted on the rear panel of the cryostat chamber circulates the atmosphere within the chamber so as to maintain a uniform temperature in the test specimen. The low temperatures are achieved by bleeding and evaporating into the chamber a controlled amount of liquid nitrogen. The temperature of the cryostat chamber and that of the test specimen are continuously monitored and recorded during a test using two separate thermocouples. The test specimen temperature monitoring thermocouple touched the specimen at a point below the gage section and well above the grip section. The cryostat chamber is made out of a molded ceramic insulation material housed in a polystyrene box. Mechanical tests at liquid nitrogen temperature (-196°C) were conducted by flooding the cryostat with liquid nitrogen, thereby immersing the specimen and grips in the refrigerant. Temperatures in the mechanical test specimens during the duration of the test were controlled within plus or minus 1°C at each required test temperature.

4.6 Smooth Tensile Tests

Tensile tests were conducted in triplicate at each test temperature on a 534 MN Baldwin Universal Testing Machine and using specimens from each of the 12 experimental alloy steel plates. The test and reporting procedures used complied with ASTM Standard E8-69 using standard 6.35 mm round tension test specimens. Tensile test data for Nitronic 40, HY-130, 9Ni-4Co, and D-6 alloy steels are respectively summarized in Tables XII through XV. Figures 6 through 9 show the effect of cryogenic temperatures on the tensile properties of alloy steels of three levels of purity. Averaged tensile properties were computed from data of Tables XII through XV, converted into metric units and have been summarized in Table XVI.

4.7 Double Edge Notch (Precracked) Tensile Tests

All DEN specimen tests were conducted on a 534 MN (120 Kips) Baldwin Universal Testing Machine. Time to P_{max} during specimen testing was from 1 to 1.5 minutes. The load versus displacement data were plotted on an automatic X-Y recorder. The stress intensity factors (K_{max}) were computed using the following equation for the DEN specimen: (1,2)*

$$K_{max} = Y \frac{P_{max}\sqrt{a}}{BW}$$

where, $Y = 1.98 + 0.36\left(\frac{2a}{W}\right) - 2.12\left(\frac{2a}{W}\right)^2 + 3.42\left(\frac{2a}{W}\right)^3$

*References appended to the text.

P_{max} = Load at fracture

B = Specimen thickness

W = Specimen width

a = Average crack length (as determined from fracture face).

The data obtained from DEN tests of each experimental alloy steel plate include net fracture strength (σ_C), σ_C/σ_{YS} ratios, and stress intensity factor K_{max}. Results of DEN tests for Nitronic 40, HY-130, 9Ni-4Co and D-6 alloy steels of three levels of purity are provided, respectively, in Tables XVII through XX. Figures 10 through 13 show the effects of cryogenic temperatures on K_{max} values and on the net fracture/yield strength (σ_C/σ_{YS}) ratio of the four experimental alloy steels at each of three purity levels. It is noteworthy that with the exception of the D-6 alloy steel, all other experimental alloy steels showed a high σ_c/σ_{ys} ratio even down to the lower temperatures.

4.8 Charpy Impact Tests

Charpy impact tests were conducted in triplicate at each test temperature in accordance with ASTM Standard E23-72, on the three grades of materials representing each of the four alloy steels. These test results are tabulated in Tables XXI through XXIV and also graphically presented in Figures 14 through 17 showing the effects of material purity level and test temperatures on the impact strength, respectively, of Nitronic 40, HY-130, 9Ni-4Co and D-6 alloy steels. Averaged DEN sharp notch fracture specimen data and charpy v-notch impact specimen test data converted into metric units which are summarized in Table XXV.

4.9 Metallographic Cleanliness Evaluation of Experimental Alloy Steels

Metallographic samples from rolled plates of air melt, ESR melt and VAR melt of each experimental alloy steel were polished and examined on the rolled surface and the thickness cross-section. Material of all three grades were cleaner than average commercial plate product of the same alloy composition. Therefore, metallographic examination and comparison of the material quality, as to the size, amount and distribution of non-metallic inclusions was performed at 1000X. Typical micrographs of each grade of alloy steel plate evaluated and representing Nitronic 40, HY-130, 9Ni-4Co and D-6 alloy steels, respectively, are shown in Figures 18 through 21. Photographs marked Plane 1 and Plane 2 represent the rolling plane and plate cross-section along the rolling direction, respectively. Typical grain structures observed in heat treated AM, ESR and VAR plates of HY-130 are shown in micrographs (100X) presented in Figure 22. The prior austenitic grain size is finer than ASTM 8. The grain boundaries are not clearly delineated.

Cleanliness of each alloy manufactured in the three grades, viz, air melt, ESR melt and VAR melt was evaluated through a determination of volume fraction of inclusions in the rolling plane. (Plane 1 - Figures 18-21.) The volume fraction of inclusions in each specimen was estimated using a grid point scanning and counting method.

A 1 cm. square grid with 336 possible crosses in it was used. The total number (N) of separate grid placements per specimen selected was 20. The number (n) of inclusions falling directly on the grid points was counted.

The volume fraction was estimated using the equation:

$$V = \frac{N_{total}}{336 \text{ X } (N)} = \frac{N_{total}}{336 \times 20} = \frac{N_{total}}{6720} .$$

Percent volume fraction was computed by multiplying $\frac{N_{total}}{6720}$ by 100.

Inclusion size, shape, distribution and volume fraction estimation data for rolled plates of the three grades of each experimental steel were developed. These data are presented in Table XXVI. Inclusion size data for the largest inclusion observed in Plane 1 - parallel to the plate surface and Plane 2 - plate thickness cross-section, both along the plate rolling direction are given in Table XXVIA. The other inclusions observed in these metallographic specimens were smaller in size. Inclusion shape and general distribution comments are provided in Table XXVIB. In Table XXVIC the volume fraction estimation results of inclusions in Plane 1 - parallel to the plate surface, are given.

5.0 MANUFACTURING COST COMPARISON OF EXPERIMENTAL ALLOY STEELS

Estimates of manufacturing costs for air melt, ESR and VAR grades of Nitronic 40, HY-130, 9Ni-4Co and D-6 alloy steels have been made using electric arc furnace heat weights of 6 tons (short tons) and 17 tons as examples.

Since high quality final product with low phosphorus and sulfur contents in the alloy steel composition is required to satisfy the specification, a more time consuming two slag practice is presumed necessary.

Other assumptions made and considerations in the computation of step-wise cost build-up and product yield are as follows:

1. A mark-up of 15 to 30% is added to the initial electric arc furnace charge cost to defray the charges of scrap transportation, sorting, mixing, storage, chemical analyses inventory maintenance, computer usage.

2. A 6 ton (short ton) electric arc furnace melt conversion cost is estimated at $325 per ton and for the 17 ton electric arc furnace heat at $270 per ton. These costs are total shop costs including laboratory costs.

3. Larger ingots will bear proportionally higher forging costs because of the scale of operation and handling equipment needed.

4. Alloys such as Nitronic 40 can be melted and processed more advantageously with resultant lower total cost by duplexing the melt, first in an electric arc furnace and then in an argon-oxygen refining vessel.

5. Step by step processing costs aggregated include all pertinent manufacturing and product testing operations.

6. The final unit cost computed for each grade of plate material falls in a realistic range. However, different producers may arrive at different costs depending on their own shop capabilities, material and labor costs.

7. For comparison, the manufacturers' list price paid in the first quarter of 1975 for rough forged billets or ingots of air melted or induction melted experimental alloy steels is as follows:

   (a) Nitronic 40 (rough forged billet) electric arc furnace plus argon-oxygen vessel refined - $0.99 per pound.

(b) HY-130 - induction melted and cast ingot - $0.98 per pound with hot top metal.

(c) 9Ni-4Co - induction melted and cast ingot - $1.175 per pound with hot top metal.

(d) D-6 - induction melted and cast ingot - $0.49 per pound with hot top metal.

Details of the costs estimated for rolled plates of each grade, namely, air-melt, ESR and VAR, of the four alloy steels are presented in Tables XXVII through XXX. The total costs estimated for each alloy steel are tabulated below. This cost analysis brings into better focus the economic advantages of ESR processing compared to air-melt and VAR processing of alloy steels.

	Cost/kg.		
Alloy	Air-melt	ESR	VAR
Nitronic 40	$3.40	$3.13	$3.42
HY-130	2.55	2.51	2.69
9Ni-4Co	3.22	3.06	3.26
D-6	1.98	1.98	2.20

6.0 DISCUSSION

On the manufacturing aspects of alloy steels characterized in this program, the following pertinent comments are offered:

a) The small heats of alloy steels made in an air-induction furnace using high purity raw materials and high quality, clean, heavy scrap are of equivalent quality to that made in a production size electric arc furnace.

b) Plate product yield from low-alloy steel, production size heats made in the electric arc furnace is around 65%, that of Electric Arc furnace plus ESR approximately 78% and that of Electric Arc furnace plus VAR, around 72%.

c) Plate product yield from ESR processed ingots can be further improved, if a slab ingot, rather than a round or round cornered square ingot is cast in the ESR operation. The use of this intermediate ESR slab casting operation also results in the lowering of the overall manufacturing cost of plate product.

The manufacture of the particular alloy steels evaluated in this program does not pose any unusual problems. The slags used in ESR of the various alloys provided ingots with good surface conditions. It is important to emphasize that the bottom contact plate used in ESR should be of the same composition as the electrode. Otherwise, appreciable dilution of chemical composition of the remelted ingot could occur to a considerable height from the ingot bottom. This mishap occurred during ESR of the 9Ni-4Co alloy electrode in which a 7-inch section had to be cut off from the bottom of the ESR ingot.

A prerequisite to the manufacture of defect-free finished material is "perfect ingots". By perfect ingot, it is meant one free from all cavities or openings and made up of material which is homogeneous throughout. Unfortunately, the natural laws that govern the solidification of the liquid metal in static ingot molds operate against the development of defect-free ingots.

Mechanical working enhances the density of the ingot metal by forcing its particles into more intimate contact, closing up cavities and refining its crystalline structure. The changes in the structure caused by mechanical working affects strength, ductility and hardness. The extent of change in each of these properties, however, is influenced by the alloy content of the steel, the distribution of the various alloying elements (segregation), the amount of work done, by the temperature at which the working is performed and finished, and the grain refinement obtained.

In the case of small size (170 to 200 mm section size) ESR ingots, the mechanical work is done more for the purpose of obtaining a final product shape rather than for the correction of solidification imperfections. This implies that strict benefits of ESR cannot be evaluated in a discriminating manner when ESR ingots are mechanically worked to the same extent as conventionally cast or VAR ingots.

During hot working, the non-metallic inclusions, as well as the small bodies of segregated material, are extended in the direction of working. In the finished material, these defects appear as lines or bands. The inclusions impart a fibrous structure to the steel. This particular structure causes a directional difference in the mechanical properties. With less inclusions present, ESR and VAR materials, therefore, exhibit lower anisotropy of mechanical properties than similar material manufactured by conventional (air-melt) techniques.

In the tensile test, when the applied stress acts parallel to the direction of material working, the fibrous structure tends to enhance the tensile strength of the material. On the other hand, if the applied stress is transverse to the direction of mechanical working, the mechanical properties are apt to be lower than in the longitudinal direction. Therefore, minimization or absence of fibrous structure in ESR and VAR grades may occasionally result in the development of somewhat lower longitudinal tensile properties compared to in air-melt grade even though the materials of three grades were applied the same amount of mechanical work (3,4,5).

The cost data presented in Tables XXVII through XXX emphasize the advantage of ESR melting of alloy steels in order to reduce overall manufacturing costs, increase product yield, conserve expensive alloying elements by reducing scrap loss and improve the cleanliness and performance characteristics. In this limited study, the advantages in product cost and yield favor the ESR route of manufacture of high-grade alloy steels rather than the VAR or air-melt routes.

Tensile Behavior

The tensile property data for the three grades of four experimental alloy steels presented in Tables XII through XV reflect the combined effects of materials melting process, ingot solidification, mechanical working and final heat treatment.

The mechanical test specimen dimensional measurements and test data computations were made in English units. Therefore, the tensile test data presented in Tables XII through XV are in these units. However, a summary of averaged tensile test data from three specimen tests conducted at each of the five test temperatures, for the four experimental alloy steels is presented in Table XVI, compiled in both English and metric units.

Tensile properties of Nitronic 40 (at room temperature), as presented in the Manufacturers' Product Data (Armco Steel Corporation, Advanced Materials Division Data Sheet S-54 for Nitronic 40) indicate the longitudinal tensile strength (UTS) for annealed 1 inch (25 MM) round bar as 690 MPa (100KSI), 0.2% YS, 393 MPa (57KSI), elongation in 2 inch (50 mm) 48% and reduction of area, 70%. For Nitronic 40 which is cold worked 15%, the UTS is 882 MPa (128KSI), 0.2% YS 745 MPa (108KSI elongation 56% and reduction of area 70%. The tensile strength of Nitronic 40 in the as-rolled condition can be expected to be in the ranc between that of annealed and slightly cold worked conditions.

The tensile properties of Nitronic 40 achieved in all three grades evaluated in this program are well above the Manufacturers' specification.

The argon shielding of ESR melt of Nitronic 40 prevented the loss of nitrogen in the resultant ESR ingot. Nitrogen analysis result for this heat is presented in the footnote of Table VII. However, this higher nitrogen content did not provide higher room temperature tensile strength values for resultant plate material as reported in Tables XII and XVI.

In the case of HY-130, the room temperature yield strength developed in all three grades is well above the minimum of 896 MPa (130K for plates of thickness 16 mm (5/8-inch) and over as noted in the Manufa urers' Specification. (U.S. Steel Corporation Data Sheet on HY-130, effective December, 1970).

In materials application practice, the primary consideration i the capability to achieve the required minimum level of tensile propertie All three grades of Nitronic 40 and HY-130 have met this criterion. However, small differences exist in the tensile behavior of airmelt, ESR and VAR grades of Nitronic 40 and HY-130. The exact reasons for the differences in the tensile behavior of the three grades at the various testing temperatures are not readily apparent from the program data.

Producers' data sheet for 9Ni-4Co alloy steel, (Republic Steel Corporation Technical Data Sheet on HP 9Ni-4Co Steels) indicates that th steel, for the given heat treatment, should achieve minimum yield streng of 1207 MPa (175KSI) and ultimate tensile strength of 1275 MPa (185KSI). The air-melted and VAR grades of 9Ni-4Co steel evaluated marginally meet the minimum specified room temperature yield and tensile strength. The ESR grade, achieved the specification minimum tensile strength but not the minimum yield strength.

For D-6 steel, the room temperature yield and tensile strength values developed in all three grades were comparable to those one would extrapolate for this heat treatment (see Code 1213, Figure 3.02124 in Reference 6).

The ESR grade of the 9Ni-4Co and D-6 alloy steels in specimens tested at the low temperatures, -50°C, -100°C, or -150°C, developed significantly lower yield and tensile strength compared to the air-melt and VAR grades. Such irregular tensile behavior is indicative of non-uniform chemical composition of the specimens used in these tests. It is suspected that the problems of ESR grade of this steel are related to:

(a) the use of low carbon steel contact pad at the bottom of the ESR ingot,

(b) insufficient discard of hot-top metal from the air-melted and air-cast ingot,

(c) excessive amount of scale on forged electrode used for the preparation of the ESR ingot.

These factors could lead to non-uniform chemical composition in the remelted ingot. No attempt has been made in this study to examine in detail the specific discrepancies noted in the tensile behavior of each grade of experimental steel.

In summary, higher than the specification minimum room temperature tensile properties were achieved in air-melt, ESR and VAR grades of Nitronic 40 and HY-130 alloy steels. Minor variations in tensile strength were noted between the air-melted and consumably remelted grades. These variations can be atrributed to the minimization of anisotropy in the plates of ESR and VAR grades. In the case of 9Ni-4Co steel, the air-melt and VAR grades developed the minimum specified tensile properties. The D-6 plate materials developed room temperature tensile strength values as estimated for the given heat treatment. The ESR grade of the 9Ni-4Co and D-6 alloys, however, developed comparatively lower tensile properties at several low test temperatures, probably because of the formation of ingots of non-uniform chemical composition.

Fracture Toughness Behavior

The D.E.N. fracture specimen tests are useful for routine screening of the capability of materials to carry load in the presence of a sharp crack under conditions of high transverse constraint and small scale yielding. When the nominal fracture strength σ_c of D.E.N. specimen is above the yield strength σ_{ys}, the material is classified as crack-tough. On the otherhand, if σ_c is lower than σ_{ys}, the material is called crack-sensitive or brittle.

Also, when the σ_c/σ_{ys} ratio is higher than 1 - a condition generally suggesting a high toughness material, the validity of Kmax values generated from the D.E.N. specimen tests becomes questionable. In such circumstances, the σ_c/σ_{ys} ratio is a meaningful approximate index of crack toughness of the material under slow rates of loading.

The general trend of fracture toughness behavior of the air melt, ESR and VAR grade of each experimental steel indicate highest σ_c/σ_{ys} ratio for ESR grade tested at all temperatures with few exceptions. These exceptions, as noted from Table XXV and relevant data plots of Figures 10 through 13, are Nitronic 40 tested at RT (22°C) and -50°C and D-6 tested at RT (22°C). For the VAR material σ_c/σ_{ys} ratio values noted from Table XXV are approximately same as or slightly higher than those for the air melt grade except for Nitronic 40 at -50°C and at -196°C, HY-130 at -196°C; 9Ni-4Co at -50°C, -100°C, -150°C; D-6 at -100°C.

These data further indicate that at equivalent yield strength levels, Nitronic 40, HY-130 and 9Ni-4Co alloy steels had similar fracture toughnesses which are significantly greater than that of D-6 alloy steel.

Charpy impact test behavior of the three grades of four experimental steels can also be evaluated from the data presented in Table XXV and plots in Figures 14 through 17. The general trend of these data is as follows:

The air melt grade of Nitronic 40 showed higher impact values at RT, and -50°C than the ESR and VAR grades. The ESR grade of Nitronic 40 displayed significantly higher impact values at testing temperature of -100°C and below. The VAR grade of Nitronic 40 exhibited lower impact energies than the ESR grade at all five testing temperatures.

In the case of HY-130, the ESR and VAR grades displayed significantly higher impact energies than the air melt grade at all five testing temperatures. However, the ESR grade developed the highest impact energies than the VAR grade at RT and -50°C.

The 9Ni-4Co alloy steel of all three grades developed approximately the same range of Charpy impact properties with the exception of VAR grade tested at -50°C, -100°C, and -150°C. All three grades of this steel developed a higher Charpy impact energy at RT than the 40.7 Joule (30 ft.lbs.) minimum specified by the developer (Republic Steel Corporation) of this alloy steel.

The ESR grade of D-6 alloy steel failed to develop the minimum required room temperature Charpy impact energy of 20.3 Joule (15 ft.lbs.) (Reference 6).

ESR and VAR melting did not significantly influence the Charpy impact properties of Nitronic 40, 9Ni-4Co and D-6 alloy steels.

ESR melting did lead to marked improvement of impact properties of HY-130 steel. The reasons for this have not been critically evaluated in this program.

Cleanliness Evaluation of Air Melt, ESR and VAR Grades of Experimental Steels

It has long been recognized that the nature, type, size, shape, orientation, total amount, and distribution of non-metallic inclusions in engineering alloys are factors which affect the physical and mechanical properties. The term "cleanliness" is often used to describe a relative condition of the presence or absence of non-metallic inclusions in engineering alloys. Non-metallic inclusions and gases concentrated in the interstices of the acicular grains weaken the cleavage strength of neighboring crystals. Reduction of inclusions in engineering alloys is one of the important objectives in the selection and optimization of manufacturing techniques.

In this program, except for a cursory evaluation of cleanliness of the three grades of alloy steels, no attempt was made to correlate the effect of inclusions on the various mechanical properties developed in each type of material.

The general trend of the inclusion size, shape and distribution studies is that the ESR grade of each experimental steel contained the smaller size, mostly globular type inclusions. The volume fraction of total number of all types of inclusions in ESR grades is significantly smaller than in air melt grades but generally appreciably larger than that in VAR grades.

7.0 CONCLUSIONS

A program directed at characterization of electroslag-refined (ESR) Nitronic 40, HY-130, 9Ni-4Co, and D-6 alloy steels was conducted. Similar material characterization work was also performed on air-melt and vacuum-arc-remelt (VAR) grades of same steels. A comparative cost analysis of manufacturing 15.2 mm thick plates of the three grades of these four iron-base alloys was also accomplished. The conclusions of this study may be summarized as follows:

(a) In the presence of sharp cracks and under slow rates of loading, the ESR grade of all four experimental steels has generally better toughness characteristics than the air-melt and VAR grades.

(b) At equivalent yield strength levels, Nitronic 40, HY-130 and 9Ni-4Co alloy steels have similar fracture toughnesses which are significantly greater than that of D-6 alloy steel.

