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ESTABLISHMENT OF A PLASMA MELTING MANUFACTURING PROCESS FOR PRODUCTION OF NICKEL-BASE ALLOYS

CARNEGIE-MELLON INSTITUTE OF RESEARCH, Pittsburgh, Pa
~~*CARNEGIE-MELLON UNIVERSITY*~~

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FINAL REPORT FOR PERIOD JUNE 1971 - SEPTEMBER 1974

Prepared for
AIR FORCE MATERIALS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This final report was submitted by Carnegie-Mellon Institute of Research, Pittsburgh, PA under Contract F33615-71-C-1681, Manufacturing Methods Project 262-1, "Establishment of a Plasma Melting Process for Production of High Quality Structural Materials." Messrs. R. L. Kennard and K. L. Love, AFML/LTM, were the laboratory monitors.

This technical report has been reviewed and is approved for publication.

K. L. LOVE
Project Monitor

FOR THE DIRECTOR

H. A. JOHNSON
Chief, Metals Branch
Manufacturing Technology Division

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Plasma melting equipment of production scale was established by modification of an existing nonconsumable electrode melting facility. A 1.2 megawatt power capability plasma torch was operated up to a power level of 600 KW and several melts were made using nickel base alloy and titanium alloy scrap. The argon gas plasmarc has been shown to be a useful high heat source for melt-consolidation of super alloy and types of scrap including reactive metal scrap into suitable electrode shapes for subsequent consumable remelting.

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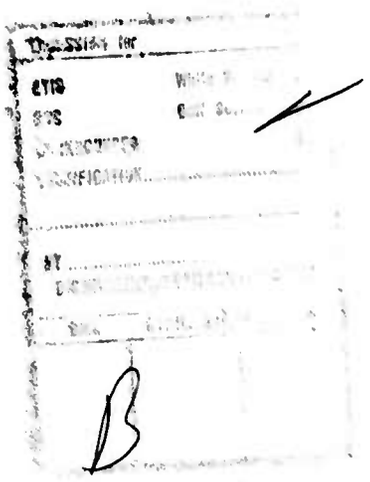
FOREWORD

This final technical report covers work performed under Contract No. F33615-71-C-1681, Project No. 262-1 on the Establishment of a Plasma Melting Manufacturing Process for Production of Nickel-Base Alloys. This contract work was done during the period beginning June 15, 1971 and ending September 30, 1974.

This contract with Carnegie-Mellon Institute of Research, 4400 Fifth Avenue, Pittsburgh, Pennsylvania, 15213, a division of Carnegie-Mellon University, was managed by Dr. G. K. Bhat, Director, Metallurgy and Materials Engineering. The sub-contract work at Schlienger, Inc., 136 Mitchell Boulevard, San Rafael, California, 94903, was done under the direction of Mr. Max Schlienger with Mr. Englebrecht von Tiesenhausen acting as the Project Engineer.

Mr. R. L. Kennard and subsequently Mr. K. L. Love, AFML/LTM, Air Force Materials Laboratory, were the Program Managers assigned to direct the work.

This project was accomplished as a part of the Air Force Manufacturing Methods Program, the primary objectives of which is to implement on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of USAF materials and components.



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1.0 INTRODUCTION

1.1 Background

The aerospace industry and many other services which use superalloys and titanium alloys have been demanding tighter specifications for these materials. This situation places a complex set of restrictions and responsibilities on the manufacturers of these materials. The restrictions pertain mainly to the high quality of starting raw materials, the type and quantity of scrap used, melt processing equipment and refining methods used. The responsibilities concern the quality levels to be achieved, cost control, product performance assurance and guaranteeing the minimum required service life.

To successfully meet the aforementioned challenges, the specialty metals industry is constantly seeking better manufacturing technology. Plasma melting offers certain unique means of refining the molten metal using mixtures of reactive gases, slags and ultra-high temperatures.

A plasmarc torch can be used as an independent heat source for accomplishing several objectives in the specialty metals industry. Plasma heat can be used for primary melting, scrap consolidation, consumable electrode remelting and refining and for alloying the melts with useful gases such as nitrogen. Single or multiple plasma torches may be used as primary heat sources or auxiliary heat sources in melting applications.

Published reports indicate that plasma melting had its early beginnings in the U.S.A. at the various metallurgical facilities of Union Carbide Corporation. The large number of patents held by Union Carbide Corporation bears testimony to the pioneering work done in the design of various types of plasma heat sources and their diversified applications (1,2,3).

Plasmarc primary melting work done at the Linde Division Laboratories of Union Carbide Corporation in 300 lbs. and 2000 lbs. capacity furnaces had indicated the possibility of producing vacuum quality melts of alloy steels, iron-base and nickel-base superalloys and alloys of other non-ferrous metals (4). This work had also demonstrated the feasibility of using various types and quality grades of scrap and other alloying charge materials.

Pursuant to the aforementioned efforts in the U.S.A., there have been reports of intensive and well directed work in the development of plasma heat sources and their application technology in the Soviet Union (5,6), Japan (7,8) and the German Democratic Republic (9,10).