(c) ESR melting leads to marked improvements in the impact properties of HY-130 steel. ESR and VAR melting does not significantly influence the Charpy v-notch impact properties of Nitronic 40, 9Ni-4Co and D-6 alloy steels.

(d) The room temperature tensile properties of all grades of the four alloys correspond to those expected from the provided heat treatments.

(e) The low temperature tensile strenghts of the Nitronic 40 and HY-130 steels are highest for the air-melt grade while ESR and VAR values range lower by as much as 12%. The low temperature tensile strengths of the 9Ni-4Co and D-6 alloys are similar for the air-melt and VAR grades, but the ESR values are lower at the intermediate low temperatures.

(f) The general trend of the inclusion size, shape, volume fraction, and distribution studies indicated that ESR grade of each experimental steel contained smaller size, mostly globular inclusions. The volume fraction of the total number of inclusions of all types in ESR grades is significantly smaller than in air-melt grades but appreciably larger than in VAR grades.

(g) On an economic basis, the lower product cost and high product yield advantages found in this limited study favor the ESR route of manufacture of high-grade alloy steels rather than the VAR or air-melt routes.

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TABLE I

EXPERIMENTAL MATERIALS INVENTORY

NITRONIC 40 ALLOY STEEL

Starting Billet 203 mm Square x 1.98 m Long Weight — 541 kg.

Product Split	AIR MELT	ESR Melt 1	ESR Melt 2	VAR
Electrode Weight (kg.)	—	311*	149	136
Ingot Weight (kg.)	—	162	131	127
Forged 127 mm x 254 mm Slab Weight (kg.)	93	161	127	121
Rolled Plates Weight (kg.)	90	158	126	118

Total Loss of Material 541 - 492 = 49 kg.

HY-130 ALLOY STEEL

Starting Air-Induction Melted and Cast Ingot Weight — 315 kg.

Hot Top Crop Loss 31 kg.

Product Split	AIR MELT	ESR	VAR
Electrode Weight (kg.)	—	128	79
Ingot Weight (kg.)	—	128	70
Forged 127 mm x 254 mm Slab Weight (kg.)	77	125	65
Rolled Plates Weight (kg.)	73	124	62

Total Loss of Material 315 - 259 = 56 kg.

*Electrode remelted into two ESR ingots.

TABLE I (CONT'D.)

EXPERIMENTAL MATERIALS INVENTORY

9Ni-4Co ALLOY STEEL

Starting Air-Induction Melted and Cast Ingot Weight -- 314 kg.

Hot Top Crop Loss 17 kg.

Product Split	AIR MELT	ESR	VAR
Electrode Weight (kg.)	---	126*	103
Ingot Weight	---	126	86
Forged 127 mm x 254 mm Slab Weight (kg.)	68	123	81
Rolled Plate Weight (kg.)	65	122	78

Total Loss of Material 314 - 265 = 49 kg.

D-6 ALLOY STEEL

Starting Air-Induction Melted and Cast Ingot Weight -- 323 kg.

Hot Top Crop Loss 30 kg.

Product Split	AIR MELT	ESR	VAR
Electrode Weight (kg.)	---	117*	100
Ingot Weight (kg.)	---	117	88
Forged 127 mm x 254 mm Slab Weight (kg.)	76	114	84
Rolled Plate Weight	73	112	82

Total Loss of Material 323 - 267 = 56 kg.

*ESR melting produced no electrode weight loss because the balance of the electrode was remelted as VAR ingot.

TABLE II

ELECTROSLAG REMELTING LOG FOR NITRONIC 40

Heat 1	
Electrode Dimensions:	178 mm dia. 1.47 m long
Electrode Weight:	289 kg.
Flux Composition:	CaF_2 - 70%; Al_2O_3 - 25%; CaO - 5%
Flux Weight:	16.6 kg.
Stabilized Voltage:	39 Volts
Current:	5800 Amps (average)
Ingot Dimensions:	241 mm dia. 400 mm long
Ingot Weight:	142 kg.
Total Melting Time:	39 Minutes

Heat 2 - Nitronic 40	
Electrode Dimensions:	178 mm dia. 635 mm long
Electrode Weight:	126 kg.
Flux Composition:	CaF_2 - 70%; Al_2O_3 - 30%; Argon Cap.
Flux Weight:	17.7 kg.
Stabilized Voltage:	38/39 Volts
Current:	5940 Amps (average)
Ingot Dimensions:	241 mm dia. 343 mm long
Ingot Weight:	123 kg.
Total Melting Time:	37 Minutes

TABLE III

ELECTROSLAG REMELTING LOG FOR HY130

Electrode Size*:	152 mm dia. 1270 mm long
Electrode Weight:	220 kg.
Flux Composition:	CaF_2 - 70%; Al_2O_3 - 26%; CaO - 4%
Flux Weight:	16.3 kg.
Stabilized Voltage:	39 Volts
Current:	5260 Amps (Initial average)
Ingot Dimensions:	241 mm dia. 368 mm long
Ingot Weight:	128 kg.
Total Melting Time:	41 Minutes

*Balance length of electrode used for VAR ingot.

TABLE IV

ELECTROSLAG REMELTING LOG FOR 9Ni-4Co STEEL

Electrode Size*:	152 mm dia. 1270 mm long
Electrode Weight:	228 kg.
Flux Composition:	CaF_2 - 65%; Al_2O_3 - 25%; CaO - 8%; MgO - 2%
Flux Weight:	17.2 kg.
Stabilized Voltage:	44 Volts
Current:	5040 Amps (average)
Ingot Dimensions:	241 mm dia. 381 mm long
Ingot Weight:	126 kg.
Total Melting Time:	24 Minutes

*Balance length of electrode used for VAR melt.

TABLE V

ELECTROSLAG REMELTING LOG FOR D6

Electrode Size*:	152 mm dia. 1270 mm long
Electrode Weight:	226.8 kg.
Flux Composition:	CaF_2 - 70%; Al_2O_3 - 20%; CaO - 10%
Flux Weight:	16.8 kg.
Stabilized Voltage:	40 Volts
Current:	5060 Amps (average)
Ingot Dimensions:	241 mm dia. 337 mm long
Ingot Weight:	116.8 kg.
Total Melting Time:	34 Minutes

*Balance of electrode used for VAR melt.

TABLE VI

VACUUM ARC REMELTING DATA FOR EXPERIMENTAL ALLOY STEELS

Nitronic 40 Alloy Steel

1) Mold and chamber evacuated to around 10^{-2} mm/Hg.
2) Start arc and stabilize.
3) Back fill mold and chamber with argon-slight positive pressure.
4) Stabilized voltage -- 31/33 Volts.*
5) Stabilized current -- 4850 Amps.*

HY-130, 9Ni-4Co and D-6 Alloy Steels

1) Mold and chamber evacuated to below 10^{-2} mm/Hg.
2) Start arc and stabilize.
3) Stabilized voltage -- 27/29 Volts.*
4) Stabilized currents -- 4500 Amps.*

Crucible Diameter -- 203 mm
Electrode Diameter -- 152 mm

	Nitronic 40	HY-130	9Ni-4Co	D-6
Weights of Electrode Supplied (kg.)	136	79	103	100
Weights of VAR Ingots Returned (kg.)	127	69	86	88

*Approximate values provided by melting source.

TABLE VII

CHEMICAL ANALYSES OF NITRONIC 40 ALLOY STEEL INGOTS AND PLATES

Alloying Elements	Ingots			Plates***		
	Air Melt*	ESR	VAR**	Air Melt	ESR	VAR
C	0.028	0.030	0.030	0.020	0.030	0.036
S	0.002	0.001	<0.001	0.003	0.001	<0.001
P	0.027	0.035	0.032	0.025	0.023	
Cr	20.08	19.51	19.88	19.88		
Co	---	---	---	---		
Fe	Bal	Bal	Bal	Bal		
Mn	9.50	9.20	8.58	9.45	NA	NA
Mo	0.19	0.20	0.19	0.20		
Ni	7.19	6.95	7.03	7.22		
Si	0.74	0.66	0.68	0.70		
V	---	---	---	---		
Al	---	---	---	---		
N	0.33	0.23	0.20	0.30		
O	0.0090	0.0086	0.0060	0.0090	0.0062	0.0050

* Air melt ingot analysis represents that of the Heat 536303 (Armco Steel).

*** Plate analyses for second check only.

NA - Not analysed because ingot analyses was satisfactory.

ESR - Electroslag remelted. Two melts were made - one under air atmosphere and the second under argon atmosphere. Argon protected ESR Melt - C-0.029, S-0.0018, N-0.28, O-0.0068. Other elements were not analysed.

** VAR - Arc melted in argon atmosphere.

TABLE VIII

CHEMICAL ANALYSES OF HY130 ALLOY STEEL
INGOTS AND PLATES

Alloying Elements	Ingots			Plates		
	Air Melt	ESR	VAR	Air Melt	ESR	VAR
C	0.10	0.11	0.10	0.13	0.094	0.091
S	0.012	0.004	0.010	0.006	0.004	0.009
P	0.010	0.010	0.010	0.010		
Cr	0.54	0.60	0.55	0.63		
Co	--	0.015	--	--		
Fe	Bal	Bal	Bal	Bal		
Mn	0.85	0.81	0.66	0.87	NA	NA
Mo	0.50	0.49	0.51	0.58		
Ni	5.04	5.08	5.02	5.06		
Si	0.25	0.24	0.20	0.35		
V	0.09	0.09	0.06	0.10		
Al	<.01	0.028	<.01	--		
N	0.005	0.005	--	--		
O	0.0053	0.0040	0.0032	0.0040	0.0039	0.0040

Air melt ingot analysis is of Cannon-Muskegon Heat AT-88.

TABLE IX

CHEMICAL ANALYSES OF 9Ni-4Co ALLOY STEEL
INGOTS AND PLATES

Alloying Elements	INGOTS				PLATES		
	Air Melt	ESR		VAR	Air Melt	ESR	VAR
		Top	Bottom*				
C	0.251	0.24	0.19	0.25	0.25	0.24	0.26
S	0.007	0.008	0.006	0.008	0.006	0.002	0.008
P	0.010	0.006	0.006	0.010	0.008	0.007	
Cr	0.42	0.48	0.42	0.40	0.48	0.42	
Co	4.00	4.05	4.00	3.95	4.05	3.61	
Fe	Bal	Bal	Bal	Bal	Bal	Bal	
Mn	0.27	0.28	0.25	0.15	0.28	0.14	NA
Mo	0.42	0.46	0.40	0.36	0.46	0.37	
Ni	8.25	7.59	7.56	8.15	7.39	7.37	
Si	--	0.01	--	--	0.01	0.01	
V	0.08	0.07	0.06	0.08	0.06	0.05	
Al	--	--	--	--	--	0.019	
N	--	--	--	--	--	0.008	
O	0.0090	0.0090	--	0.0060	0.0090	0.0078	0.0020

*ESR ingot bottom analyses was determined to cut off composition diluted section because of the use of a mild steel contact plate to start the ESR melt.

NA - Not analysed because ingot analysis was within specification.

TABLE X

CHEMICAL ANALYSES OF D6 ALLOY STEEL
INGOTS AND PLATES

Alloying Elements	INGOTS			PLATES		
	Air Melt	ESR	VAR	Air Melt	ESR	VAR
C	0.43	0.44	0.45	0.45	0.43	0.44
S	0.025	0.010	0.020	0.018	0.008	0.021
P	0.023	0.012	0.018	0.025		
Cr	1.07	1.04	1.05	1.09		
Co	--	--	--	--		
Fe	Bal	Bal	Bal	Bal		
Mn	0.65	0.60	0.70	0.70	NA	NA
Mo	1.00	0.95	0.99	1.01		
Ni	0.56	0.57	0.55	0.60		
Si	0.22	0.15	0.18	0.30		
V	0.09	0.09	0.10	0.10		
Al	--	0.021	--	0.021		
N	--	0.008	--	0.008		
O	0.0050	0.0050	0.0030	0.0060	0.0046	0.0024

NA - Not analysed as the ingot analysis was satisfactory.

TABLE XI

HEAT TREATMENT FOR MECHANICAL TEST SPECIMENS OF EXPERIMENTAL ALLOY STEELS

Nitronic 40 Alloy Steel

As rolled and rack cooled condition.

HY-130 Alloy Steel

(a) Normalize 871°C, 1 hr., air-cool.
(b) Austenitize 816°C, 1 hr., water quench.
(c) Temper 538°C, 1 hr., water quench.

9Ni-4Co Alloy Steel

(a) Normalize 899°C, 1 hr., air-cool.
(b) Austenitize 830°C, 1 hr., water quench.
(c) Temper 538°C, 5 hrs. air-cool.

D-6 Alloy Steel

(a) Normalize 927°C, 3/4-hr., air-cool.
(b) Austenitize 899°C, 1 hr., oil quench.
(c) Temper 538°C, 2 hrs., air-cool.

TABLE XII

TENSILE STRENGTH DATA FOR NITRONIC 40

	AIR MELT*			ESR			VAR		
Room Temperature Tensile Tests	1	2	3	1	2	3	1	2	3
Ultimate Tensile Strength (KSI)**	151	150	148	149	147	142	147	145	142
Yield Strength 0.2% (KSI)	132	128	123	126	123	116	122	117	115
Elongation % in 1 in. gage length	34	33	32	34	35	37	35	36	35
Reduction of Area %	72	73	72	67	74	75	71	73	73
-50°C Tensile Tests									
UTS (KSI)	173	172	177	165	164	161	164	166	158
YS (KSI)	144	145	148	135	136	132	133	140	126
Elong. %	34	36	34	39	38	38	39	35	37
RA %	68	65	68	71	72	72	73	71	73
-100°C Tensile Tests									
UTS (KSI)	191	190	193	174	168	165	180	176	177
YS (KSI)	172	170	176	143	134	133	154	144	150
Elong. %	31	32	31	37	35	35	36	38	37
RA %	70	67	65	71	72	71	71	72	73

*Nitronic 40 heat is made in electric arc furnace and finished in argon-oxygen vessel.

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

** - See Table XVI for averaged tensile test data presented in Metric Units.

Note: 1 KSI = 6.895 MPa.

TABLE XII CONT'D.

TENSILE STRENGTH DATA FOR NITRONIC 40

	AIR MELT*			ESR			VAR		
-150°C Tensile Tests	1	2	3	1	2	3	1	2	3
UTS (KSI)	219	219	216	198	192	183	190	195	194
YS (KSI)	209	208	203	176	164	150	160	165	166
Elong. %	28	24	30	29	33	33	31	33	34
RA %	70	63	68	71	69	70	71	70	72
-196°C Liquid N_2 Immersed Tests									
UTS (KSI)	274	230	271	269	265	265	267	272	275
YS (KSI)	242	214	244	227	224	218	222	232	228
Elong. %	15	15	15	34	32	26	36	33	31
RA %	54	62	53	61	64	66	60	61	59

*Nitronic 40 heat is made in electric arc furnace and finished in argon-oxygen vessel.

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

Note: 1 KSI = 6.895 MPa.

TABLE XIII

TENSILE STRENGTH DATA FOR HY130 STEEL

	AIR MELT			ESR			VAR		
Room Temperature Tension Tests	1	2	3	1	2	3	1	2	3
UTS (KSI)**	156	158	156	147	160	156	152	157	149
YS (KSI)	145	145	144	144	146	145	133	146	138
Elong. %	18	19	20	20	19	19	20	21	20
RA %	65	66	67	73	71	68	74	70	72
-50°C Tension Tests									
UTS (KSI)	174	170	172	166	166	167	165	164	164
YS (KSI)	162	160	160	156	157	155	156	152	156
Elong. %	21	20	20	23	23	20	20	20	22
RA %	64	65	65	69	71	69	69	67	70
-100°C Tension Tests									
UTS (KSI)	180	178	179	170	167	168	171	156	172
YS (KSI)	168	168	167	159	156	160	158	139	161
Elong. %	19	21	20	19	21	19	22	23	22
RA %	63	64	64	69	72	71	66	50	71

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
Air Melt - Air induction melted heat.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

Note: 1 KSI = 6.895 MPa.

** - See Table XVI for averaged tensile test data presented in Metric Units.

TABLE XIII CONT'D.

TENSILE STRENGTH DATA FOR HY130 STEEL

	AIR MELT 1	AIR MELT 2	AIR MELT 3	ESR 1	ESR 2	ESR 3	VAR 1	VAR 2	VAR 3
-150°C Tension Tests									
UTS (KSI)	188	192	188	176	174	176	176	177	162
YS (KSI)	178	182	178	164	164	167	165	167	146
Elong. %	21	20	22	21	20	24	21	21	23
RA %	63	62	64	68	68	71	67	67	70
-196°C Liquid Nitrogen Immersed Tension Tests									
UTS (KSI)	212	211	213	206	203	205	211	209	209
YS (KSI)	201	202	204	198	195	197	198	199	199
Elong. %	20	20	18	25	23	25	22	9	22
RA %	50	57	52	55	57	59	47	16	54

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
Air Melt - Air induction melted heat.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

Note: 1 KSI = 6.895 MPa.

TABLE XIV

TENSILE STRENGTH DATA FOR 9Ni-4Co ALLOY STEEL

	AIR MELT			ESR			VAR		
Room Temperature Tension Tests	1	2	3	1	2	3	1	2	3
UTS (KSI)**	184	180	186	185	186	186	185	187	190
YS (KSI)	174	172	176	155	158	157	174	175	177
Elong. %	18	19	18	20	19	20	21	19	19
RA %	66	66	64	60	61	62	67	67	67
-50°C Tension Tests									
UTS (KSI)	200	198	202	174	161	157	202	200	202
YS (KSI)	194	186	193	165	149	146	192	192	194
Elong. %	18	17	21	20	21	21	20	20	18
RA %	59	59	63	60	64	64	65	64	64
-100°C Tension Tests									
UTS (KSI)	211	204	207	171	169	171	206	207	208
YS (KSI)	200	198	200	163	158	160	193	196	198
Elong. %	19	20	17	22	22	20	19	21	20
RA %	60	64	61	65	59	61	62	63	64

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
Air Melt - Air induction melted heat.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

Note: 1 KSI = 6.895 MPa.

** - See Table XVI for averaged tensile test data presented in Metric Units.

TABLE XIV CONT'D.

TENSILE STRENGTH DATA FOR 9Ni-4Co ALLOY STEEL

	AIR MELT			ESR			VAR		
	1	2	3	1	2	3	1	2	3
-150°C Tension Tests									
UTS (KSI)	222	220	222	--	215	201	210	213	210
YS (KSI)	214	214	210	--	193	173	200	202	200
Elong. %	19	19	19	--	18	16	20	19	19
RA %	59	59	58	--	54	55	62	62	63
-196°C Liquid Nitrogen Immersed Tensile Tests									
UTS (KSI)	217	218	218	--	206	205	249	247	249
YS (KSI)	208	210	212	--	194	194	236	236	240
Elong. %	18	18	18	--	25	23	19	16	19
RA %	52	57	59	--	59	58	52	49	55

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
Air Melt - Air induction melted heat.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

Note: 1 KSI = 6.895 MPa.

TABLE XV

TENSILE STRENGTH DATA FOR D6 ALLOY STEEL

	AIR MELT			ESR			VAR		
Room Temperature Tensile Tests	1	2	3	1	2	3	1	2	3
UTS (KSI)**	188	168	192	183	193	194	183	182	182
YS (KSI)	161	134	159	151	166	168	146	146	144
Elong. %	18	20	17	17	18	18	17	18	18
RA %	54	52	53	58	61	60	55	53	54
-50°C Tensile Tests									
UTS (KSI)	193	206	186	206	200	195	190	190	192
YS (KSI)	160	178	155	168	174	166	159	157	162
Elong. %	18	18	16	12	18	18	19	18	18
RA %	48	52	47	42	60	57	53	50	50
-100°C Tensile Tests									
UTS (KSI)	204	213	186	171	170	168	196	204	196
YS (KSI)	174	187	152	160	157	154	162	170	162
Elong. %	16	17	18	18	20	21	18	17	19
RA %	45	53	48	62	60	63	50	50	50

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
Air Melt - Air induction melted heat.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

Note: 1 KSI = 6.895 MPa.

** - See Table XVI for averaged tensile test data presented in Metric Units.

TABLE XV CONT'D.

TENSILE STRENGTH DATA FOR D6 ALLOY STEEL

	AIR MELT			ESR			VAR		
	1	2	3	1	2	3	1	2	3
-150°C Tensile Tests									
UTS (KSI)	200	210	206	168	171	179	201	200	201
YS (KSI)	169	173	174	155	160	170	168	168	166
Elong. %	16	19	18	21	20	16	19	19	18
RA %	46	44	45	58	63	59	49	48	47
-196°C Tensile Tests									
UTS (KSI)	222	208	216	210	228	202	230	234	236
YS (KSI)	216	183	186	195	200	190	200	Samples broke	
Elong. %	1	17	15	20	15	20	8	outside gage	
RA %	2	42	40	52	47	52	11.6	marks	

UTS - Ultimate tensile strength (value rounded off to nearest KSI).
YS - 0.2% offset yield strength (value rounded off to nearest KSI).
Elongation - Measured in 1 inch gage length, reported in %.
Reduction of Area - Reported in %.
Air Melt - Air induction melted heat.
VAR - Vacuum arc remelted grade.
ESR - Electroslag remelted grade.

Note: 1 KSI = 6.895 MPa.

TABLE XVI

AVERAGED* TENSILE STRENGTH DATA FOR NITRONIC 40, HY-130, 9Ni-4Co AND D-6 ALLOY STEELS OF AIR MELT, ESR AND VAR GRADES TESTED AT FIVE TEMPERATURE LEVELS

Material	RT Tests (22°C)						-50°C Tests						-100°C Tests						-150°C Tests						-196°C Tests					
	YS		UTS		El	RA	YS		UTS		El	RA	YS		UTS		El	RA	YS		UTS		El	RA	YS		UTS		El	RA
Nitronic 40	MPa	KSI	MPa	KSI	%	%	MPa	KSI	MPa	KSI	%	%	MPa	KSI	MPa	KSI	%	%	MPa	KSI	MPa	KSI	%	%	MPa	KSI	MPa	KSI	%	%
AM	883	128	1,034	150	33	72	1,007	146	1,200	174	35	67	1,193	173	1,317	191	31	67	1,427	207	1,503	218	27	67	1,675	243	1,882	273	27	54
ESR	841	122	1,007	146	35	72	924	134	1,124	163	38	72	945	137	1,165	169	36	71	1,124	163	1,317	191	32	70	1,538	223	1,834	266	31	64
VAR	814	118	1,000	145	35	72	917	133	1,124	163	37	72	1,027	149	1,227	178	37	72	1,131	164	1,331	193	33	71	1,565	227	1,868	271	33	60
HY-130																														
AM	1,000	145	1,082	157	19	66	1,110	161	1,186	172	20	65	1,158	168	1,234	179	20	64	1,234	179	1,303	189	21	63	1,393	202	1,462	212	19	53
ESR	1,000	145	1,062	154	19	71	1,076	156	1,145	166	22	70	1,089	158	1,158	168	20	71	1,138	165	1,207	175	22	69	1,358	197	1,413	205	24	57
VAR	958	139	1,054	153	20	72	1,069	155	1,131	164	21	69	1,069	155	1,131	164	22	62	1,096	159	1,186	172	22	68	1,372	199	1,448	210	22	51
9Ni-4Co																														
AM	1,200	174	1,262	183	18	65	1,317	191	1,379	200	19	60	1,372	199	1,427	207	19	62	1,469	213	1,524	221	19	59	1,448	210	1,503	218	18	56
ESR	1,082	157	1,282	186	20	61	1,054	153	1,131	164	21	63	1,103	160	1,172	170	21	62	1,262	183	1,434	208	17	55	1,338	194	1,420	206	24	59
VAR	1,207	175	1,289	187	20	67	1,324	192	1,386	201	19	64	1,351	196	1,427	207	20	63	1,386	201	1,455	211	19	62	1,634	237	1,720	248	18	52
D-6																														
AM	1,041	151	1,262	183	18	53	1,131	164	1,344	195	17	53	1,179	171	1,386	201	17	49	1,186	172	1,413	205	18	45	1,344	195	1,482	215	16	41
ESR	1,117	162	1,310	190	18	60	1,165	169	1,379	200	16	60	1,082	157	1,172	170	20	62	1,117	162	1,193	173	19	60	1,344	195	1,469	213	18	50
VAR	1,000	145	1,255	182	18	54	1,096	159	1,317	191	18	54	1,138	165	1,372	199	18	50	1,151	167	1,386	201	19	48	1,379	200	1,606	233	-	-
Nitronic 40 Argon Capped ESR Melt																														
	779	113	979	142	35	73																			1,641	238	1,910	277	30	62

*Averaged value of three tensile tests conducted at each testing temperature.

TABLE XVII

D.E.N. SPECIMEN TEST DATA FOR AIR MELT NITRONIC 40 ALLOY STEEL

Speci-men Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
U-2	R.T.	0.331	0.347	0.694	2.56	0.161	127.3	30.6	190.1	1.49	85.1	93.5	>0.5
U-14	R.T.	0.323	0.340	0.680	2.34	0.168	127.3	30.4	181.0	1.42	83.0	91.2	>0.5
U-1	-50	0.340	0.310	0.620	2.195	0.175	146.0	40.5	231.4	1.58	99.0	108.8	>0.5
U-5	-100	0.350	0.325	0.65	2.25	0.163	172.6	40.2	246.6	1.43	103.1	113.3	≈0.5
U-8	-100	0.330	0.360	0.72	2.425	0.155	172.6	30.9	199.4	1.16	89.9	98.8	0.5
U-11	-150	0.330	0.342	0.684	2.325	0.164	206.5	37.7	229.9	1.11	102.5	112.6	>0.5
U-E	-150	0.340	0.320	0.640	2.230	0.170	206.5	41.5	244.1	1.18	104.7	115.0	>0.5
U-6	-196	0.330	0.375	0.750	2.378	0.1475	233.6	39.5	267.8	1.15	115.0	126.4	≈0.5
U-7	-196	0.340	0.365	0.730	2.378	0.1475	233.6	35.5	240.7	1.03	102.0	112.1	≈0.5

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1] Fracture Mode

[2] Shear Fraction

TABLE XVII CONT'D.

D.E.N. SPECIMEN TEST DATA FOR ESR NITRONIC 40 ALLOY STEEL

Specimen Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Average Crack Length "a"-inch Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
U-7	R.T.	0.248	Est. 0.258	0.558*	2.135	0.210	121.5	>32.8	>156.2	>1.23	>71.1	78.1	PHF[3]
U-8	R.T.	0.325	0.350	0.70	2.365	0.163	121.5	24.8	152.15	1.25	69.4	76.3	0.25
U-10	R.T.	0.325	0.350	0.70	2.365	0.163	121.5	27.7	169.9	1.40	75.5	83.0	0.25
U-14	-50	0.33	0.345	0.69	2.35	0.1625	134.5	32.2	198.2	1.47	88.9	97.7	>0.5
U-11	-50	0.33	0.390	0.78	2.58	0.140	134.5	26.3	187.9	1.40	84.8	93.2	>0.5
U-3	-100	0.345	0.355	0.71	2.39	0.150	137.0	33.6	224.0	1.64	95.7	105.2	≈0.5
U-1	-100	0.330	0.360	0.72	2.42	0.155	137.0	30.4	196.1	1.43	88.3	97.0	>0.5
U-17	-150	0.335	0.375	0.75	2.51	0.145	163.5	36.6	252.4	1.54	112.5	123.6	>0.5
U-15	-150	0.335	0.380	0.76	2.54	0.1425	163.5	29.8	209.1	1.28	93.3	102.5	>0.5
U-5	-196	0.340	0.395	0.79	2.66	0.133	223.2	34.7	260.9	1.17	116.0	127.5	>0.5
U-6	-196	0.350	0.390	0.78	2.58	0.130	223.2	33.2	255.4	1.14	107.0	117.6	0.5

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

*w = .925 [1]Fracture Mode [2]Shear Fraction [3]Pin hole failure

TABLE XVII CONT'D.

D.E.N. SPECIMEN TEST DATA FOR VAR NITRONIC 40 ALLOY STEEL

Specimen Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
Z-10	R.T.	0.330	0.370	0.74	2.48	0.15	118.0	25.2	168.0	1.42	76.0	83.5	0.60
Z-16	R.T.	0.330	0.370	0.74	2.48	0.15	118.0	25.5	170.0	1.44	76.9	84.5	0.60
Z-8	-50						133.1						NF[3] EY
Z-4	-50	0.340	0.380	0.76	2.54	0.140	133.1	26.9	192.1	1.44	84.2	92.5	>0.5
Z-15	-100	0.330	0.330	0.660	2.26	0.17	149.4	39.1	230.0	1.54	101.5	111.5	≈0.5
Z-11	-100	0.340	0.372	0.744	2.50	0.144	149.4	28.8	200.0	1.34	86.1	94.6	>0.5
Z-17	-150	0.330	0.390	0.780	2.60	0.140	163.9	34.9	249.3	1.52	113.3	124.5	>0.5
Z-12	-150	0.330	0.380	0.760	2.54	0.145	163.9	33.2	229.0	1.40	104.0	114.3	>0.5
Z-9	-196	0.340	0.400	0.80	2.68	0.130	227.8	27.6	212.3	0.93	93.6	102.8	>0.5
Z-20	-196	0.340	0.370	0.74	2.48	0.145	227.8	35.6	245.5	1.08	107.0	117.6	>0.5

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mold [2]Shear Fraction [3]NF Excessive Yielding

TABLE XVIII

D.E.N. SPECIMEN TEST DATA FOR AIR MELT HY-130 ALLOY STEEL

Specimen Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Average Crack Length "a"-inch Actual	2a/w	K Calib Y	Net Area in^2	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi × $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
Y-2	R.T.	0.319	0.330	0.660	2.27	0.176	145.0	34.3	194.9	1.34	65.3	71.8	≈0.4
Y-6	R.T.	0.339	0.315	0.63	2.21	0.173	145.0	36.1	208.7	1.44	89.5	98.3	0.5
Y-6	-50	0.340	0.325	0.65	2.25	0.168	160.6	37.8	225.0	1.40	97.0	106.6	70.5
Y-4	-50	0.330	0.365	0.73	2.45	0.1725	160.6	28.3	164.1	1.02	83.8	92.1	0.5
Y-9	-100	0.330	0.372	0.744	2.50	0.149	167.7	26.6	178.5	1.06	81.1	89.1	0.5
Y-5	-100	0.330	0.380	0.760	2.535	0.145	167.7	25.3	174.5	1.04	79.1	86.9	0.5
Y-15	-150	0.330	0.368	0.736	2.46	0.151	179.2	29.6	196.0	1.09	88.3	97.0	0
Y-8	-150	0.335	0.390	0.780	2.60	0.1375	179.2	26.1	189.8	1.06	84.8	93.2	0
Y-3	-196	0.340	0.370	0.740	2.48	0.145	202.0	18.3	126.2	0.625	52.2	57.4	0
Y-7	-196	0.330	0.364	0.728	2.45	0.153	202.0	20.6	134.6	0.665	58.0	63.7	0

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode. [2]Shear Fraction

TABLE XVIII CONT'D.

D.E.N. SPECIMEN TEST DATA FOR ESR HY-130 ALLOY STEEL

Specimen Ident.	Test Temp. ^{o}C	Average Crack Length "a"-inch Balance	Actual	2a/w	K Calib. Y	Net Area $in.^2$	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi × $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
Y-4	R.T.	0.309	Est. 0.319	0.638	2.23	0.186	145.0	38.6	>207.5	>1.43	>74.1	81.4	PRF[3]
Y-16	R.T.	0.390	0.395	0.790	2.63	0.1075	145.0	23.7	220.5	1.52	78.35	86.1	
Y-13	R.T.	0.400	0.415	0.830	2.80	0.0925	145.0	20.3	219.5	1.51	72.45	79.7	<0.5
Y-6	-50	0.330	0.350	0.700	2.37	0.160	156.0	37.0	231.2	1.48	103.7	114.0	>0.5
Y-2	-50	0.340	0.340	0.680	2.31	0.160	156.0	34.4	215.0	1.38	92.7	101.9	>0.5
Y-12	-100	0.340	0.345	0.69	2.345	0.158	158.1	34.3	217.0	1.37	94.5	103.8	0.1
Y-10	-100	0.340	0.390	0.78	2.60	0.135	158.1	29.6	219.0	1.39	96.1	105.6	0.5
Y-8	-150	0.340	0.400	0.80	2.68	0.130	165.1	29.1	223.8	1.36	98.6	108.3	0.2
Y-15	-150	0.340	0.390	0.78	2.60	0.135	165.1	30.3	224.4	1.36	98.4	108.1	0.1
Y-11	-196	0.360	0.370	0.74	2.48	0.135	196.5	31.7	234.8	1.19	95.6	105.0	0
Y-14	-196	0.340	0.345	0.69	2.35	0.158	196.5	25.0	158.2	0.81	69.0	75.8	0

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode [2]Shear Fraction [3]Pull rod failure

TABLE XVIII CONT'D.

D.E.N. SPECIMEN TEST DATA FOR VAR HY-130 ALLOY STEEL

Specimen Ident.	Test Temp. °C	Average Crack Length 'A'-inch Balance	Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] / SF[2]
R-10	R.T.	0.330	0.355	0.710	2.385	0.1575	139.0	29.5	187.3	1.35	83.7	92.0	>0.5
R-4	R.T.	0.340	0.352	0.704	2.380	0.1540	139.0	32.8	213.0	1.53	92.6	101.8	>0.5
R-7	-50	0.330	0.350	0.700	2.365	0.160	154.6	33.4	208.8	1.35	93.5	102.7	>0.5
R-5	-50	0.340	0.390	0.780	2.60	0.135	154.6	25.8	195.1	1.24	83.8	92.1	>0.5
R-14	-100	0.330	0.3402	0.680	2.350	0.165	152.4	35.5	215.2	1.41	97.3	106.9	0
R-20	-100	0.340	0.383	0.766	2.555	0.1385	152.4	28.7	207.2	1.36	90.8	99.8	>0.25
R-8	-150	0.310	0.335	0.670	2.295	0.1775	159.5	35.0	197.2	1.24	93.0	102.2	0
R-16	-150	0.335	0.382	0.764	2.550	0.1415	159.5	30.6	216.2	1.36	96.8	106.4	≈0.1
R-18	Liq.N	0.320	0.390	0.780	2.60	0.145	198.5	14.9	102.8	0.518	48.4	53.2	0
R-1	Liq.N	0.295	0.350	0.700	2.363	0.178	198.5	18.1	101.7	0.512	50.6	55.6	0

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode [2]Shear Fraction

TABLE XIX

D.E.N. SPECIMEN TEST DATA FOR AIR MELT 9Ni-4Co ALLOY STEEL

Specimen Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Average Crack Length "a"-inch Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
K-1	R.T.	0.255	0.265	0.530	2.08	0.240	174.0	>34.4	>143.3	>0.873	>73.7	81.0	PRF[3]
K-13	R.T.	0.335	0.350	0.700	2.37	0.1575	174.0	35.1	222.8	1.28	98.4	108.1	≃0.5
K-4	-50	0.340	0.360	0.72	2.42	0.150	190.7	36.4	242.7	1.27	105.7	116.1	≈0.5
K-9	-50	0.335	0.395	0.79	2.66	0.135	190.7	27.9	206.7	1.08	93.3	102.5	<0.5
K-11	-100	0.330	0.350	0.70	2.37	0.160	199.3	37.9	236.9	1.19	106.3	116.8	<0.5
K-7	-100	0.340	0.390	0.78	2.60	0.135	199.3	29.5	218.5	1.10	95.8	105.3	<0.25
K-15	-150	0.325	0.317	0.634	2.23	0.179	212.7	40.5	226.2	1.06	101.7	111.8	<0.5
K-6	-150	0.330	0.392	0.784	2.63	0.139	212.7	28.6	205.8	0.97	94.2	103.5	<0.25
K-8	-196	0.330	0.361	0.730	2.45	0.153	212.9	23.9	156.2	0.734	70.8	77.8	0
K-3	-196	0.340	0.387	0.774	2.58	0.137	212.9	19.85	144.9	0.680	63.7	70.0	0

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode [2]Shear Fraction [3]Pull rod failure

TABLE XIX CONT'D.

D.E.N. SPECIMEN TEST DATA FOR ESR 9Ni-4Co ALLOY STEEL

Specimen Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
K-3	R.T.	0.340	0.347	0.694	2.34	0.1565	156.7	30.5	194.9	1.24	84.1	92.4	0
K-2	R.T.	0.330	0.348	0.696	2.355	0.1610	156.7	32.4	201.2	1.28	90.0	99.0	0.25
K-15	R.T.	0.360	0.375	0.750	2.510	0.1325	156.7	26.1	197.0	1.26	80.2	88.1	0.25
K-9	-50	0.330	0.330	0.660	2.26	0.170	153.2	35.2	207.0	1.35	91.4	100.4	0.5
K-5	-50	0.360	0.385	0.77	2.56	0.1275	153.2	26.3	206.3	1.35	83.6	91.9	0.5
K-12	-100	0.360	0.360	0.72	2.42	0.140	160.2	33.75	241.0	1.50	98.0	107.7	≈0.5
K-11	-100	0.340	0.380	0.76	2.54	0.140	160.2	27.0	192.8	1.20	84.6	93.0	≈0.5
K-13	-150	0.320	0.385	0.77	2.56	0.1475	177.0	27.6	187.1	1.06	87.7	96.4	≈0.5
K-1	-150	0.350	0.400	0.80	2.68	0.1250	177.0	25.5	204.0	1.15	86.4	94.9	≈0.5
K-6	-196	0.340	0.397	0.794	2.67	0.132	201.2	24.1	182.6	0.908	81.1	89.1	<0.1
K-4	-196	0.340	0.385	0.77	2.56	0.138	201.2	28.3	205.0	1.02	89.9	98.8	≈0.1

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode [2]Shear Fraction

TABLE XIX CONT'D.

D.E.N. SPECIMEN TEST DATA FOR VAR 9Ni-4Co ALLOY STEEL

Specimen Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Actual	2a/W	K Calib. Y	Net Area in.^{2}	0.2y Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
G-1	R.T.	0.330	0.475	0.950	3.35	0.0975	175.4	17.1	175.4	1.00	79.0	86.8	≈0.30
G-3	R.T.	0.330	0.380	0.760	2.54	0.145	175.4	30.7	211.7	1.20	96.1	105.6	0.25
G-5	-50	0.340	0.400	0.80	2.68	0.130	192.7	26.8	206.1	1.07	90.8	99.8	
G-8	-50	0.330	0.410	0.82	2.77	0.130	192.7	25.7	196.7	1.03	91.2	100.2	0.25
G-13	-100	0.330	0.425	0.85	2.93	0.123	195.9	24.8	201.6	1.03	94.7	104.1	≈0.25
G-4	-100	0.330	0.410	0.82	2.77	0.130	195.9	24.5	188.5	0.96	86.9	95.5	≈0.25
G-2	-150	0.330	0.392	0.784	2.63	0.139	201.0	28.8	207.2	1.03	94.8	104.2	>0.25
G-10	-150	0.330	0.437	0.874	2.95	0.1165	201.0	19.8	170.0	0.85	77.3	84.9	0.2
G-11	-196	0.335	0.470	0.94	3.29	0.098	237.5	14.6	149.0	0.627	65.9	72.4	0
G-12	-196	0.340	0.410	0.82	2.77	0.125	237.5	25.3	202.0	0.852	89.7	98.6	≈0.2

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1] Fracture Mode [2] Shear Fraction

TABLE XX

D.E.N. SPECIMEN TEST DATA FOR AIR MELT D-6 ALLOY STEEL

Speci-men Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Actual	2a/w	K Calib Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi × $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
A-5	R.T.	0.293	0.306	0.612	2.18	0.200	150.0	31.1	155.0	1.03	75.5	83.0	0
A-4	R.T.	0.410	0.275	0.550	2.10	0.158	150.0	7.4	46.8	0.312	16.3	17.9	0
A-8	-50	0.380	0.310	0.62	2.20	0.155	164.3	10.5	67.7	0.412	24.5	26.9	0
A-2	-50	0.320	0.320	0.64	2.23	0.180	164.3	24.6	136.7	0.832	62.1	68.2	0
A-15	-100	0.330	0.333	0.666	2.28	0.1685	171.3	22.75	135.0	0.788	59.9	65.8	0
A-13	-100	0.315	0.360	0.720	2.42	0.1625	171.3	12.2	75.1	0.438	32.8	36.0	0
A-16	-150	0.340	0.320	0.640	2.23	0.170	172.0	15.0	88.2	0.513	37.8	41.5	0
A-10	-150	0.330	0.320	0.640	2.23	0.175	172.0	19.0	108.6	0.631	47.9	52.6	0
A-14	-196	0.330	0.305	0.610	2.175	0.182	216.0	17.0	93.4	0.432	40.8	44.8	0

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode [2]Shear Fraction

TABLE XX CONT'D.