These overseas studies have indicated several novel advantages of plasma melting which include melt-casting of shaped ingots and an opportunity to skillfully blend into a single processing system the advanced technologies of continuous addition and melting of charge materials, molten metal purification, progressive solidification of ingot in water-cooled mold and under inert atmospheric conditions.

1.2 Purpose and Objective

The purpose of this program was to investigate, evaluate and to establish plasma melting as an economically viable production process for melting and casting nickel-base superalloys and titanium alloys capable of meeting the progressively higher performance requirements in materials for Air Force applications.

The specific objectives of the program were:

(a) To establish plasma melting production capability in the United States of America for the production of nickel-base alloys and titanium alloys.

(b) To investigate and evolve optimized designs of plasma primary melting and plasmarc remelting heat sources and system for economically producing superalloys and titanium alloys.

(c) To investigate and evaluate materials produced by plasma induction melting, cold crucible plasma melting, hot wall crucible plasma melting and plasmarc remelting so as to characterize the material and assure a reliable, reproducible process.

This report summarizes the work performed and achievements in the four phases of this Air Force sponsored program.

The Schlienger Company of San Rafael, California, a builder of specialty metal melting equipment, was a major collaborator of this program effort.

In Phase I plasma melted materials were procured from overseas sources and evaluated for the main purpose of process/product characterization.

Phase II was concerned with establishment of a domestic plasma-melting capability of the multi-duty type to conduct plasma melting investigations using various forms of charge materials, remelting and ingot solidification systems. Phase III efforts were directed towards proving out the process itself, equipment modification and optimization of the parameters of viable plasma melting techniques. In Phase IV the plasma melted materials, superalloys and titanium alloys were put through certain fabrication procedures in order to evaluate the hot workability and subsequently the mechanical properties of wrought plasma melted materials.

2.0 PHASE I - CHARACTERIZATION OF PLASMA MELTED SUPERALLOYS

Plasma melted materials needed in this phase were procured from two overseas sources because in 1971 a domestic commercial plasma melting capability was non-existent.

Four basic types of plasma melting were being commercially pursued, two of these types in Japan, the third in the U.S.S.R. and the fourth in the German Democratic Republic. However, not much was known regarding the GDR plasma facility until 1973.

In Japan, the Daido Steel Company had introduced the plasma induction melting process as a specialty alloy melting tool to meet the requirements of producing superior quality (vacuum quality) metal by small foundries, electronic industry and manufacturers of magnetic alloys, resistance alloys.

Also in Japan, the Ulvac Company, a manufacturer of high vacuum equipment, had designed and operated plasma beam furnaces for one-step melting of titanium sponge and alloy aggregates into ingots of various shapes and sizes.

In the Soviet Union, plasmarc consumable remelting had been advanced as a process capable of producing materials, especially titanium alloys, bearing steels, noble metal alloys and high nitrogen stainless steels with overall quality higher than those produced in Soviet vacuum arc remelting furnaces.

The Daido plasma induction furnace was more readily accessible than other overseas plasma melting facilities in order to prepare the materials needed in this phase. Several superalloy heats were made in the Daido plasma induction furnace using different types of scrap of the selected alloys, mixture of scrap and virgin metal charges and all virgin metal charges. These plasma heats were melted in a 600 kg crucible. A Linde design transferred arc plasma torch with thoriated tungsten as cathode and water-cooled copper anode was used. The electrode at the bottom of the induction furnace crucible for arc transfer was made out of graphite. This electrode is emplaced in such a manner as to be not directly in contact with the molten metal. Carbon contamination of molten metal is thus avoided.

The 600 kg Daido plasma induction furnace was coupled with combined power of 200 KW by induction heating and 200 KW by plasma heating. The plasma torch had a maximum current capability of 2300 amps. The amount of argon gas used is a process variable. It is in the range 4 to 7 cubic meters per hour under normal operating conditions when the plasma torch current is around 2000 amps.

Plasma induction furnace melt logs of heats of A-286 alloy and Inconel 718 alloy prepared from a charge consisting of a mixture

of virgin metal and revert mill scrap are given in Table 1 and Table 2. It can be readily seen that in the A-286 heat the titanium recovery was 88%. Metal recovery in the ingot was 94% of all metallics charged in the furnace in the case of A-286 melt and 95.5% in the melt of alloy Inconel 718. Table 3 shows the average recovery of alloy additions made to various alloy compositions produced in the Daido plasma induction furnace.

Casting of plasma induction melted metals at Daido Steel was done by bottom pouring technique as shown in Figure 1. The molten metal during the pouring is protected by an argon shroud. The launder opening is in an enclosed box which is also flushed with argon.

Chemical analyses including gas content of plasma induction melted A-286 alloy evaluated in this phase are given in Table 4. These data show the consistency of achieving a given chemical composition including gas content in plasma induction melted superalloys.

The plasma induction melted A-286 ingot from heat 4131 (Table 4) was forged in a GFM forging machine into 3 inch diameter bar. After cutting out necessary length of material from the 3 inch diameter forged bar, the remainder of this bar was electroslag remelted into 6 inch diameter ingot (heat 1017-05).

Room temperature and elevated temperature tensile test data for plasma induction melted and electroslag remelted A-286 are as given in Table 5. These mechanical property values of plasma induction melted ingot are well within the AMS specification range for A-286 alloy.