D.E.N. SPECIMEN TEST DATA FOR ESR D-6 ALLOY STEEL

Speci-men Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
A-2	R.T.	0.288	0.308	0.616	2.185	0.202	162.0	19.5	96.53	0.596	47.30	52.0	0
A-4	R.T.	0.349	0.305	0.610	2.175	0.173	162.0	18.5	106.9	0.660	44.4	48.8	0
A-12	R.T.	0.350	0.285	0.570	2.120	0.183	162.0	17.3	94.5	0.584	39.2	43.1	0
A-12-1	-50	0.340	0.360	0.720	2.420	0.150	169.7	16.0	106.7	0.63	46.5	51.1	0
A-10	-50	0.330	0.290	0.58	2.125	0.155	169.7	24.25	161.6	0.95	55.5	61.0	0
A-6	-100	0.330	0.350	0.70	2.37	0.160	157.1	17.75	111.0	0.71	49.8	54.7	0
A-7	-100	0.330	0.330	0.66	2.265	0.170	157.1	23.8	140.0	0.89	61.9	68.0	0
A-3	-150	0.320	0.330	0.66	2.265	0.175	161.4	18.8	107.4	0.67	49.9	54.8	0
A-15	-196	0.320	0.312	0.624	2.20	0.184	194.2	17.7	96.2	0.495	43.5	47.8	0
A-11	-196	0.330	0.312	0.624	2.20	0.179	194.2	18.7	104.4	0.538	46.0	50.5	0

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode [2]Shear Fraction

TABLE XX CONT'D.

D.E.N. SPECIMEN TEST DATA FOR VAR D-6 ALLOY STEEL

Speci-men Ident.	Test Temp. °C	Average Crack Length "a"-inch Balance	Actual	2a/w	K Calib. Y	Net Area in.^{2}	$\sigma_{0.2y}$ Ksi	Load P_{max} Klbs.	σ_c Ksi	σ_c/σ_y	Kmax Ksi x $\sqrt{in}$	Kmax MPA $\sqrt{m}$	FM[1] SF[2]
S-18	R.T.	0.360	0.325	0.65	2.25	0.1575	145.5	30.2	191.8	1.32	74.5	81.9	0
S-4	R.T.	0.370	0.325	0.65	2.25	0.1525	145.5	32.6	213.8	1.47	83.6	91.9	0
S-8	-50	0.350	0.280	0.56	2.01	0.185	159.4	16.9	91.4	0.573	36.0	39.6	0
S-15	-50	0.360	0.317	0.634	2.22	0.161	159.4	22.4	139.1	0.873	56.0	61.5	0
S-17	-100	0.310	0.327	0.654	2.25	0.1815	164.7	19.0	104.7	0.636	48.9	53.7	0
S-7	-100	0.400	0.300	0.60	2.16	0.150	164.7	13.0	86.7	0.526	30.8	33.8	0
S-16	-150	0.330	0.370	0.74	2.5	0.150	167.7	14.5	96.7	0.576	44.1	48.5	0
S-5	-150	0.340	0.320	0.64	2.23	0.170	167.7	18.0	105.9	0.631	45.5	50.0	0
S-20	Liq. N	0.310	0.345	0.69	2.35	0.172	203.0	11.8	68.6	0.338	32.6	35.8	0
S-14	Liq.N	0.300	0.300	0.60	2.16	0.200	203.0	19.9	99.5	0.490	47.1	51.8	0
S-3	Liq.N	0.360	0.320	0.640	2.23	0.160	203.0	20.7	129.3	0.637	52.2	57.4	0

Note: See Table XXV for averaged D.E.N. Specimen and Charpy Impact Specimen Test Data presented in Metric Units.

[1]Fracture Mode [2]Shear Fraction

TABLE XXI

CHARPY IMPACT TEST DATA FOR NITRONIC 40 ALLOY STEEL

Test Temperature	Impact Energy					
	Air Melt		ESR		VAR	
	Joule	ft. lbs.	Joule	ft. lbs.	Joule	ft. lbs.
RT	295.6	218	257.6	190	230.5	170
RT	286.1	211	250.8	185	245.4	181
RT	291.5	215	268.5	198	238.6	176
-50°C	268.5	198	223.7	165	198.0	146
-50°C	263.0	194	244.0	180	227.8	168
-50°C	257.6	190	265.8	196	221.0	163
-100°C	101.6	75	198.0	146	184.4	136
-100°C	196.6	145	200.7	148	181.7	134
-100°C	99.	73	203.4	150	176.3	130
-150°C	127.4	94	162.7	120	123.4	91
-150°C	127.4	94	165.4	122	132.9	98
-150°C	122.0	90	164.1	121	136.9	101
-196°C*	69.1	51	122.0	90	78.6	58
-196°C*	74.6	55	113.9	84	73.2	54
-196°C*	66.4	49	118.0	87	82.7	61

Charpy specimens contained V-notch in RW direction as shown in Figure 3.

Air Melt - Electric arc furnace melted and argon-oxygen reactor refined.

ESR - Electroslag remelted.

VAR - Vacuum arc remelted.

* - Specimens immersed in liquid nitrogen.

TABLE XXII

CHARPY IMPACT TEST DATA FOR HY130 ALLOY STEEL

Test Temperature	Impact Energy					
	Air Melt		ESR		VAR	
	Joule	ft. lbs.	Joule	ft. lbs.	Joule	ft. lbs.
RT	77.3	57	160.0	118	130.2	96
RT	84.1	62	149.1	110	130.2	96
RT	74.6	55	162.7	120	123.4	91
-50°C	65.1	48	132.9	98	108.4	80
-50°C	67.8	50	128.8	95	109.8	81
-50°C	65.1	48	135.6	100	99.0	73
-100°C	31.2	23	84.1	62	90.8	67
-100°C	38.0	28	92.2	68	88.1	65
-100°C	38.0	28	81.3	60	80.0	59
-150°C	16.3	12	27.1	20	40.7	30
-150°C	23.0	17	33.9	25	46.1	34
-150°C	20.3	15	29.8	22	47.5	35
-196°C*	5.4	4	13.6	10	21.7	16
-196°C*	6.8	5	16.3	12	20.3	15
-196°C*	6.8	5	16.3	12	13.6	10

Charpy specimens contained V-notch in RW direction as shown in Figure 3.

Air Melt - Air induction melted heat.

ESR - Electroslag remelted.

VAR - Vacuum arc remelted.

* - Specimens immersed in liquid nitrogen.

TABLE XXIII

CHARPY IMPACT TEST DATA FOR 9Ni-4Co ALLOY STEEL

Test Temperature	Impact Energy					
	Air Melt		ESR		VAR	
	Joule	ft. lbs.	Joule	ft. lbs.	Joule	ft. lbs.
RT	77.3	57	77.3	57	69.1	51
RT	73.2	54	67.8	50	66.4	49
RT	71.9	53	73.2	54	67.8	50
-50°C	67.8	50	70.5	52	55.6	41
-50°C	67.8	50	74.6	55	58.3	43
-50°C	74.6	55	74.6	55	54.2	40
-100°C	62.4	46	59.7	44	52.9	39
-100°C	61.0	45	56.9	42	48.8	36
-100°C	59.7	44	61.0	45	48.8	36
-150°C	50.2	37	40.7	30	33.9	25
-150°C	43.4	32	42.0	31	38.0	28
-150°C	50.2	37	47.5	35	35.3	26
-196°C*	27.1	20	32.5	24	27.1	20
-196°C*	31.2	23	29.8	22	25.8	19
-196°C*	27.1	20	16.3	12	31.2	23

Charpy specimens contained V-notch in RW direction as shown in Figure 3.

Air melt - Air induction melted heat.

ESR - Electroslag remelted.

VAR - Vacuum arc remelted.

* - Specimens immersed in liquid nitrogen.

TABLE XXIV

CHARPY IMPACT TEST DATA FOR D6 ALLOY STEEL

Test Temperature	Impact Energy					
	Air Melt		ESR		VAR	
	Joule	ft. lbs.	Joule	ft. lbs.	Joule	ft. lbs.
RT	27.1	20	12.2	9	23.0	17
RT	23.0	17	19.0	14	20.3	15
RT	24.4	18	14.9	11	21.7	16
-50°C	16.3	12	6.8	5	17.6	13
-50°C	14.9	11	5.4	4	14.9	11
-50°C	16.3	12	6.8	5	16.3	12
-100°C	12.2	9	9.5	7	10.8	8
-100°C	9.5	7	5.4	4	10.8	8
-100°C	6.8	5	8.1	6	12.2	9
-150°C	6.8	5	2.7	2	8.1	6
-150°C	6.8	5	4.1	3	6.8	5
-150°C	5.4	4	2.7	2	8.1	6
-196°C*	4.1	3	2.7	2	4.1	3
-196°C*	5.4	4	2.7	2	5.4	4
-196°C*	5.4	4	2.7	2	4.1	3

Charpy specimens contained V-notch in RW direction as shown in Figure 3.

Air melt - Air induction melted heat.

ESR - Electroslag remelted.

VAR - Vacuum arc remelted.

* - Specimens immersed in liquid nitrogen.

TABLE XXV

AVERAGED D.F.N. FRACTURE STRENGTH AND CHARPY IMPACT ENERGY DATA FOR
NITRONIC 40, HY-130, 9Ni-4Co and D-6 ALLOY STEELS OF AIR MELT, ESR AND VAR GRADES
TESTED AT FIVE TEMPERATURE LEVELS

Material	RT Tests (22°C) $\sigma_{0.2ys}$ MPa	σ_c MPa	σ_c/σ_y	K_{max} MPa$\sqrt{m}$	Impact Energy Joule	-50°C Tests $\sigma_{0.2ys}$ MPa	σ_c MPa	σ_c/σ_y	K_{max} MPa$\sqrt{m}$	Impact Energy Joule
Nitronic 40										
AM	876	1,282	1.46	93	291.5	1,007	1,593	1.58	109	263.0
ESR	841	1,096	1.30	79	259.0	931	1,331	1.43	96	244.0
VAR	814	1,165	1.43	84	238.6	917	1,324	1.44	93	215.6
HY-130										
AM	1,000	1,393	1.39	85.1	78.6	1,100	1,344	1.22	99.4	68.4
ESR	1,000	1,489	1.49	82.4	157.3	1,076	1,538	1.43	108.0	132.9
VAR	958	1,379	1.44	96.9	127.4	1,069	1,393	1.30	97.4	103.8
9Ni-4Co										
AM	1,200	1,262	1.05	94.6	74.6	1,317	1,551	1.18	109.3	70.5
ESR	1,082	1,365	1.26	93.2	71.9	1,054	1,427	1.35	96.2	73.2
VAR	1,207	1,338	1.11	96.2	67.8	1,331	1,386	1.04	100.0	55.6
D-6										
AM	1,034	696	0.67	50.5	24.4	1,131	703	0.62	47.6	16.3
ESR	1,117	683	0.61	48.0	14.9	1,172	924	0.79	56.1	6.8
VAR	1,007	1,400	1.39	86.9	21.7	1,096	793	0.72	50.6	16.3

Material	-100°C Tests $\sigma_{0.2ys}$ MPa	σ_c MPa	σ_c/σ_y	K_{max} MPa$\sqrt{m}$	Impact Energy Joule	-150°C Tests $\sigma_{0.2ys}$ MPa	σ_c MPa	σ_c/σ_y	K_{max} MPa$\sqrt{m}$	Impact Energy Joule
Nitronic 40										
AM	1,193	1,538	1.29	106	132.9	1,427	1,634	1.15	114	126.1
ESR	945	1,448	1.53	101	200.7	1,131	1,593	1.41	114	164.1
VAR	1,027	1,482	1.44	103	180.3	1,131	1,648	1.46	119	131.5
HY-130										
AM	1,158	1,220	1.05	88.0	35.3	1,234	1,331	1.08	95.0	20.3
ESR	1,089	1,503	1.38	104.7	85.4	1,138	1,544	1.36	108.2	29.8
VAR	1,048	1,455	1.39	103.4	86.8	1,103	1,427	1.29	104.3	44.7
9Ni-4Co										
AM	1,372	1,572	1.15	111.1	61.0	1,469	1,489	1.01	107.7	47.5
ESR	1,103	1,496	1.36	100.3	59.7	1,220	1,351	1.11	95.7	43.4
VAR	1,351	1,344	0.99	99.8	50.2	1,386	1,303	0.94	94.6	35.3
D-6										
AM	1,179	724	0.61	50.9	9.5	1,186	676	0057	47.6	6.8
ESR	1,082	869	0.80	61.4	8.1	1,110	738	0.66	54.8	2.7
VAR	1,138	662	0.58	43.8	10.8	1,158	696	0.60	49.3	8.1

Material	-196°C Tests $\sigma_{0.2ys}$ MPa	σ_c MPa	σ_c/σ_y	K_{max} MPa$\sqrt{m}$	Impact Energy Joule
Nitronic 40					
AM	1,613	1,758	1.09	119	70.5
ESR	1,538	1,779	1.16	123	118.0
VAR	1,572	1,579	1.00	110	78.6
HY-130					
AM	1,393	896	0.64	60.6	6.8
ESR	1,358	1,358	1.00	90.4	14.9
VAR	1,372	703	0.51	54.4	19.0
9Ni-4Co					
AM	1,469	1,041	0.71	73.9	28.5
ESR	1,386	1,338	0.97	94.0	25.8
VAR	1,641	1,213	0.74	85.5	28.5
D-6					
AM	1,489	641	0.43	44.8	5.4
ESR	1,338	690	0.52	49.2	2.7
VAR	1,400	683	0.49	48.3	4.1

TABLE XXVI

Inclusions Size, Shape, Distribution and Volume Fraction in Air Melt, ESR and VAR Grade Rolled Plates of Experimental Steels

A. Inclusions Size

Plane 1 - Parallel to Plate Surface and

Plane 2 - Plate Cross-Section, Both Along Rolling Direction

	Inclusion Size*, µm Parallel to Plate Plane 1 - Surface						Inclusion Size, µm Plate Cross-Section Plane 2 - Along Rolling Direction					
	AM		ESR		VAR		AM		ESR		VAR	
	D(1)	L(2)	D	L	D	L	D	L	D	L	D	L
Nitronic 40	2	13	3	3	4	4	4	40	3	9	3	3
HY-130	4	15	5	6	2	16	3	70	3	30	13**	24
9 Ni-4Co	7	13	6	10	2	12	2	23	4	7	2	19
D6	8	13	5	19	6	24	3	27	7	12	7	15

* The dimensions given in each case are for the largest inclusion observed. Smaller inclusions were present in each microstructure examined.

** An unusually large inclusion occasionally found in VAR product.

(1) D - Diameter or width of inclusion.

(2) L - Longest dimension of inclusion or stringer length.

TABLE XXVI (continued)

B. Inclusions Shape and Distribution - Plane 1 and Plane 2

	Nitronic 40	HY-130	9NI-4Co	D6
AIR MELT				
Plane 1	Globular and Rectangular Small Clusters	Mostly Globular Small Clusters	Rectangular Shaped	Globular Colony
Plane 2	Heavy Stringers	Stringers	Stringers (fine)	Stringers Globular
ESR				
Plane 1	Globular, Uniformly Distributed	Globular with Tails	Globular, Colony	Globular
Plane 2	Globular, with Tails	Small Stringers	Globular	Globular
VAR				
Plane 1	Globular - Occasional Clusters	Globular	Rectangular	Elongated Colony
Plane 2	Globular, Colony	Small Stringers	Small Stringers	Globular

Table XXVI (continued)

C. Inclusions Volume Fraction - Plane 1 Only

Material	Volume Fraction $\bar{V}$ (%)	Deviation σ(%)
Nitronic 40 - Air Melt	0.804	±0.109
Nitronic 40 - ESR	0.268	±0.063
Nitronic 40 - VAR	0.208	±0.056
HY130 - Air Melt	1.470	∓0.147
HY130 - ESR	0.551	±0.090
HY130 - VAR	0.238	±0.060
9Ni-4Co - Air Melt	0.342	±0.071
9Ni-4Co - ESR	0.268	∓0.063
9Ni-4Co - VAR	0.119	±0.042
D6A - Air Melt	0.818	∓0.110
D6A - ESR	0.446	±0.081
D6A - VAR	0.223	∓0.059

TABLE XXVII

PLATE MANUFACTURING COST ESTIMATE

Nitronic 40 (21-6-9) - 17 Ton

Electric Arc Furnace Heat

Scrap + Makeup Alloy Cost - $800/Ton* (approximate)			
Charge	AM	ESR	VAR
Scrap + Makeup Alloys**	$1040/Ton	$1040/Ton	$1040/Ton
Electric Arc Furnace (Melting ($240/Ton)	$1280/2000#	$1280/2000#	$1280/2000#
Argon-Oxygen Refining ($100/Ton)	$1380/1950#	$1380/1950#	$1380/1950#
Electrode or Ingot Casting (AM - 3¢/1b) (ESR and VAR - 2¢/1b)	$1439/1730#	$1419/1840#	$1419/1840#
Electrode Preparation (1¢/1b ESR and VAR) no scale	--	$1437/1820#	$1437/1820#
ESR or VAR Melting 30" dia. or larger ingots (ESR - 12¢/1b; VAR with Argon 12¢ 1b)	--	$1655/1780#	$1655/1780#
Ingot Preparation (AM and ESR - 1¢/1b;Var - 2¢/1b)	$1456/1670#	$1673/1730#	$1691/1680#
Homogenize and Forge into Slab (23¢/1b)	$1840/1370#	$2071/1670#	$2077/1540#
Roll into Plate (14¢/1b)	$2032/1320	$2305/1620#	$2293/1480#
Cost/kg.***	$3.40	$3.13	$3.42

*Short ton (2,000 lbs.)

**Includes mark up of 30% for transportation, inventory, storage, charge preparation, charge analyses verification and such other costs.

*** /kg = 2.205 /lb.

TABLE XXVIII

PLATE MANUFACTURING COST ESTIMATE

HY-130 -- 6 Ton Electric Arc Furnace Heat

Scrap + Makeup Alloy Cost - $400/Ton* (approximate)			
Charge	AM	ESR	VAR
Scrap + Makeup Alloys**	$520/Ton	$520/Ton	$520/Ton
Electric Arc Furnace Melting ($325/Ton)	$845/2000#	$845/2000#	$845/2000#
Electrode or Ingot Casting (AM-3¢/lb, ESR and VAR - 2¢/lb	$905/1720#	$885/1840#	$885/1840#
Electrode Preparation (1¢/lb - ESR; 2¢/lb - VAR)	--	$903/1820#	$922/1800#
ESR or VAR Melting (ESR - 14¢/lb; VAR - 12¢/lb)	--	$1158/1770#	$1138/1750#
Ingot Preparation (AM & ESR - 1¢/lb; VAR - 2¢/lb)	$922/1660#	$1166/1720#	$1173/1660#
Homogenize and Forge into Slab (22¢/lb)	$1287/1360#	$1544/1650#	$1538/1520#
Roll into Plate (15¢/lb)	$1491/1280#	$1792/1570#	$1766/1450#
Cost/kg.***	$2.55	$2.51	$2.69

*Short ton (2,000 lbs.)

**Includes mark up of 30% for transportation, inventory, storage, charge preparation, charge analyses verification and such other costs.

*** /kg - 2.205/lb.

TABLE XXIX

PLATE MANUFACTURING COST ESTIMATE

9Ni-4Co - 6 Ton Electric Arc Furnace Heat

Scrap + Makeup Alloy Charge Cost - $690/Ton* (approximate)			
Charge	AM	ESR	VAR
Scrap + Makeup Alloys**	$897/Ton	$897/Ton	$897/Ton
Electric Arc Furnace Melting -($325/Ton)	$1222/2000#	$1222/2000#	$1222/2000#
Electrode or Ingot Casting (AM - 3¢/lb) (ESR and VAR - 2¢/lb)	$1282/1720#	$1262/1840#	$1262/1840#
Electrode Preparation (1¢lb - ESR; 2¢/lb - VAR)	--	$1280/1820#	$1299/1800#
ESR or VAR Melting (ESR - 14¢/lb; VAR - 12¢/lb)	--	$1535/1770#	$1515/1750#
Ingot Preparation (AM and ESR - 1¢/lb; VAR - 2¢/lb)	$1299/1660	$1553/1720#	$1550/1660#
Homogenize and Forge into Slab (22¢/lb)	$1664/1360#	$1931/1650#	$1915/1520#
Roll into Plate (15¢/lb)	$1868/1280#	$2179/1570#	$2143/1450#
Cost/kg.***	$3.22	$3.06	$3.26

*Short ton (2,000 lbs.)

**Includes mark up of 30% for transportation, inventory, storage, charge preparation, charge analyses verification and such other costs.

*** /kg. = 2.205/lb.

TABLE XXX

PLATE MANUFACTURING COST ESTIMATE

D-6 - 17 Ton Electric Arc Furnace Heat

Scrap + Makeup Alloy - $340/Ton* (approximate)

Charge	AM	ESR	VAR
Scrap + Makeup Alloys**	$442/Ton	$442/Ton	$442/Ton
Electric Arc Furnace Melting (270/Ton)	$512/2000#	$512/2000#	$512/2000#
Electrode or Ingot Casting (AM - 3¢/lb) (ESR and VAR - 2¢/lb)	$572/1740#	$552/1850#	$552/1850#
Electrode Preparation (1¢/lb ESR; 2¢/lb - VAR)	--	$571/1830#	$589/1810#
ESR or VAR Melting (30" dia. or larger dia. ingots) (ESR - 12¢/lb; VAR - 11¢/lb)	--	$791/1780#	$788/1760#
Ingot Preparation (AM and ESR 1¢/lb; VAR - 2¢/lb)	$589/1680#	$809/1730#	$823/1670#
Homogenize and Forge into Slab (23¢/lb)	$975/1380#	$1207/1660#	$1207/1530#
Roll into Plate (14¢/lb)	$1168/1300#	$1439/1600#	$1421/1460#
Cost/kg.***	$1.98	$1.98	$2.20

*Short ton (2,000 lbs.)

**Includes mark up of 30% for transportation, inventory, storage, charge preparation, charge analyses verification and such other costs.

*** /kg. = 2.205/lb.

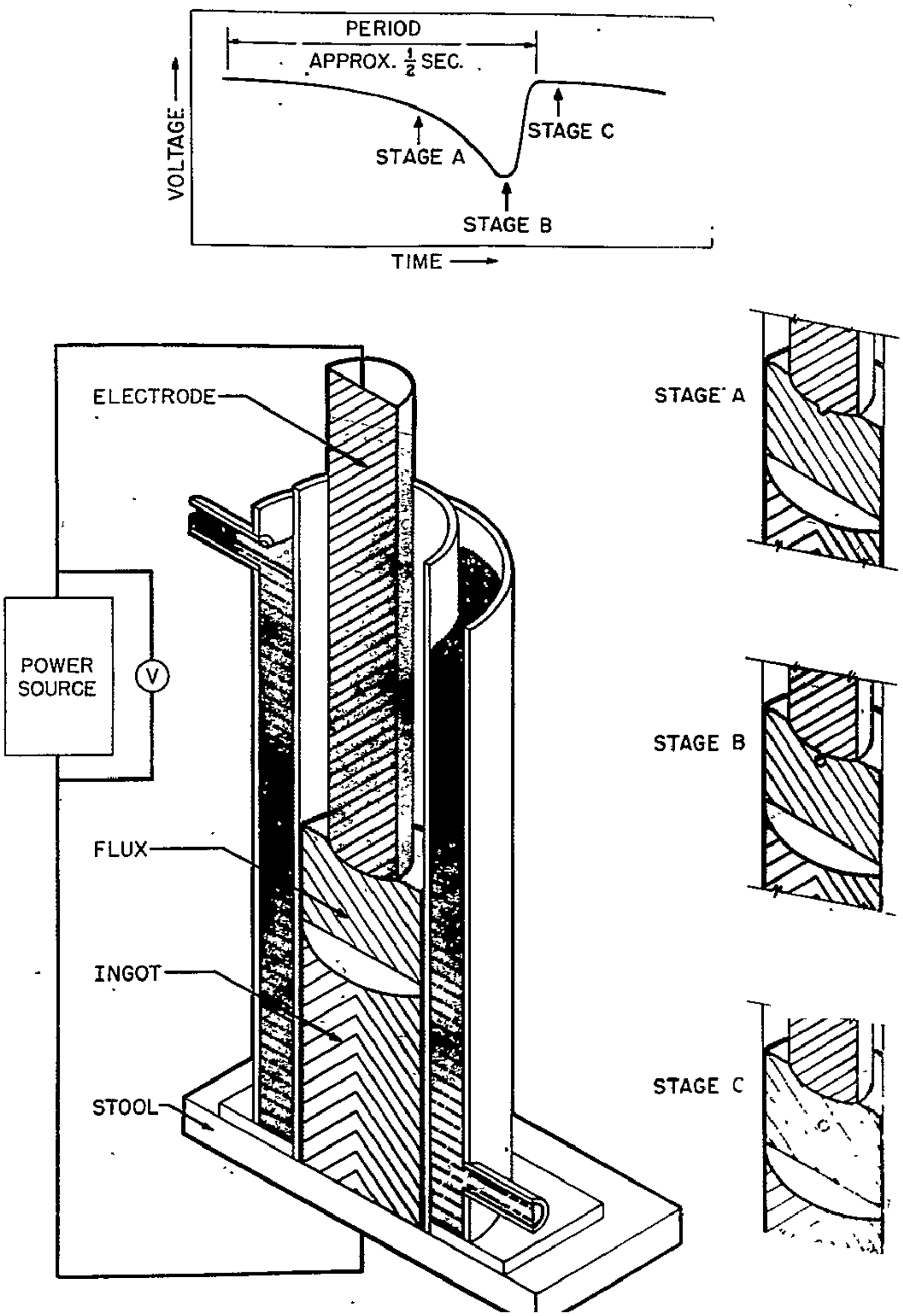


Figure 1. SCHEMATIC ILLUSTRATION OF PRINCIPLE OF THE ELECTROSLAG REMELTING PROCESS. - (Top and right hand side illustrations show electrode consumption and metal droplet formation).

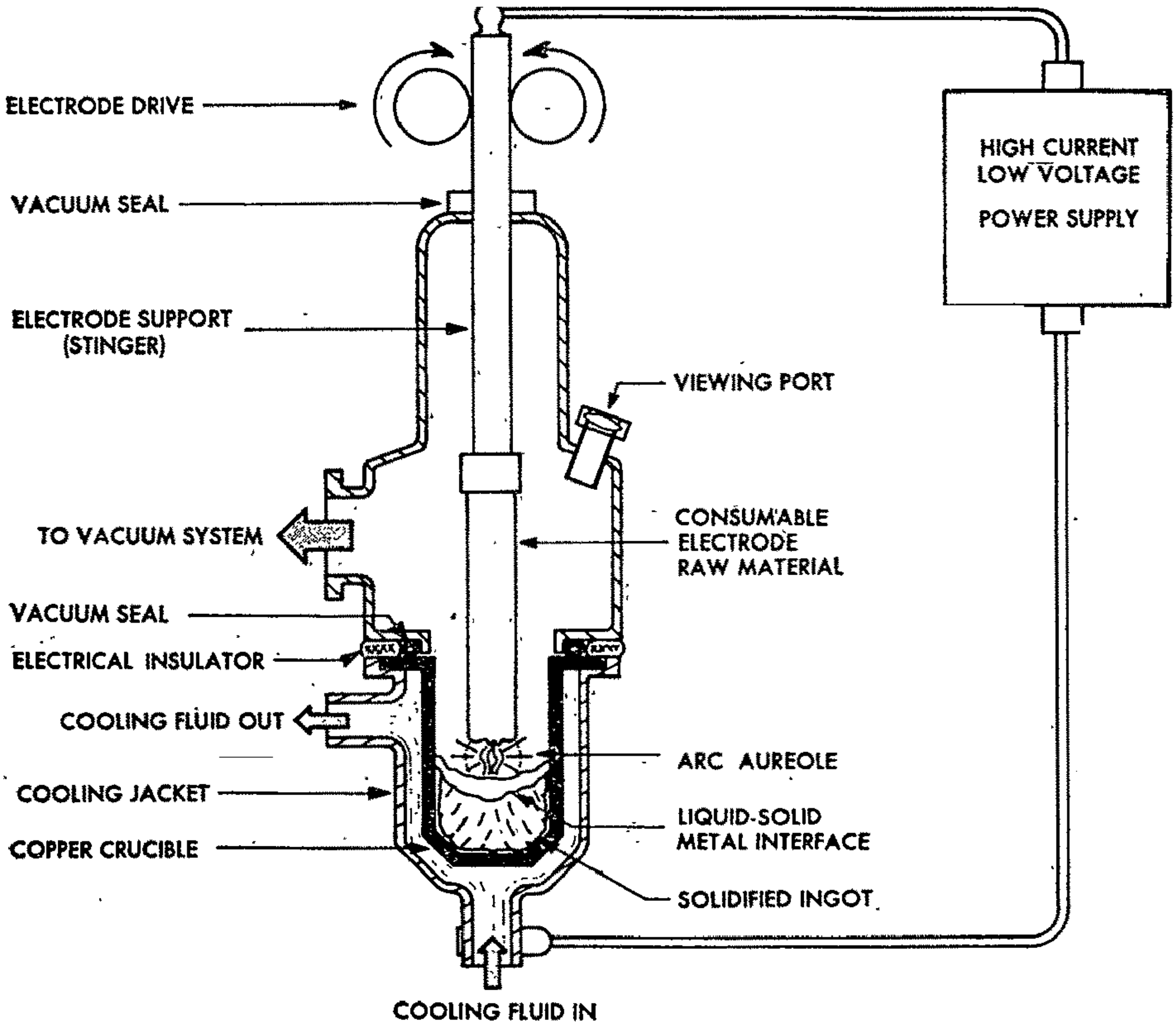


Fig. 2 CONSUMABLE ELECTRODE VACUUM ARC REMELTING FURNACE (Schematic)

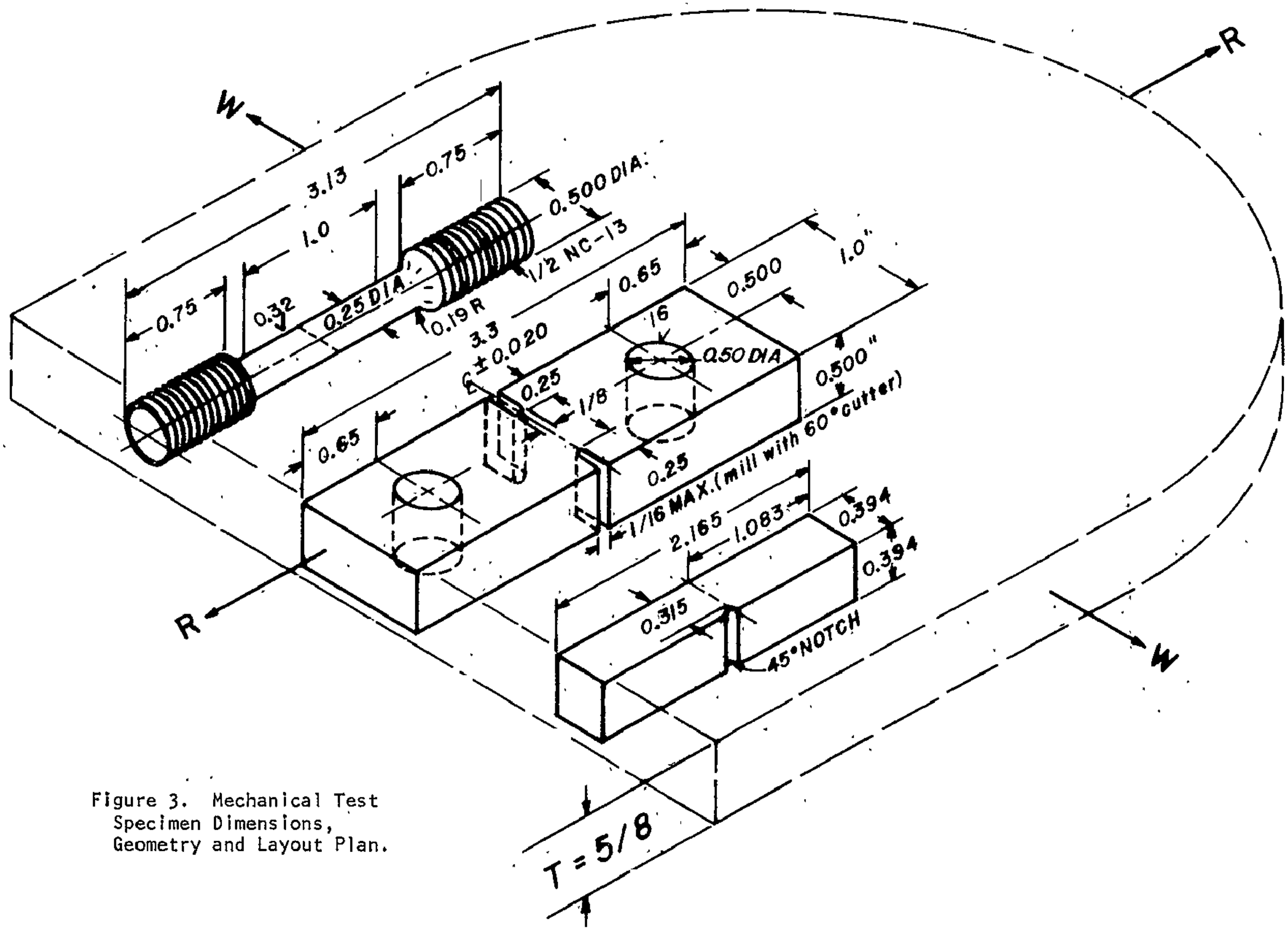


Figure 3. Mechanical Test
Specimen Dimensions,
Geometry and Layout Plan.

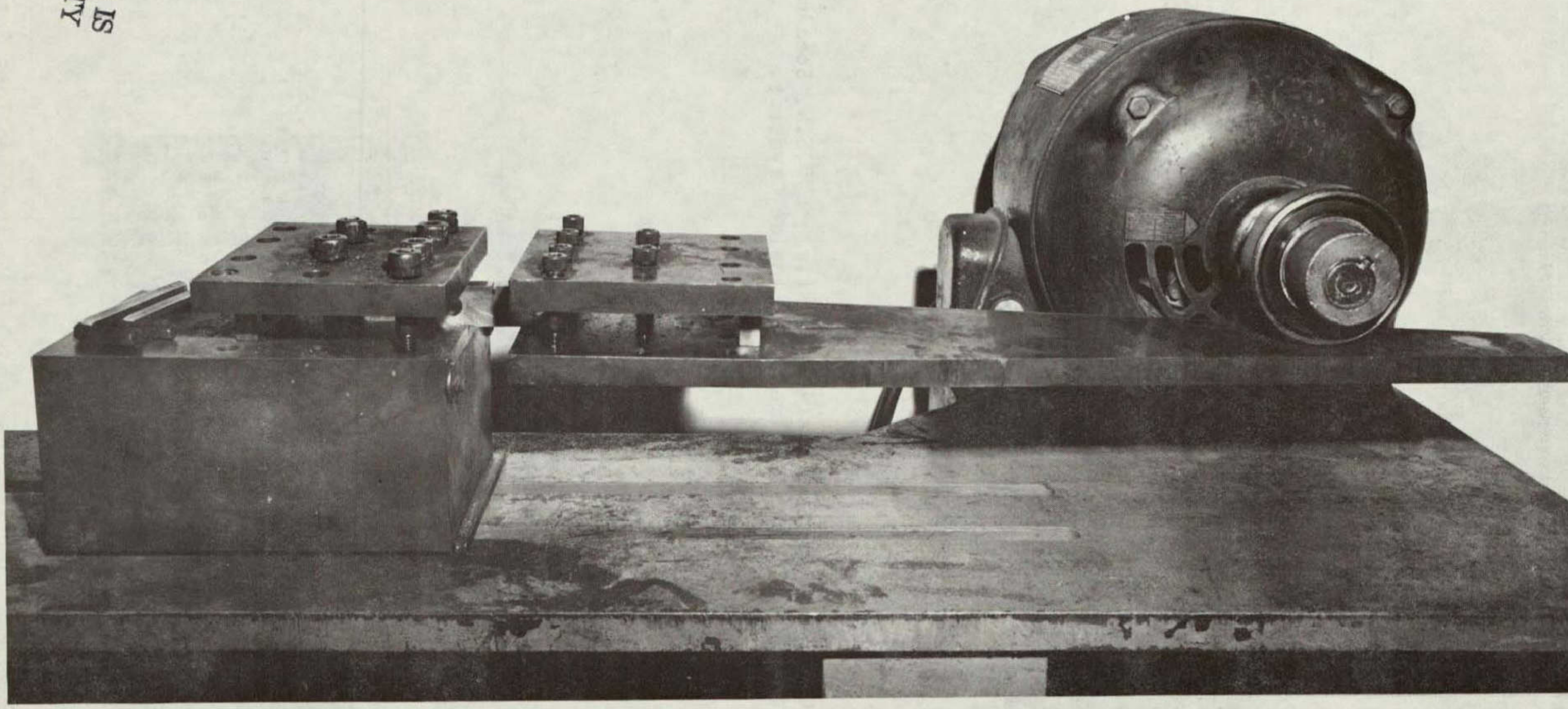


Figure 4. Machine Used for
Initiation of a Fatigue
Crack in D.E.N. Specimen.

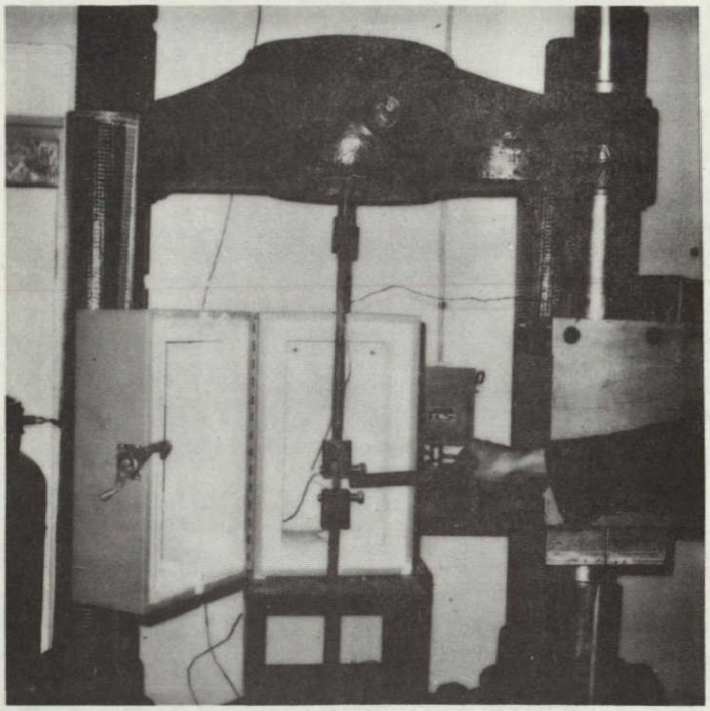


Figure 5(a) - Cryostat Used for Testing Tensile and D.E.N. Specimens -- View of Tensile Specimen Grip Inside Cryostat.

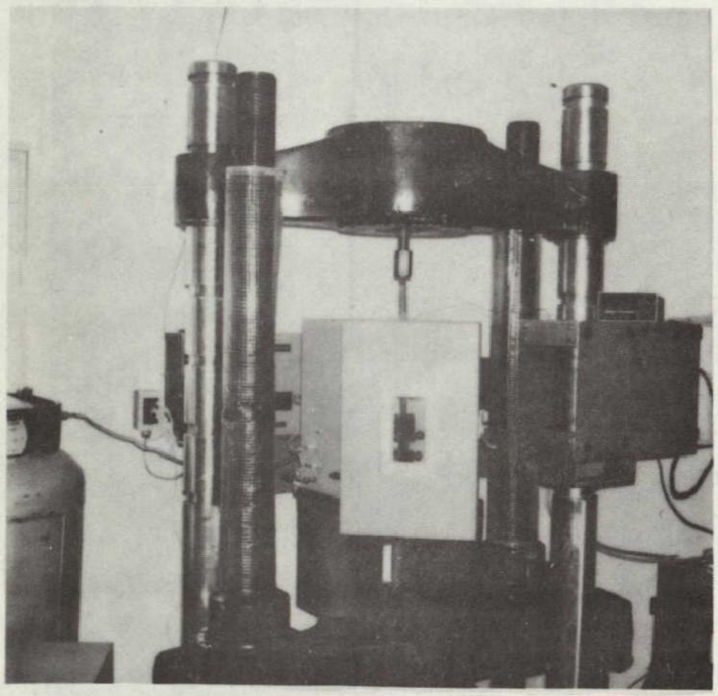


Figure 5(b) - Cryogenic Tensile Test and D.E.N. Specimen Test Set-Up.