Two 600 kg heats of Inconel 718 alloys were melted using 100 percent scrap charge in the Daido plasma induction furnace. The scrap consisted of a variety of rejected components, heavy machining and sheet stamping scrap generated at aircraft engine manufacturing industry.

The Inconel 718 scrap was fully segregated but not otherwise cleaned by a scrap processor. Chemical analyses of the scrap charged in the plasma induction furnace, that of the molten metal prior to tapping, and of the ingot are as given in Table 6.

This melting exercise indicated that a charge comprising 100 percent segregated superalloy scrap generated by the aircraft engine builder can be processed via plasma induction melting into ingots of quality similar to that of the starting or parent material. Furthermore, the melting could be accomplished without encountering significant losses of various alloying elements.

The trace elements were monitored in the scrap charged into the plasma induction furnace and in the resultant ingot product. Comprehensive data of trace elements from these studies are as presented in Table 7. These results indicate that lead and bismuth contents of the scrap were very low, but there was a pickup of these elements in the plasma melted ingot.

It is evident from the data of Table 7 that the contents of Ag, As, Se and Ga are hardly changed by plasma induction melting.

The Inconel 718 bar scrap showed considerable amounts of Zr, La, Ce. However, in the plasma melted ingot, excess amounts of these trace elements were not found.

Vanadium and tungsten contents were rather high in the scrap and their average content remained high in the ingot. Plasma melting thus had little effect in reducing the amounts of these alloying elements in the final alloy composition.

The oxygen content in the plasma induction melted Inconel 718 is around 15 PPM which is considered to be a fairly low value. However, the nitrogen content is over 150 PPM.

The plasma induction melted, bottom poured 8 inch diameter ingots of Inconel 718 were directly forged in a GFM forging machine into 6 inch diameter bars with one end of each bar forged to 4 inch diameter section. An 8 inch section of Inconel 718 ingot from plasma induction melted heat S-5405 was reserved for mechanical property evaluation of cast condition material. Figure 2 shows the surface appearance and the four inch end section of the forged bar. No surface cracks or other defects developed in these bars during forging. Forgeability was judged to be excellent.

Prior to forging, the ingot was homogenized at 2000°F for 1 hour and air cooled. It was reheated to 1950°F and directly forged from 8 inch cross section down to 6 inch and one end further down to 4 inch cross section. A 4 inch slug from the 4 inch diameter end of this bar was cut and subsequently hammer forged into a 3/4 inch thick plate. Mechanical property evaluation specimens were then cut from this plate.

Tensile test and stress rupture test data developed for plasma induction melted and cast and subsequently upset forged Inconel 718 are as given, respectively, in Tables 8 and 9.

The 100 hour stress rupture data for tests conducted in the temperature range 1000°F to 1300°F for the wrought plasma induction melted Inconel 718 is as shown in Figure 3. Thermal stability tests were not conducted on wrought plasma induction melted Inconel 718 because consumable arc remelting is a normal requirement of aircraft engine material specifications. These tests were conducted on plasma drip melted material as reported in a later section.

Another task in Phase I was characterization of plasmarc remelted materials. The only operating plasmarc remelting facility was in the U.S.S.R. A plasmarc remelted ingot of high nitrogen austenitic stainless type steel was obtained from the Soviet Union through ENERGOMASHEXPORT.

A specific reason for examining plasmarc remelted material is to note the unique grain orientation - almost all grains disposed parallel to the ingot axis. Other claims made for plasmarc remelted materials in the Soviet literature included the possibility of alloying melts directly with gaseous nitrogen, rather than through the addition of expensive high nitrogen bearing ferrochromium and the removal of inclusions during remelting in a high pressure, high temperature argon-nitrogen environment.

Information relative to the Soviet plasmarc remelted high nitrogen austenitic nickel-chromium-manganese steel, including its chemical analyses, is provided in Table 10.

This plasma remelted ingot was made through drip melting an electrode and continuous withdrawal of the solidified ingot. Minor surface tears were noted on the ingot surface. The hot top of the ingot was flat. Figures 4a and 4b show photographs of the hot top and surface condition of this ingot.

Ingot sectioning was done as shown schematically in Figure 5.

Chemical analyses checks made of ingot samples indicated rather close conformity with vendor's certified values for each major alloying element.

However, the nitrogen content of the ingot and forged bar samples indicated lower values than that reported in the vendor's certification.

Figure 6 shows the macrostructure seen in the bottom centerline section of this ingot. The grains exhibited a pronounced tendency to run parallel to the ingot axis. This picture provides definitive proof of the uniformity of temperature distribution and flat bottom shape of the molten metal pool formed during plasmarc remelting and ingot solidification.

The ingot section, prior to forging, was lightly surface conditioned to remove all visible cracks and other surface imperfections. The ingot was heated to 2000°F, soaked for 3 hours and subsequently forged in a rotary forging (GFM) machine to 4 inch diameter bar. Macrostructure through a cross section and a longitudinal section of the forged bar are as shown respectively in Figures 7 and 8. A very fine grained structure is observed in Figure 7 and a fiber-like structure in Figure 8.

Mechanical property data of plasmarc remelted high nitrogen chromium-nickel-manganese steel for the cast and wrought condition are as provided respectively in Tables 11 through 14.

This Soviet high nitrogen steel is similar in chemical composition to the Nitronic series marketed by Armco Steel in the U.S.A. The plasmarc remelted material in the cast condition displays good ductility and yield strength comparable to Armco's nitrogen strengthened austenitic steel Nitronic 40.

The Soviet plasmarc remelted steel was judged to be clean. The tiny (less than 2μ size) inclusions were uniformly distributed in the samples from various locations of the rolled bar.

Plasma melted material characterization studies of Phase I provided optimistic conclusions and impetus to establish plasma melting capabilities in the U.S.A.

3.0 PHASE II - ESTABLISHMENT OF A MULTIPURPOSE DOMESTIC PLASMARC MELTING-PRODUCTION CAPABILITY

3.1 Design Considerations of a Multipurpose Plasma Melting System

The first objective in this phase was to arrive at a good understanding of the requirements of a multiduty plasma melting system. Plasma induction melting studies conducted at Daido Steel and an examination of the work done in a Linde design, single torch overhead plasma melting system indicated that crucible refractory contamination of melts was less than that in vacuum induction melts. It is also known that in a cold wall crucible, which is normally used in a non-consumable rotary arc melting system, molten metal contamination is avoided.

The Schlienger pilot scale non-consumable rotary-electrode vacuum melting system had most of the desirable features required to conduct plasma melts. Furthermore, this furnace had an adequate size scrap charging system, a static ingot casting system, consumable electrode feed system and a capability to incorporate an ingot withdrawal system.

This furnace was judged to be the most desirable and readily available facility which could be modified into a multiduty plasma melting furnace. The system conversion was done by lifting out the rotary non-consumable electrode and replacing it with a Linde 1 megawatt capability plasma torch. The plasma torch is gimbal mounted so as to allow for X, Y, Z directional movement. The plasma arc termination spot on the metallic charge in the crucible or on the molten metal pool surface may be changed as desired.

This plasma torch was provided with electrical power from a 600 KVA DC power supply with a rated maximum of 3000 amperes of current through the torch at 200 volts. The argon system was designed to supply argon gas to the plasma torch at flow rates in the range 60 SCF to 1800 SCF per hour.

The power source for plasma torch operation was designed, built and installed by Schlienger, Inc. The available open circuit voltage of this power source permitted plasma torch operation using only argon gas.

Figure 9 shows schematically the primary operating components and the major support features of a plasma melting system assembled for conducting the preliminary plasma melting studies in this program.

3.2 Plasma Melting Trials at Schlienger, Inc.

Preliminary plasma melting studies were conducted in a rugged water-cooled copper crucible of top diameter approximately 24 inches tapering to 20 inches incorporating a bottom contact plug.

Initial heats made in the plasma melting setup were of type 304 stainless steel using bar and billet scrap. These studies showed that even after using the maximum available plasma heat, only the top part of the charge in the skull crucible could be fused. The molten metal permeated through the charge and partially fused some of the solid charge. At some point in the melting process a pool of molten metal approximately 2 to 4 inch depth would form and the solid charge at the bottom of the crucible would remain unfused. The molten metal pool then begins to radiate the heat to the walls and the roof of the furnace chamber.

In subsequent melting trials, the furnace chamber at the top was fully insulated so as to incorporate more heat into the crucible. Inspite of all the steps taken to direct most of the heat into the crucible, the molten metal pool depth could not be increased beyond about 4 inches.

It was reasoned that a higher resistivity charge, such as a superalloy, might melt much easier than stainless steel and create a deeper metal pool. Figure 10 shows the results of three attempts to melt Inconel 718 using a more uniform and easier melting charge consisting of solids, ferroalloys, master alloys and sheet clippings. These efforts clearly indicated that deep molten metal pool could not be created in a cold wall crucible.

The next effort was to drip melt a consumable electrode of Inconel 718 into the 20 inch diameter skull mold (cold wall crucible). In this effort, mechanical difficulties were encountered in the feeding of the consumable electrode. The electrode feed system did not have a variable speed motor which resulted in uneven burn-off of the electrode. A 230 lb. ingot of Inconel 718 thus obtained is shown in Figure 11.

In summary, these melting studies indicated that a full compliment of charge in the cold wall crucible consisting of large chunks of superalloy scrap could not be melted. Also, the charge could not be fed gradually and melted because the plasma torch tip could not be lowered into the crucible. Such a procedure caused plasmarc shorting between the nozzle and crucible side wall.

The next step was to place a superalloy stub in the crucible so as to raise the level of charge to be melted high enough to avoid plasmarc shorting with the crucible side wall. The charge added consisted of Inconel 718 sheet clipping of uniform size. This melting

procedure produced an ingot weighing approximately 600 lbs. as shown in Figure 12. The rough surface condition and unfused but partially welded condition of the charge at the bottom end of the ingot precluded forging of this ingot.

However, this ingot was sectioned using a plasma cutting torch. Additional sections from the plasma cut ingot were made as shown in Figure 13 using an abrasive cut-off wheel.