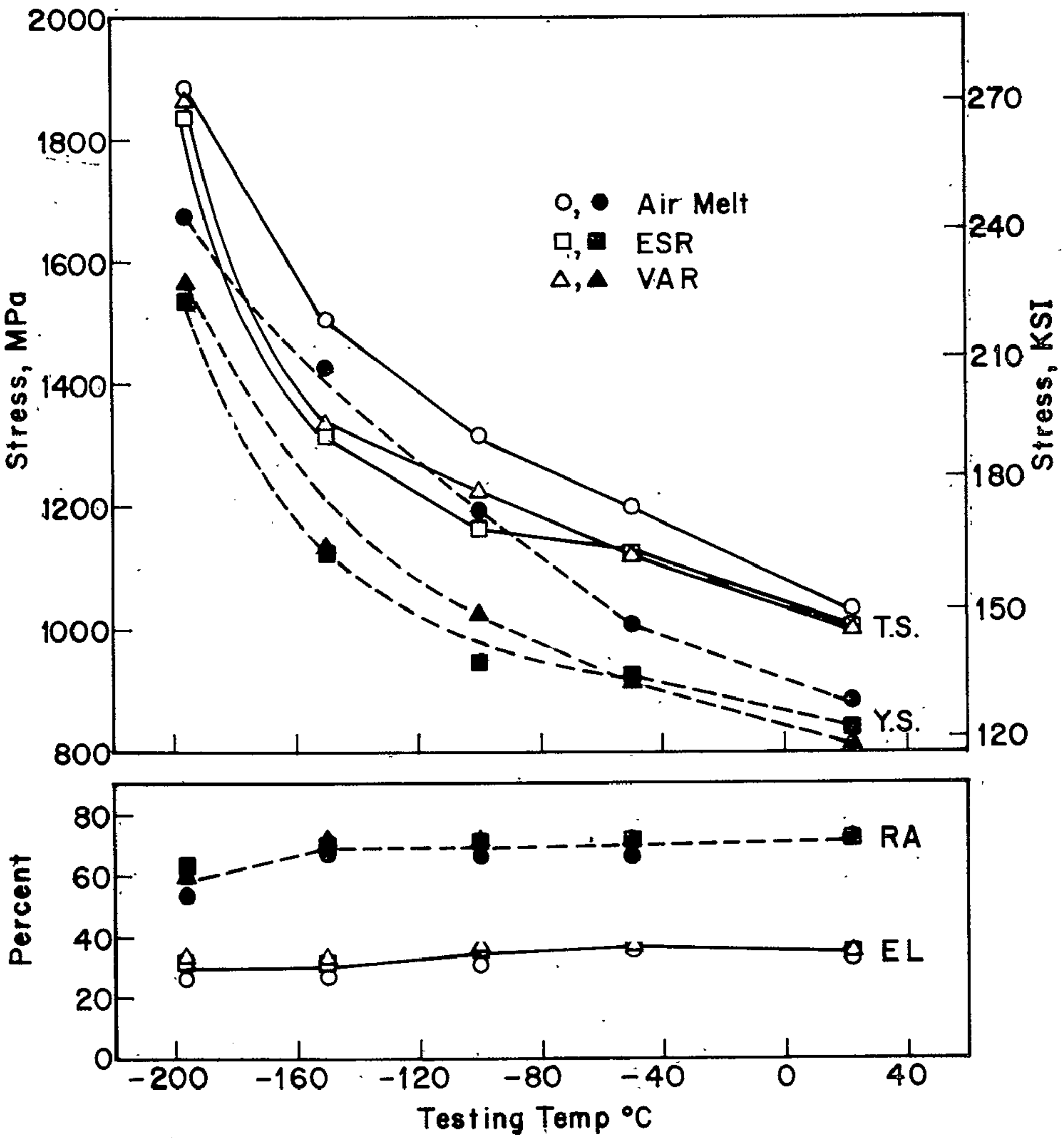


Fig. 6 Tensile Test Data for Nitronic 40 Alloy Steel

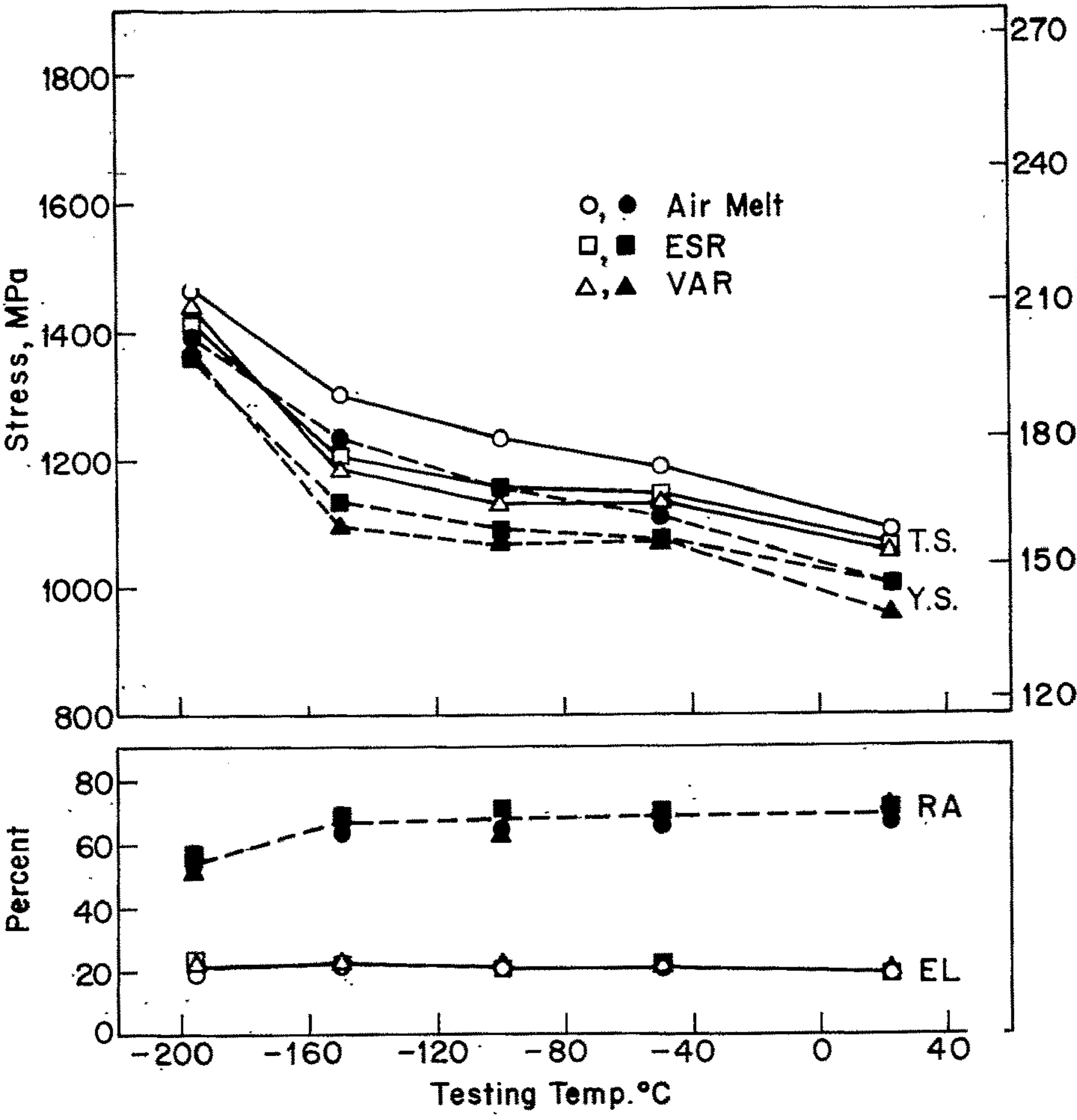


Fig.7 Tensile Test Data for HY-130 Alloy Steel

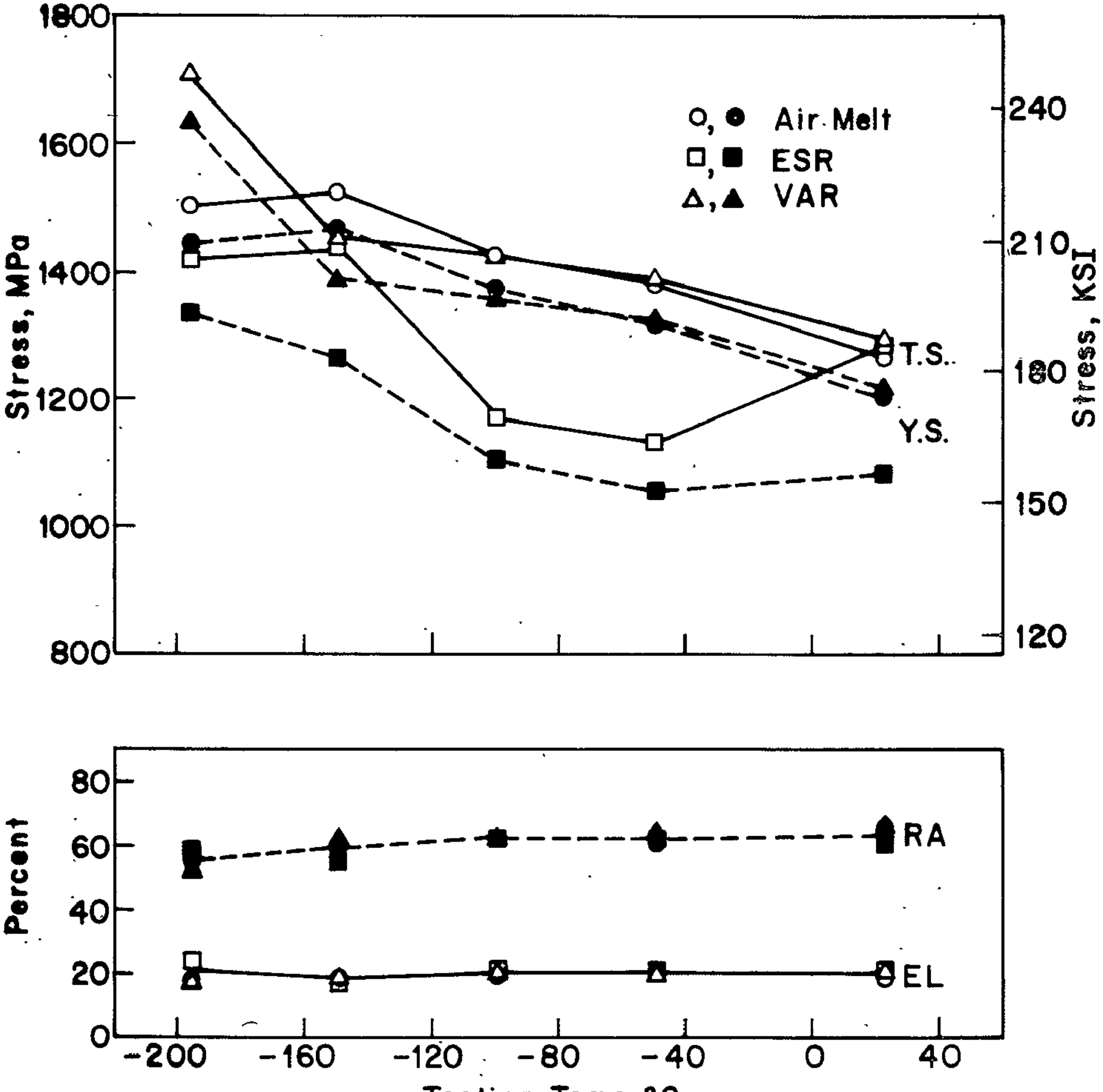


Fig. 8 Tensile Test Data for 9Ni-4Co Alloy Steel

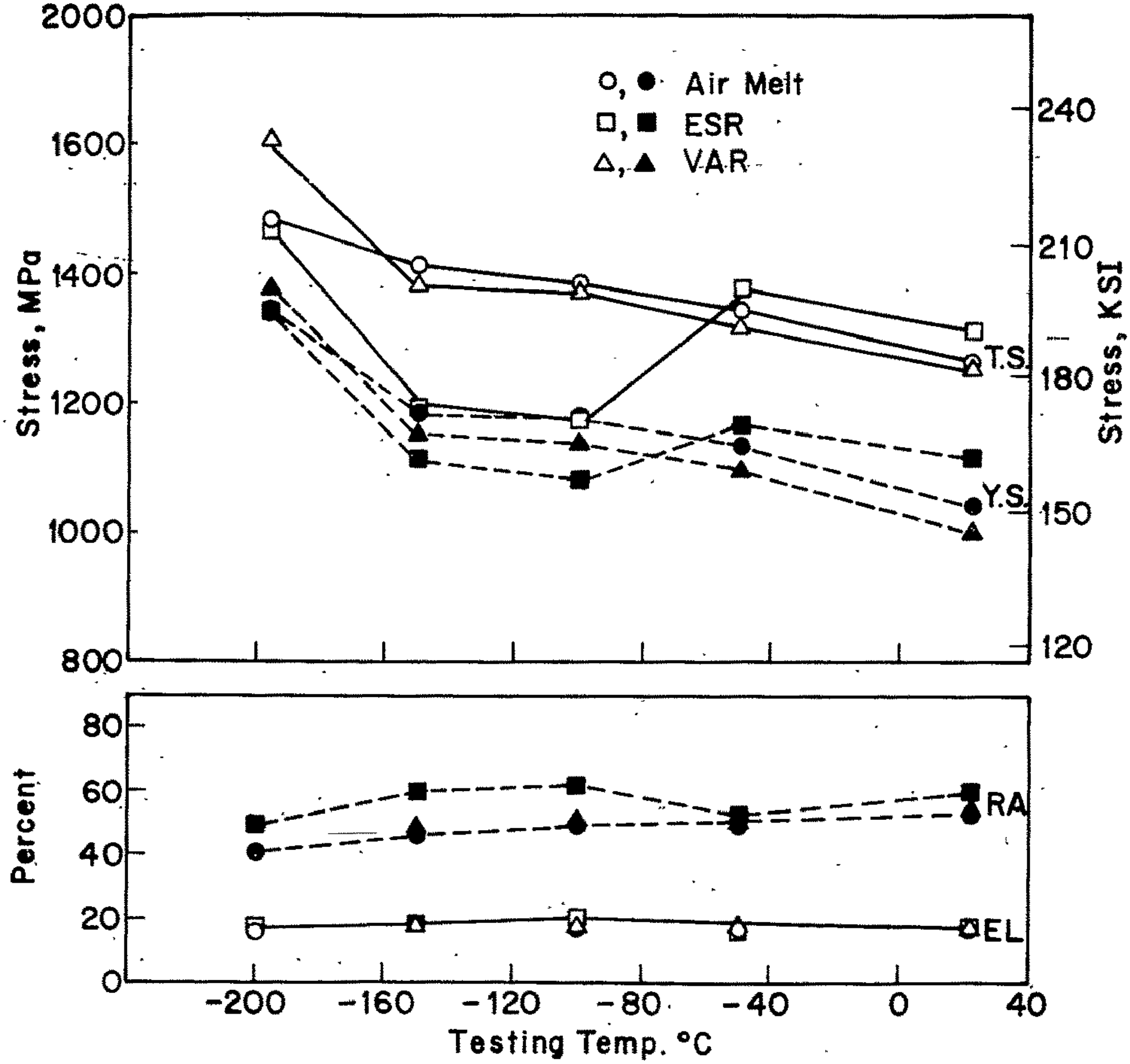


Fig. 9 Tensile Strength Data for D-6 Alloy Steel

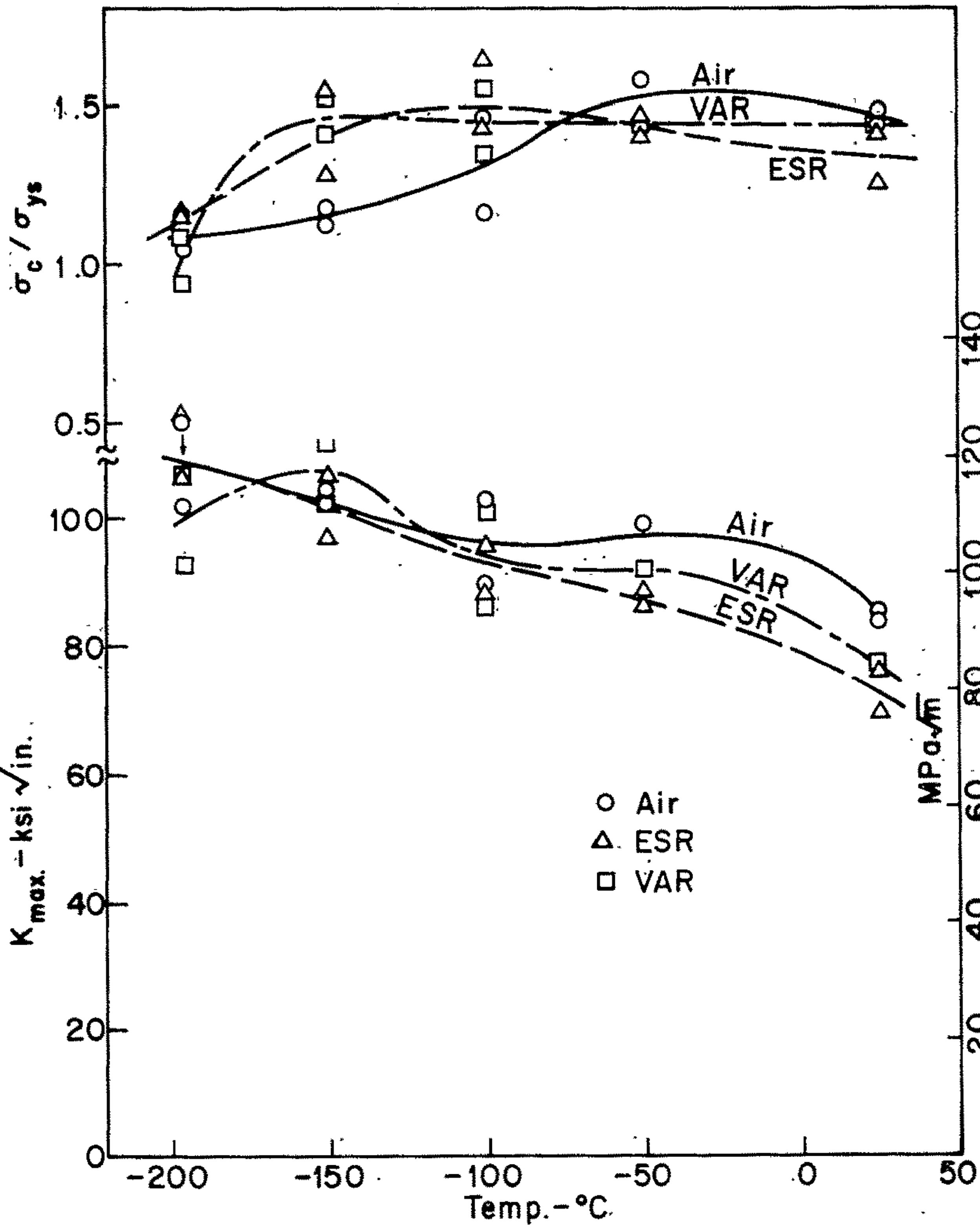


Fig.10 D.E.N. Fracture Toughness Test Results for Nitronic 40 Alloy Steel

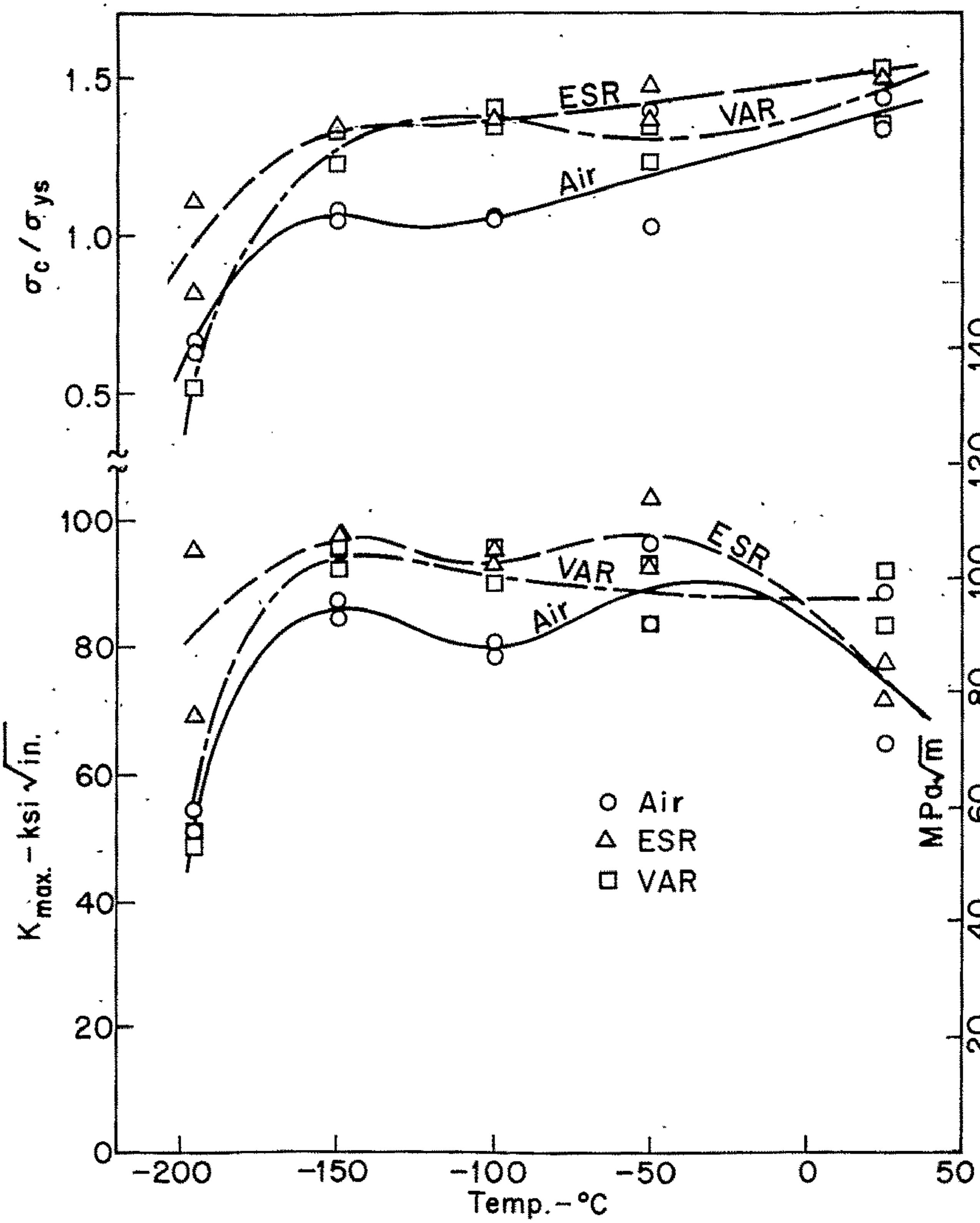


Fig.11 D.E.N. Fracture Toughness Test Results for HY-130 Alloy Steel

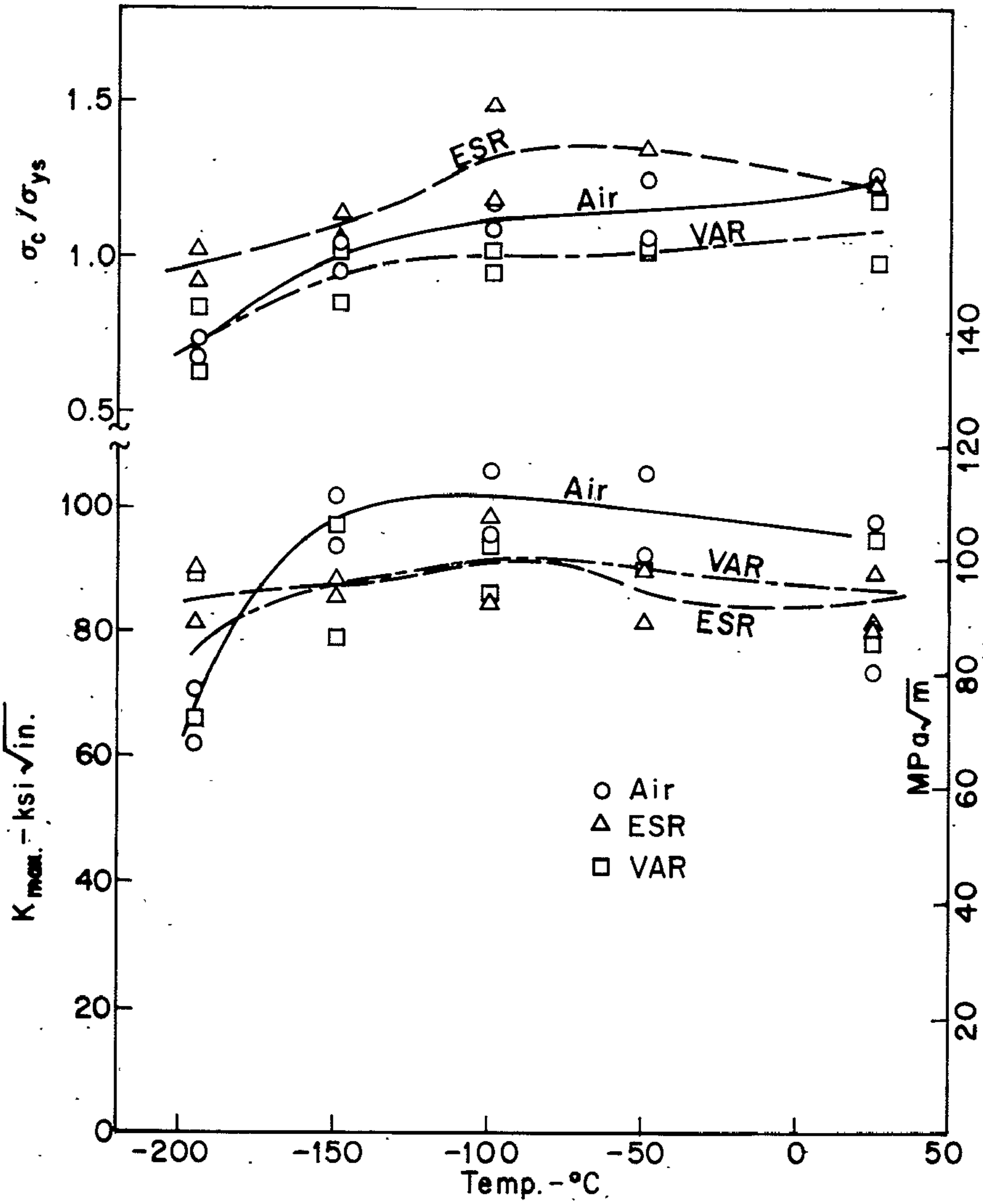


Fig.12 D.E.N. Fracture Toughness Test Results for 9 Ni-4Co Alloy Steel

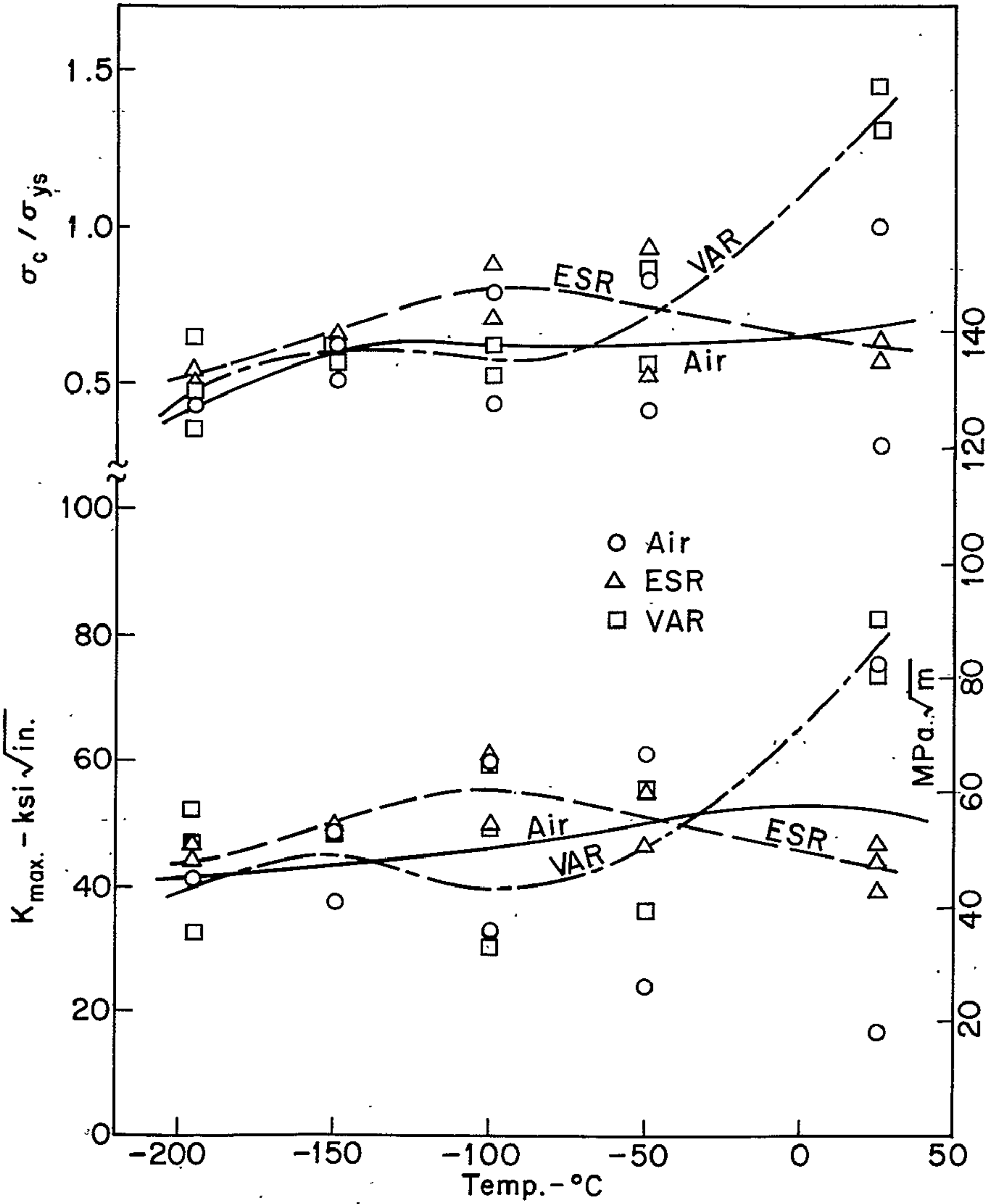


Fig.13 D.E.N. Fracture Toughness Test Results for D-6 Alloy Steel

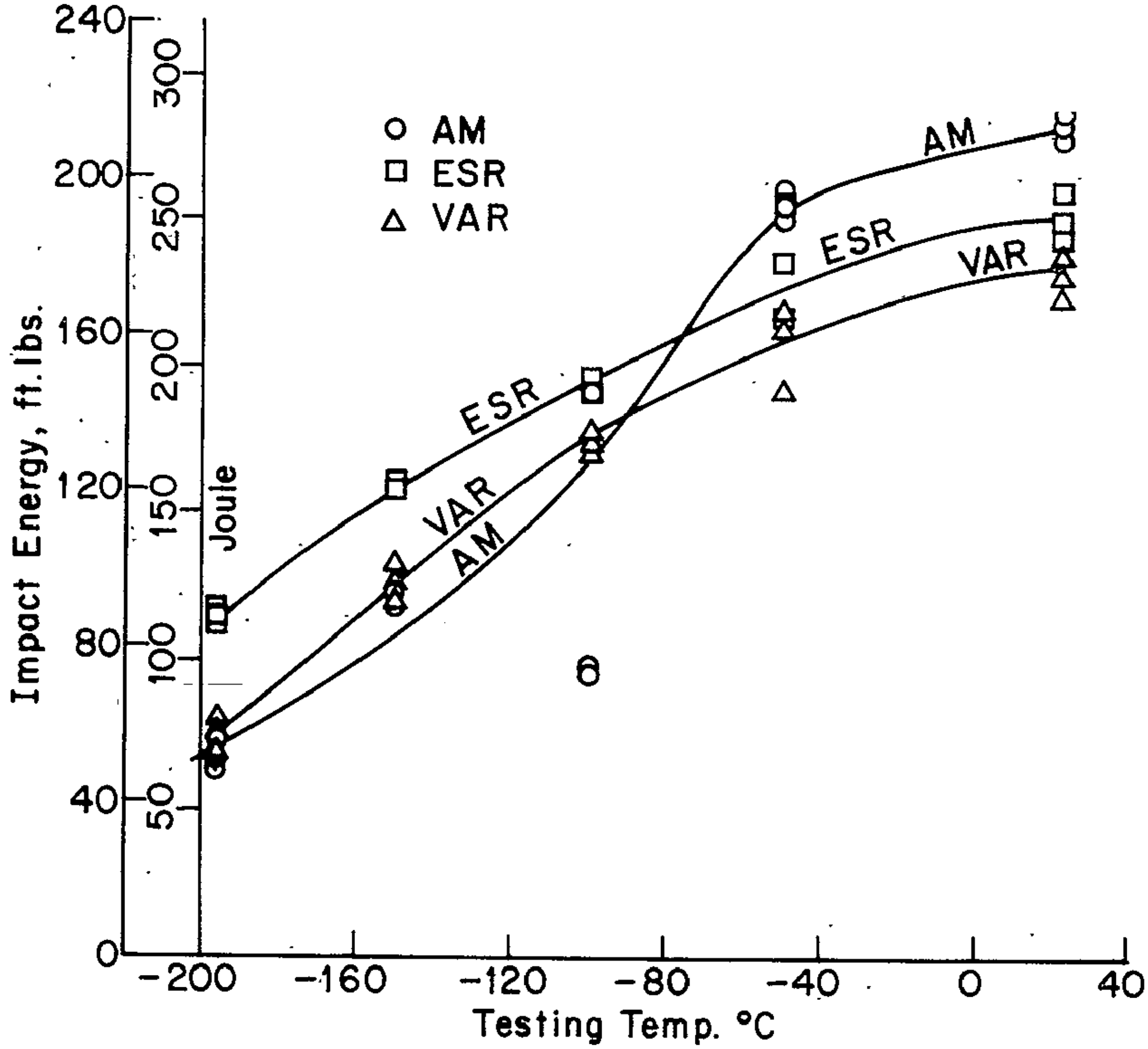