Various sections of this ingot were used to assess the chemical composition, macrostructure, ingot solidification features and pool shape profile of the plasma melted Inconel 718 alloy in a cold wall crucible.

The first noteworthy feature of this plasma melted ingot was the flatness of the top surface. There was no shrinkage cavity in the 19 inch diameter ingot.

The macrostructure of a vertical section through the center of the plasma melted 19 inch diameter ingot indicated grains oriented parallel to the vertical axis as shown in Figure 14. This solidification pattern explained the absence of a shrinkage cavity in the ingot. The molten metal pool was shallow and its profile was of the shape of a "pie-plate". Examination of the sections of other plasma melted ingots also indicated that the molten metal depth in the cold wall crucible seldom exceeded 3-1/2 inches. The molten metal pool profile of all ingots had a flat bottom.

Chemical analyses reports of at least three plasma melted ingots made in the Schlienger furnace showed remarkable uniformity of chemical composition in the fully fused portion of the entire ingot. A chemical analyses report representative of the scrap used and the resultant 600 pound ingot shown in Figure 12 is given in Table 15. The Inconel 718 ingot produced is virtually of the same chemical composition as the scrap used, indicating almost full recovery of each alloying element. The Inconel 718 scrap used contained Sn, Pb, Bi, As and Sb each in amounts greater than 20 ppm. Analyses of the plasma melted ingot showed that the contents of these individual trace elements had been reduced to values below 5 ppm.

The plasma melts made in the cold wall crucible could not be poured out into the mold in the manner of titanium melts from the same crucible. The plasma melts solidified too rapidly in the cold wall crucible. This experience forced termination of further efforts of plasma melting in a cold wall crucible.

3.3 Hot Wall Crucible Plasma Melting Trials at Schlienger, Inc.

Preparations for hot wall crucible plasma melting were made by fitting a zirconia liner in the water-cooled copper crucible as shown in Figure 15. Zirconia sand was tamped in the annular space between the zirconia liner and the water-cooled copper crucible. The zirconia liner had an opening at the bottom to allow for placement of the arc transfer electrode.

The crucible was charged with a small amount of Inconel 718 sheet clippings [Figure 16(a)]. The plasma torch was lowered as far as possible into the crucible and melting begun. Inconel 718 scrap charge was gradually made as the melting progressed. When a sizeable pool of molten metal was made in the zirconia crucible, it was poured into the mold. The resultant ingot is shown in Figure 16(b). During the pouring of this ingot, a large amount of zirconia sand also fell into the mold. Therefore, this ingot was set aside.

The next melt made in the hot wall crucible was an attempt to prepare a primary alloy melt of Inconel 718. The basic charge used was Inconel 600 alloy and the remainder consisted of ferroalloys and master alloys required to provide the chemical analyses of alloy 718.

Once again, the scrap which settled at the bottom of the crucible remained partially unfused. The top four to five inch layer fused completely. This ingot is shown in Figure 17.

In the next plasma melting trial, sheet clippings of Inconel 718 were used. This melting effort clearly indicated that even in a hot wall crucible it is difficult to produce a deep molten metal pool. Figure 18 shows the plasma melted ingot produced from Inconel 718 clippings.

Plasma melt log for heat 103 is as shown in Table 16-A and that for heat 104 in Table 16-B. These data indicated that when the charge material was large chunks of scrap, the melting was rather slow and the plasma melting power consumption per ton of Inconel 600 scrap was of the order of 1500 KWH. When the scrap was in the form of sheet clippings of Inconel 718, the power consumption for melting per se was 340 KWH per ton. The melting efficiency was at least 60 percent. The total power consumption was in the order of 600 KWH/ton.

An analyses of the plasma melting studies conducted up to this point indicated the following:

(a) Plasma melting for scrap consolidation may be more expensive than rotatrode or Durarc type melting

(b) Plasma heat melting was faster than rotatrode melting -- which could offset some of the higher energy costs

(c) Negligible loss of alloying elements during plasma melting was a distinct advantage

(d) Oxygen analyses of the plasma melted ingot of Inconel 718 was less than 0.003 percent

(e) Small size of molten metal pool created during plasma melting contained seldom more than 300 lbs. of molten metal in a 15 inch diameter hot wall crucible

Thus, the only available avenue for continuation of plasma melting study was to melt in a sleeve mold followed by withdrawal of the ingot as shown schematically in Figure 19. The same ingot casting system could also be applied for plasmarc remelting of consumable electrodes.

Accordingly, the next effort of this program was directed towards modification of the ingot casting system of the Schlienger furnace into a melt-withdrawal arrangement.

3.4 Design, Construction, Installation of an Ingot Withdrawal and Consumable Electrode Feed System in the Schlienger Plasmarc Melting Furnace (Phase III)

An ingot withdrawal system was integrated into the Schlienger non-consumable electrode melting furnace. Other subsystems were also added so as to conduct plasma melts using scrap charge, raw material charge and consumable electrodes.

The crucible sleeve is 14 inches diameter, 20 inches length section of a centrifugally cast chromium-copper alloy. The external jacket providing an annular space for water cooling the copper sleeve is made from non-magnetic stainless steel.

A variable speed DC drive was incorporated into the electrode feed system to enable smooth and continuous control of electrode feed stock for plasma drip melting into the withdrawal mold.