Fig.14 Charpy Impact Test Results for Nitronic 40 Alloy Steel

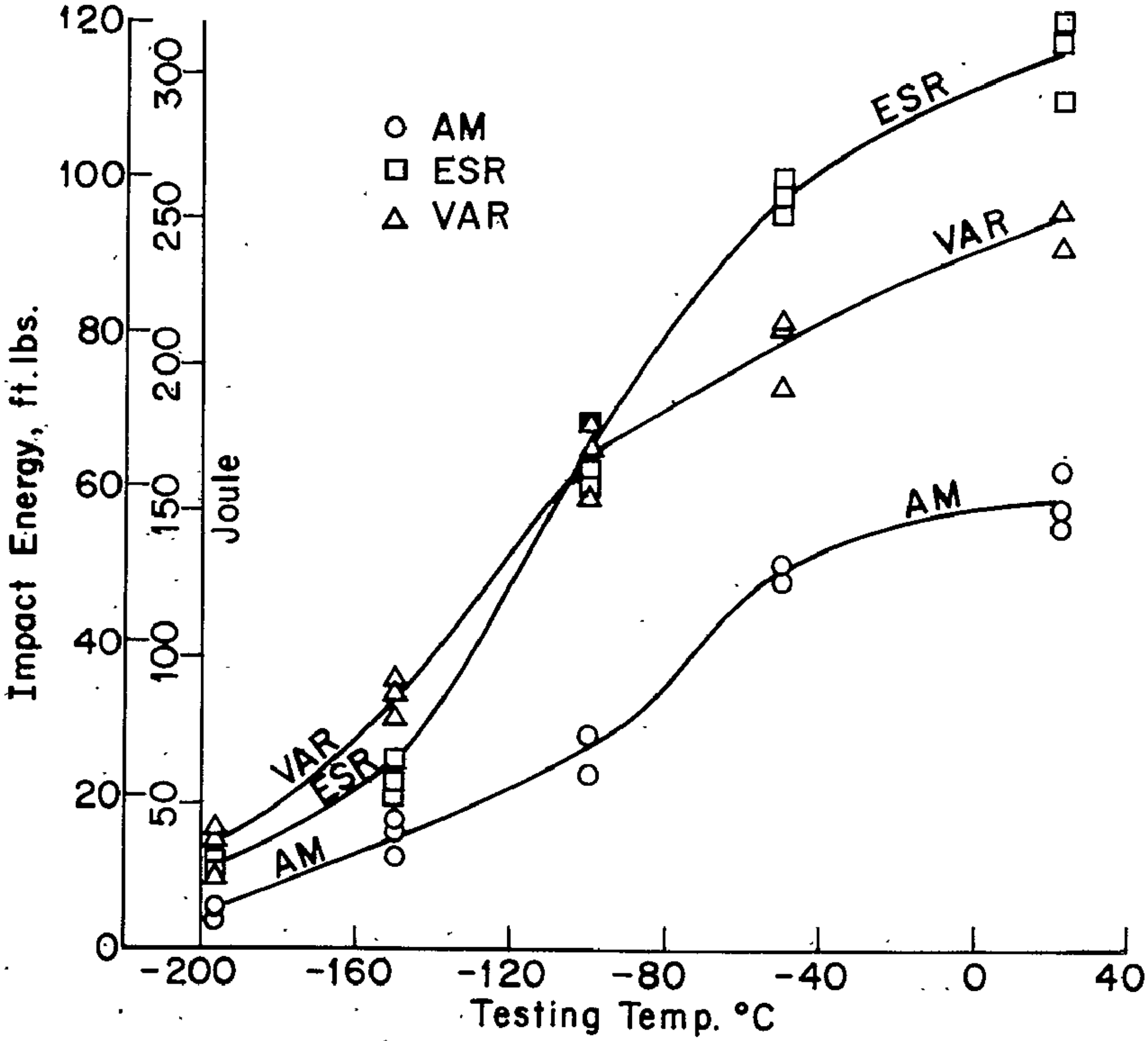


Fig.15 Charpy Impact Test Results for HY130 Alloy Steel

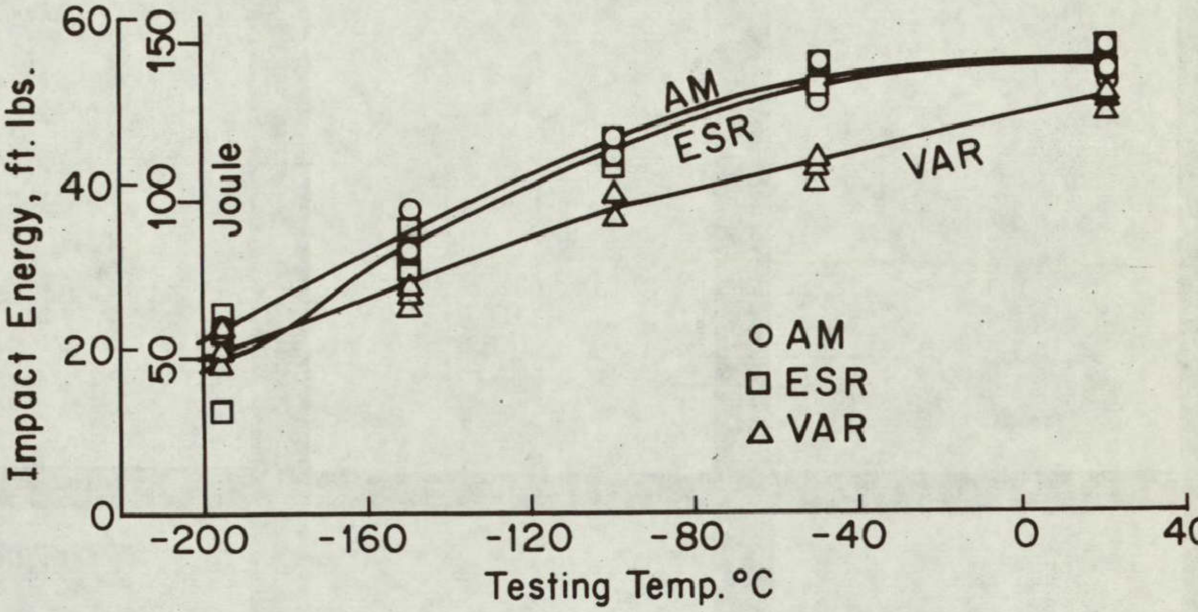


Fig.16 Charpy Impact Test Results for 9Ni-4Co Alloy Steel

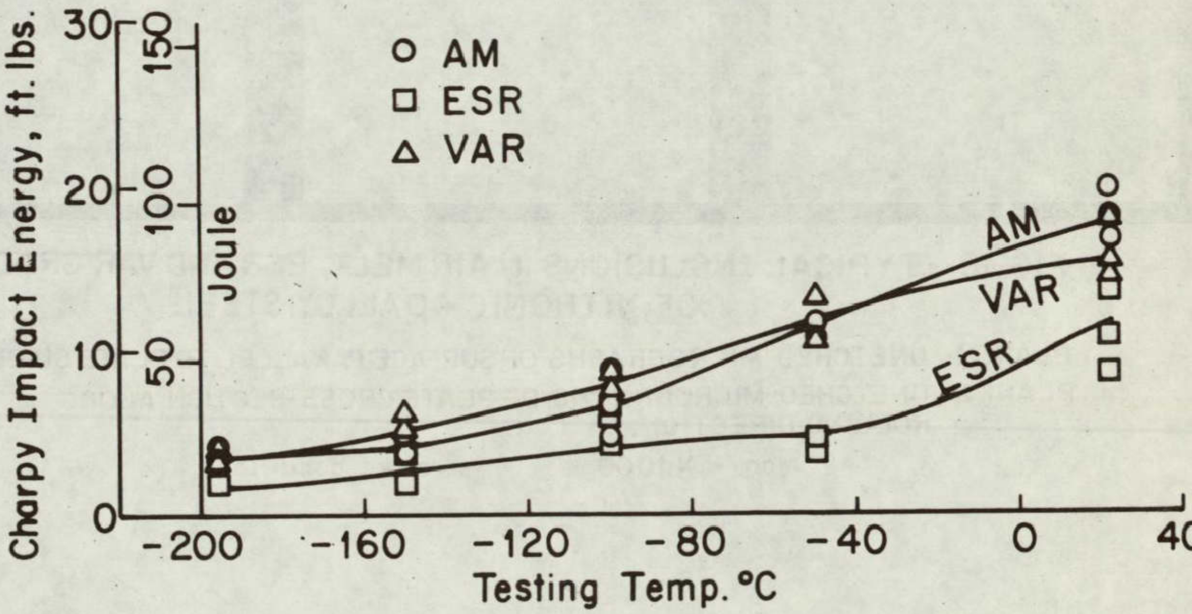


Fig.17 Charpy Impact Test Results for D6 Alloy Steel

C.2

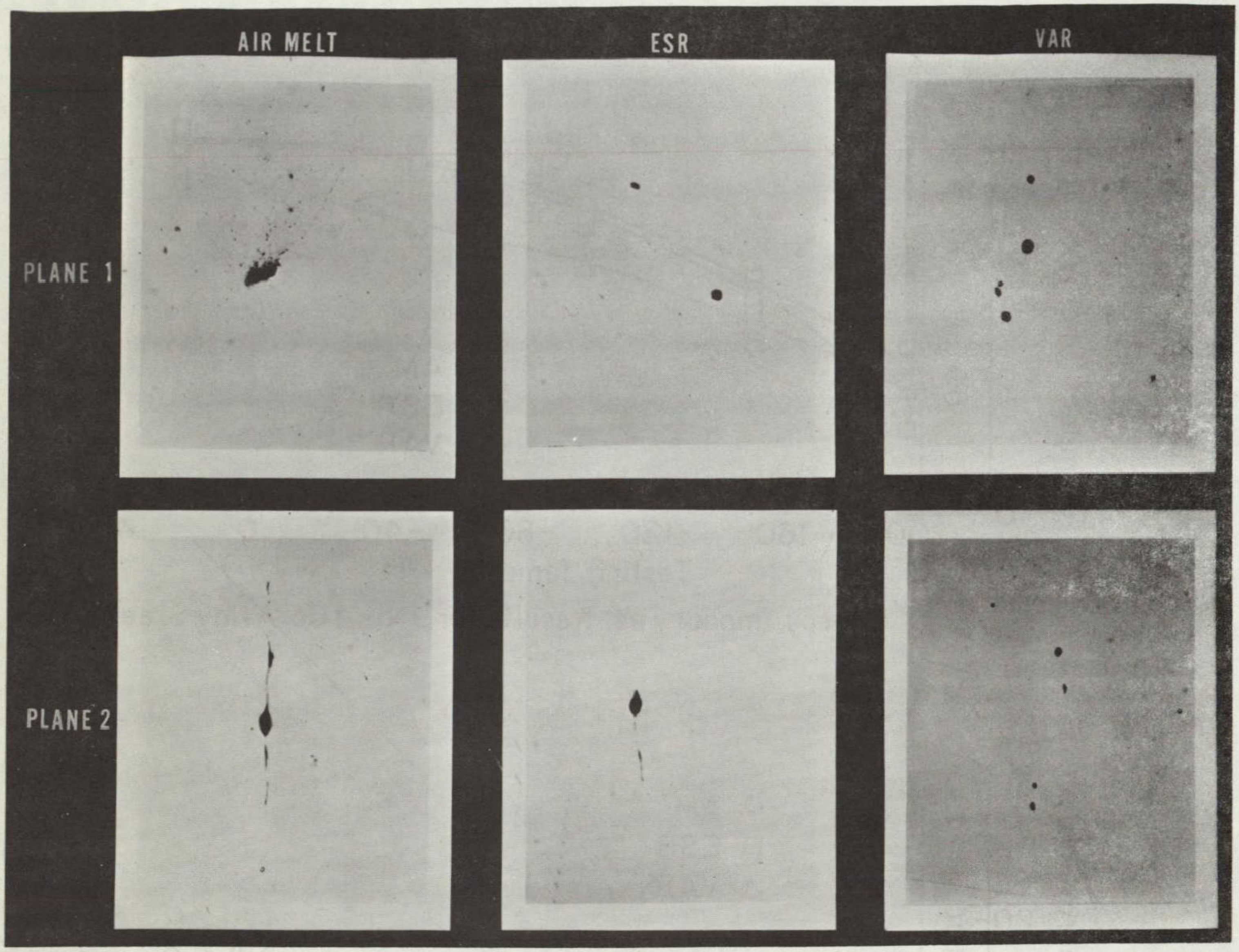


FIG. 18 TYPICAL INCLUSIONS IN AIR MELT, ESR AND VAR GRADES OF NITRONIC 40 ALLOY STEEL

PLANE 1 UNETCHED MICROGRAPHS OF SURFACE PARALLEL TO PLATE SURFACE

PLANE 2 UNETCHED MICROGRAPHS OF PLATE CROSS-SECTION ALONG ROLLING DIRECTION.

Mag. – X 1000 As rolled condition

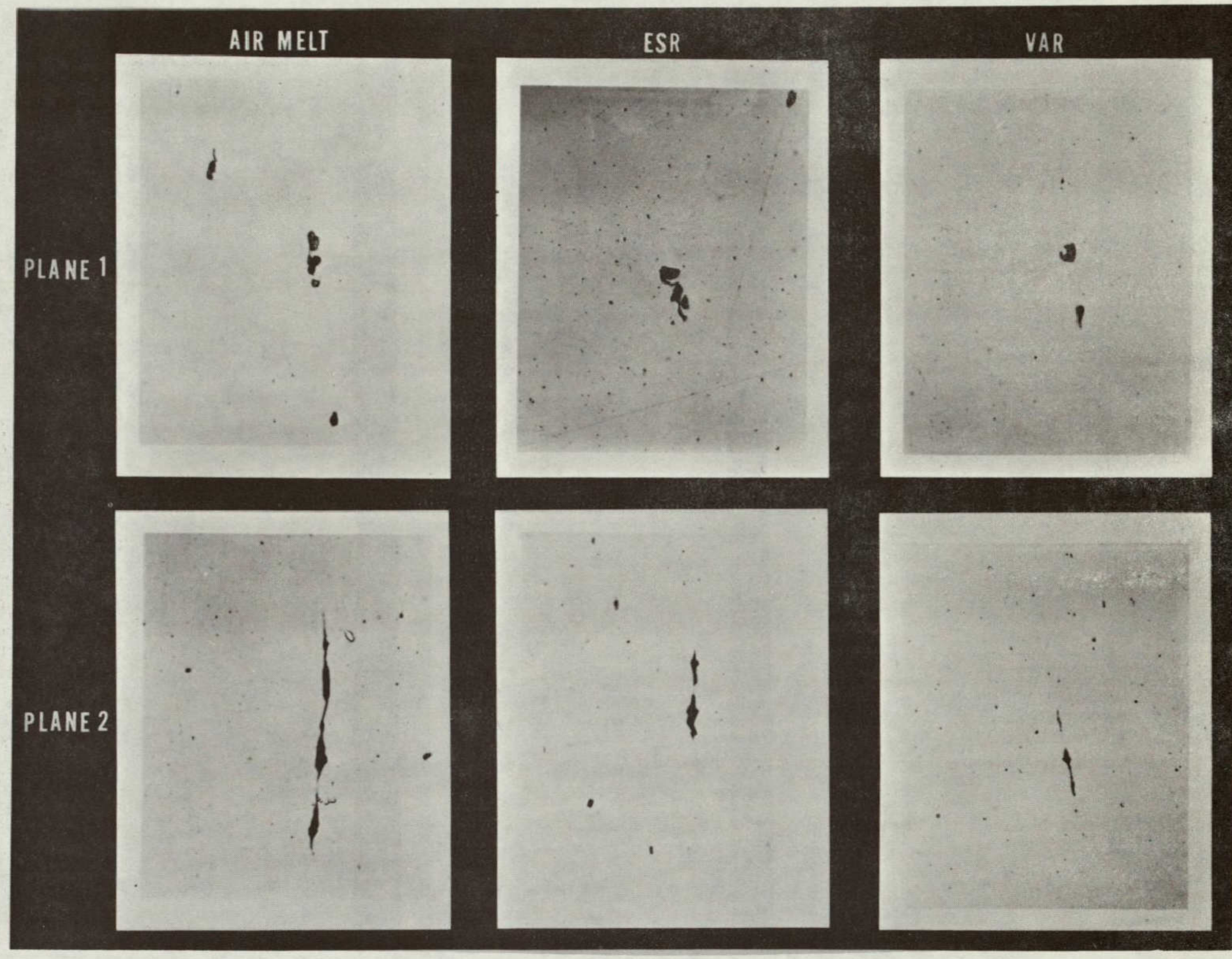


FIG.19 TYPICAL INCLUSIONS IN AIR MELT, ESR AND VAR GRADES OF Hy-130 ALLOY STEEL

PLANE 1 UNETCHED MICROGRAPHS OF SURFACE PARALLEL TO PLATE SURFACE

PLANE 2 UNETCHED MICROGRAPHS OF PLATE CROSS-SECTION ALONG ROLLING DIRECTION.