Alterations were made to the scrap material feeding chute to attach an air operated vibratory feeder so as to facilitate feeding scrap or charge material of individual piece size 3/4 inch square to 1-1/2 inches square and length up to 6 inches.

The above modifications of the melting and casting system also necessitated change of plasma torch column length to provide for a longer plasma arc. Previous studies had indicated that side feeding of 8 inch diameter consumable electrodes may require a stable plasmarc length of 12 to 18 inches.

All aforementioned design changes in the Schlienger plasma melting system were completed in April 1973. A new 600 KW plasma torch with a longer arc column length was also designed, specially constructed and installed in the modified plasma melting system.

3.5 Plasma Melting with Ingot Withdrawal

Plasmarc melting and ingot withdrawal systems check out operations commenced in May 1973.

A summary report of these test melts furnished by Schlienger, Inc. is provided in Table 17. A listing of materials furnished to Schlienger for plasma melting is given in Table 18. This list includes Inconel 718 scrap, CP titanium sponge, titanium sponge-6Al-4V alloy mixture, maraging steel scrap for ingot withdrawal system try-out melts, and 6 inch diameter consumable electrodes of Inconel 718 alloy.

The test melts conducted with the new plasma torch, modified crucible and ingot withdrawal system provided the following plasma melt processing information:

(a) Plasma torch ignition conditions

Pilot arc initiation was accomplished using a high frequency arcing device. Argon flow through the torch during pilot arc initiation should be about 5 to 7 S.C.F.M. After the pilot arc is established, the argon flow rate is increased to 15-17 S.C.F.M. The plasma torch is driven down and the arc is transferred. The argon flow is then continually raised to 29 to 30 S.C.F.M. while the current is gradually raised to 2500 amps. This procedure normally takes about 1 to 2 minutes. The voltage drop across the plasmarc settles down in the range 140-160 volts.

A molten metal pool is first established by partial melting of the contact stub attached to the transfer electrode. After the molten metal pool is enlarged to the diameter of the mold, the torch is raised to add either the scrap or other charge material to be melted. In the case of plasma drip melting of consumable electrode, the longest possible stable plasmarc is to be established in order to accommodate largest possible size electrode.

The lengthening of the plasmarc causes the voltage drop to reach the top limit allowed by the power source at which stable current tends to drop. The longest arc column which could be sustained in the Schlienger plasmarc melting system was of the order of 12 to 14 inches. The physical limitations imposed by plasma arc length and the angle of consumable electrode entry above the mold in this case limited the electrode size to an absolute maximum of 6 inch diameter.

(b) Plasma torch operating features

Plasma torch operating parameters which provided for high efficiency and extremely fast scrap melt rates were from 145 to 165 volts and current up to 2500 amperes with argon flow rates in the range 20 to 30 S.C.F.M.

(c) Electrode feeding

The rotating drum type feeder worked in a highly satisfactory manner for feeding scrap and other charge material in the form of briquettes, nodules, granules, sponge and uniformly sized chunks.

However, while using this feeder for feeding of consumable electrodes, difficulty in advancing the electrode at a uniform rate was experienced. This difficulty was responsible for interruption of several consumable electrode plasma melts.

(d) Ingot withdrawal

Withdrawal of plasma melted ingot from the sleeve mold was accomplished without unusual difficulties, as long as a good molten metal pool was created at the start of each melt. So long as the metal pool on top of the solidified ingot remained completely molten, no ingot withdrawal problems were encountered. Operator care was required to ensure adequate dwell time for large chunks of charge materials to become completely molten prior to ingot withdrawal or introduction of additional charge material into the crucible.

3.6 Plasma Melting of Inconel 718 Scrap into 14 Inch Diameter Ingots

The first withdrawal melted 14 inch diameter ingot of Inconel 718 from a charge consisting of sheet clippings was plasma melted at Schlienger, Inc. during the first week of June 1974. This production size melting operation was accomplished with ease. Plasma melt logs of this heat are provided in Table 19. A photograph of this ingot is shown in Figure 20.

It became clear from this and previous experimental melts made from maraging steel scrap that the chances of obtaining a completely fused, smooth surface ingot through intermittent charging of scrap directly into the molten metal pool are not good.

The plasma melted maraging steel ingots shown in Figure 21 further indicated that despite the faster melt rates achieved with plasma heat, the larger chunks of scrap remained partially unfused.

The Inconel 718 ingot produced above was sectioned in order to observe the extent of melting which had occurred. In the center zone of the ingot melting appeared to be complete. At the periphery of the ingot the molten metal had squeezed out, thus welding the unfused scrap charged into the molten metal pool.

Chemical analyses check of the fully fused ingot (Table 20) showed negligible or no change in the chemical composition between the ingot and the scrap charged. Any dirt, grease or oxide films on the scrap seemingly had not affected the chemical composition. Microscopic analysis of the fused metal showed no unusual concentration of inclusions.

The Inconel 718 scrap consolidated ingots made in the Schlienger withdrawal unit supported their own weight. One of these ingots was electroslag remelted. The scrap consolidated ingot carried the full compliment of current to the molten slag bath during electroslag remelting. The remelting operation into a 16 inch diameter mold proceeded without any difficulty. The remelted ingot thus produced had the capability to meet even the most stringent aircraft specification requirements. This is evident from mechanical test data presented in Table 21 for both cast condition and wrought condition Inconel 718 from the aforementioned experimental melt.