Mag. – X 1000 As rolled condition

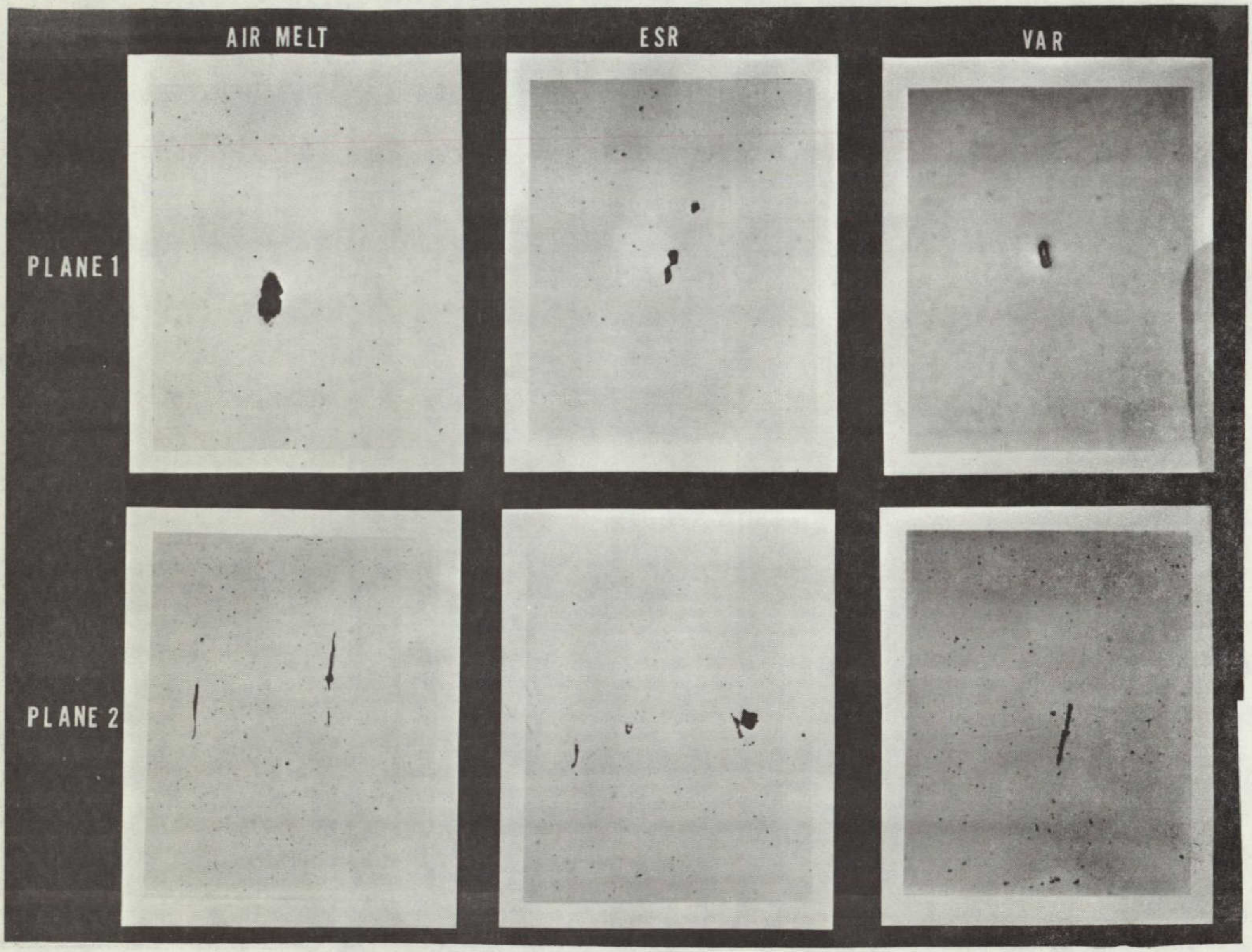


FIG. 20 TYPICAL INCLUSIONS IN AIR MELT, ESR AND VAR GRADES OF 9Ni-4Co ALLOY STEEL

PLANE 1 UNETCHED MICROGRAPHS OF SURFACE PARALLEL TO PLATE SURFACE

PLANE 2 UNETCHED MICROGRAPHS OF PLATE CROSS-SECTION ALONG ROLLING DIRECTION.

Mag. - X1000 As rolled condition

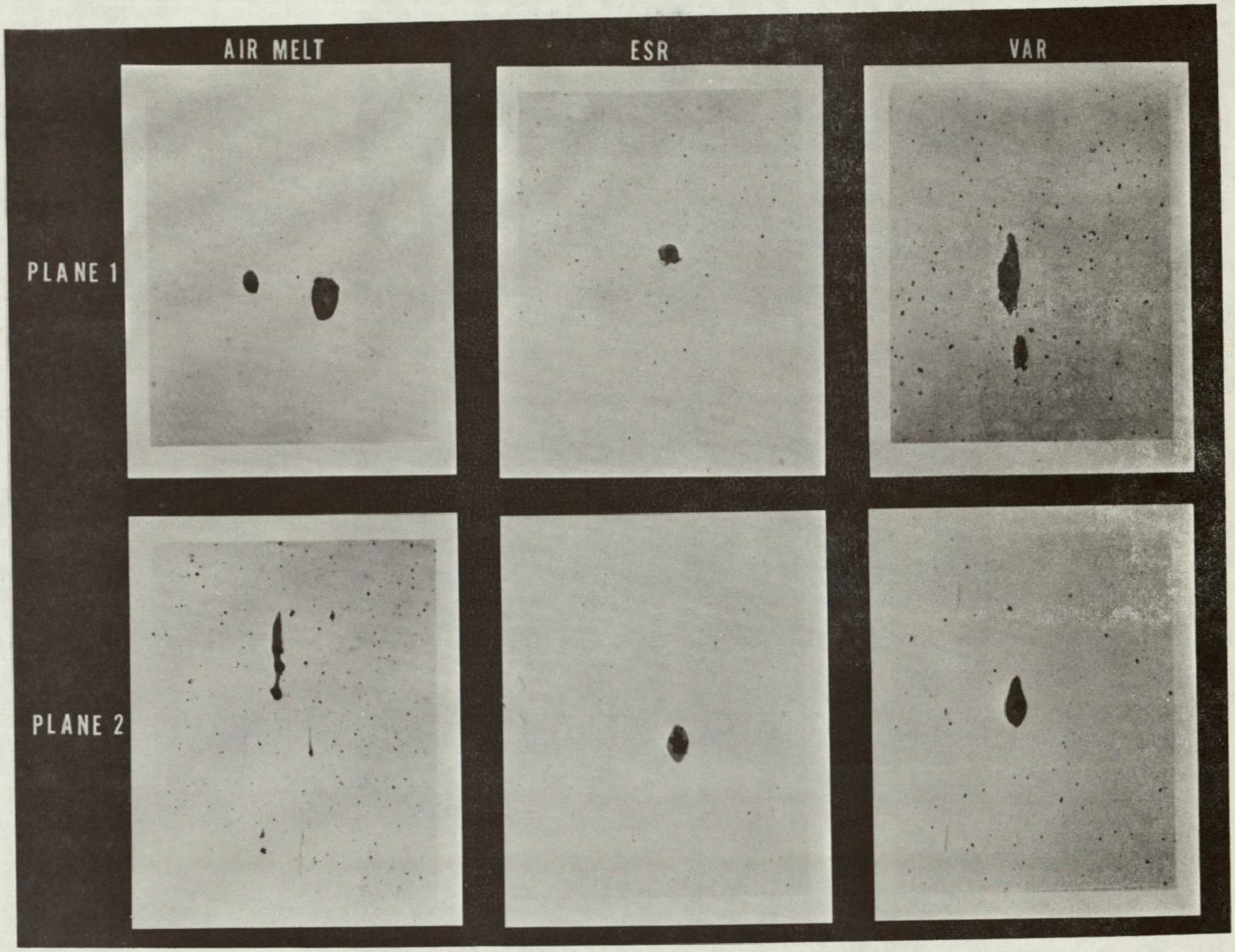
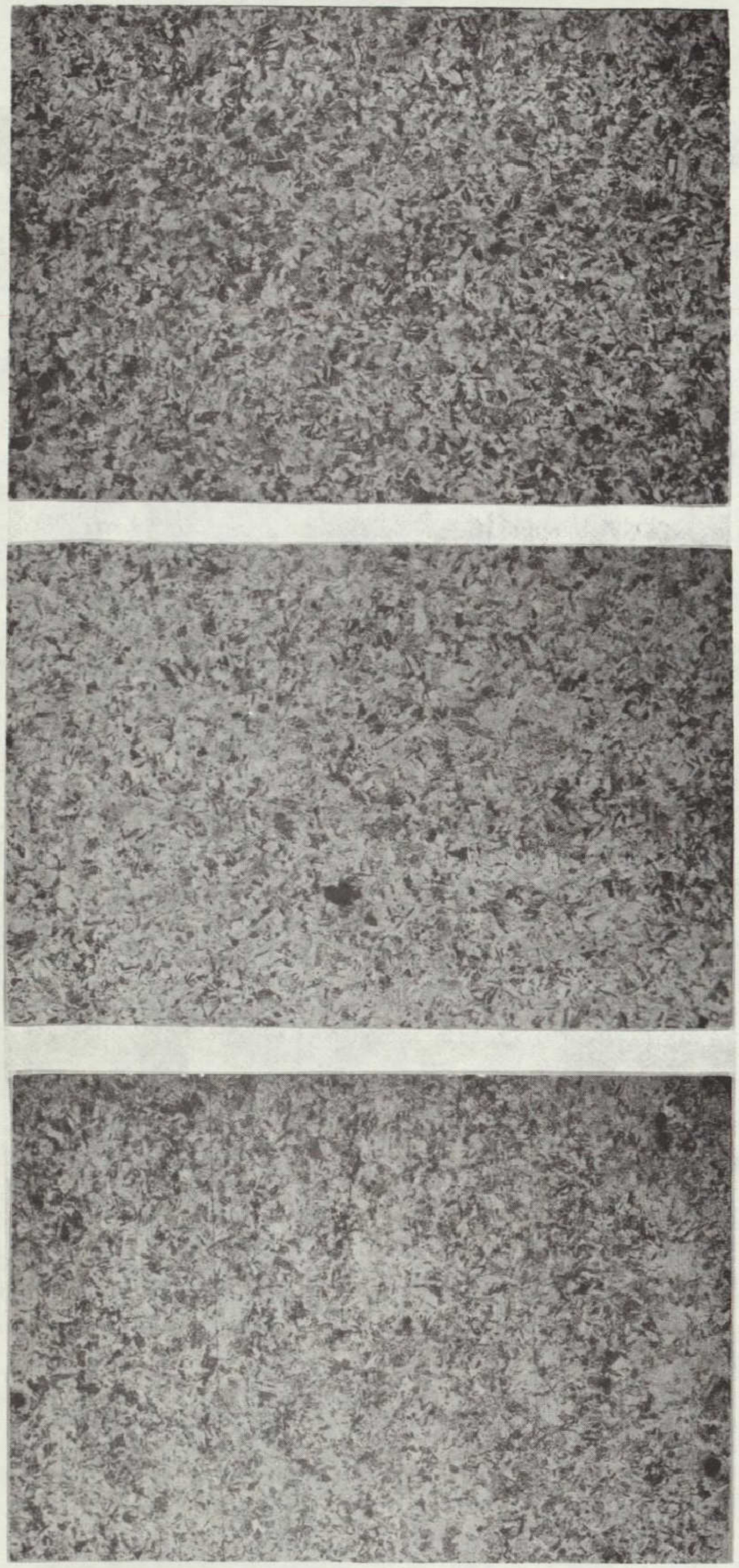


FIG. 21 TYPICAL INCLUSIONS IN AIR MELT, ESR AND VAR GRADES OF D-6 ALLOY STEEL

PLANE 1 UNETCHED MICROGRAPHS OF SURFACE PARALLEL TO PLATE SURFACE

PLANE 2 UNETCHED MICROGRAPHS OF PLATE CROSS-SECTION ALONG ROLLING DIRECTION.

Mag. – X 1000 As rolled condition



Air Melt

ESR

VAR

Figure 22. Typical Microstructure and Grain Size Observed in Heat Treated HY-130 Plate Specimens. (Plane 1 - Parallel to Plate Surface Along Rolling Direction.) 100X. Picral Etch.