3.7 Plasma Drip Melting of Consumable Electrodes in the Schlienger Plasma Melting System

Plasma drip melting of consumable electrodes in the Schlienger plasma melting system commenced in June 1974.

The types of consumable electrodes which were plasma drip melted as a part of this project effort included Inconel 718 alloy, C.P. titanium, titanium-6Al-4V alloy. After completion of this project effort, other materials, such as zirconium alloys, copper alloys, were also successfully remelted using this plasmarc melting system.

The Inconel 718 alloy electrodes were prepared from two special heats, one made in the Daido Steel's plasma induction furnace and the other in a 2000 pound vacuum induction furnace. The charge in these two primary melting furnaces was mostly Inconel 718 bundled sheet scrap. The final melt composition was corrected to the desired analysis through additions of vacuum melt quality charge materials.

The electrodes supplied by both producers were too large for direct use in the Schlienger plasma melting system. Therefore, these electrodes were forged down to 6 inch diameter bars in a GFM rotary forging machine.

It should be mentioned here that this type of electrode preparation was necessitated by equipment limitations and not due to plasma melting process limitations. This matter is further discussed in a later section of this report.

The melt record of the first 750 pound plasma drip melted Inconel 718 is given in Table 22. This melt log readily shows that plasma drip melting of this electrode did not proceed smoothly or continuously. The ingot cast, shown in Figure 22(a), has rough surface appearance as well as folds and surface laps of the kind shown in Figure 22(b).

Plasma drip melting logs for subsequent two Inconel 718 withdrawal melted ingots are given in Tables 23 and 24. Serious difficulties had been encountered with proper functioning of the plasma torch, the electrode feed mechanism and the ingot withdrawal system. Therefore, process interruptions have occurred frequently during plasma drip melting of almost all electrodes.

It became clear that a six inch diameter consumable electrode is too large for the present design of the Schlienger plasma melting system.

The plasma heat could not be evenly distributed simultaneously on the advancing electrode as well as the molten pool surface in the sleeve mold.

3.8 Metallurgical and Mechanical Property Evaluation of Plasma Melted Superalloy and Titanium Ingots (Phase IV)

The plasma drip melted Inconel 718 ingots which exhibited most satisfactory surface condition were sent to the forge shop. An attempt was made to forge these ingots down to a size suitable for cutting and handling.

Unfortunately, both ingots developed severe cracks at melt interruption locations, as shown in Figure 23.

The distorted section of the forged ingot shown in Figure 23 indicates laminated solidification condition where the drip melted ingot is welded to the withdrawal pad.

This problem was rectified in subsequent ingots as the operators developed the necessary skills and starting pads of proper design were attached to the withdrawal ram.

The top section of the plasma drip melted Inconel 718 ingot shown in the rear of Figure 23 was severed from the ingot. It was in a condition satisfactory to be forged down to approximately 1-1/4 inch thick plate section as shown in Figure 24(a).

Various types of test specimens were extracted from this forged plate as indicated schematically in Figure 24(b).

Chemical analyses data of samples from the forged plasma drip melted Inconel 718 and that of the parent electrode are given in Table 25 . The correspondence between the compositions of the parent electrode and the plasma drip melted ingot is excellent.

There appears to be some indication of removal of certain trace elements. These trace elements are Sn, Pb, Bi, As and Sb.

Macrostructural examination of two sections from the forged plasma drip melted Inconel 718 indicated exceptionally clean material devoid of freckles or other ingot solidification problems. Macrostructural photographs of these specimens are displayed in Figure 25.

Mechanical test data developed for forged plasma drip melted Inconel 718 are provided in Table 26 and also in Figure 26.

Time and material were insufficient to generate fracture toughness and crack propagation test results representative of the plasma drip melted Inconel 718.

The other plasma drip melted ingots were evaluated to study only the chemical homogeneity and macrostructural features.

One of these plasma drip melted Inconel 718 ingots was sectioned through the diameter so as to obtain approximately 10 inch long sections representing the ingot bottom and top. These segments were further split along the vertical axis through the center of the ingot. Figure 27 shows vertical macrostructure from the bottom segment and Figure 28 displays vertical macrostructure from the top segment.

The important observation to be made is the unidirectional orientation of grains in the ingot throughout its entire length. Melt interruption is clearly visible including evidence of a "pie-plate" shaped shallow molten metal pool. Chemical analysis samples taken from the various ingot locations shown in Figure 29 provides an evaluation regarding the uniformity of chemical composition as shown in Table 27.

Of particular significance is the unidirectional, axial growth of the grains in the entire cross section of the 14 inch diameter ingot. At the chilled surface of the ingot which was in direct contact with the water-cooled copper mold, there are some smaller size grains with curved orientation. Except for this region, grains in all other parts of the ingot appear to be oriented markedly parallel to the ingot axis.

Macrostructural features of plasma drip melted C.P. titanium ingot are shown in Figure 30. Incomplete melting of the sponge at the very bottom of the ingot is observed. This problem was rectified in ingots melted subsequently by allowing additional time at the beginning of the melt in order to form a deeper molten metal pool prior to feeding sponge.

The surface and hot-top features of the plasma drip melted titanium-6Al-4V alloy 14 inch diameter ingot may be seen in Figure 31. A titanium stub was not readily available. Instead a steel stub was used which accounts for the blue color of this ingot and contamination of the melt by iron.

3.9 Plasma Melting Process Economics Projection

This program was expected to generate process economics of production scale plasma melting. Unfortunately, the plasma melting work performed at Schlienger, Inc., turned out to be of preliminary nature.

The program studies and plasma melting equipment performance indicated the necessity for further major improvements in the mode of plasma heat application and the method of feeding the consumable electrode. Full scale plasmarc remelting of superalloy and titanium alloy electrodes could not be achieved without melt interruptions. Therefore, meaningful cost data could not be obtained from the program studies. However, from the several pilot scale plasmarc melting and plasmarc remelting studies

conducted at Schlienger, Inc., guidelines for cost estimation of plasma melting processes have been developed. These process economics guidelines are as follows:

(a) Plasma torch and power source acquisition costs have to be amortized over at least a ten-year period. Therefore, the designs of both should be rugged and their initial acquisition costs should not exceed those of a non-consumable electrode and its electrical power system.

(b) Replaceable parts of the plasma torch are the back-electrode and the nozzle. These should provide a minimum life time of 100 hours.

(c) Power Source - The total power requirements for the torch and the operation of all other electrical equipment in the plasma melting system is estimated from the present program studies to be in the range 1200 KW to 1500 KW per operating hour. These estimates are within acceptable range compared to highly developed non-consumable electrode melting systems. Nonetheless, further attempts should be made to reduce electrical power requirements of plasma melting systems through the use of smaller size multiple torches.

(d) Gas Consumption - Normal flow rate of argon gas through a one megawatt size plasma torch is the range 1200 S.C.F.H. The volume of gas used in the furnace chamber, feed chamber, sight ports would be an additional 80 S.C.F.H. This high rate of argon gas consumption indicates the need for reclamation, purification, and recycling of the gas so as to reduce the cost of consumables.

(e) The production rate of the plasmarc remelting system is limited only by the rate of solidification of molten metal in an ingot mold of given shape and size. Therefore, casting of shaped ingots, such as slabs, squares, hollows would lead to higher process economics.

(f) The utilization of plasma heat radiated from molten metal pool in an ingot casting system to heat up the charge will lead to better process economics.

(g) Single torch plasmarc furnace operation has indicated problems of heat control in the molten metal pool and uniform melting of electrode. There is a need to evaluate multi-torch plasmarc melting systems. The latter type of systems may be more efficient and thus accelerate the evolution of larger plasmarc melting and remelting systems for specialty metals.

4.0 PLASMARC MELTING PROCESS PARAMETRIC STUDIES

4.1 Plasmarc Torches

Engineering use of arc-jet devices or plasma torches for heating gases to high temperatures dates back to the beginning of the present century.

The development of the first melting type plasma torches in the United States of America may be credited to Union Carbide Corporation. Plasma melting furnaces developed at various facilities of Union Carbide used plasma torches as direct burners or heat sources.

Because arc plasma generating equipment is thought to have considerable proprietary interest, the technical literature pertaining to this subject is usually guarded.

Little information on the engineering designs of industrial size plasma torches, plasma torch operational parameters, their performance capabilities and commercial application aspects appear in the technical literature. However, a recent report generated in the Soviet Union (12) provides some insight into plasma process in metallurgy limited to small-scale devices.

The chief advantages of arc plasma generators in materials processing over combustion torches are the extremely high temperatures produced, capability of process operation under inert or reactive atmospheres and in a variety of high and low pressure conditions.

The arc established by a plasma torch is a high pressure electric arc between an electrode housed in the plasma torch and a workpiece which is placed at a distance away from the torch. The plasma torch and the workpiece are connected to the same power source as shown schematically in Figure 32.

Plasma arcs are different from ordinary electric arcs in that the mass flow of gas through forced convection in the arc chamber represents an independent parameter for heat generation. Substantial ionization of the gas fed into the plasma device begins at temperatures 2000 to 3000°K. At about 5000°K, the ionized gas becomes an electrical conductor. As the temperature is raised to 10,000°K and above, the degree of ionization achieved is such that the plasma becomes an electrical conductor like metals capable of transporting large amounts of current.

In contrast to metals, plasma behaves like a compressible fluid. Thus, the plasma obeys the laws of electromagnetic principles as well as those of fluid mechanics.

The arc plasma in a plasma device is maintained by thermal ionization of the gas.

Energy dissipation occurs thourgh the flow of electricity between two electrodes. Self-induced magnetic fields produced by the high currents in the arc compress the plasma. These fields cause radial and axial pressure gradients in the arc. The axial gradient leads to plasma effluent which transports heat between the electrodes.

The hot gas stream from the plasmajet may take part in a reaction or it may act as a pure heat source. An inert gas such as argon or helium is used as a source of heat. Chemically reactive plasmas using nitrogen, hydrogen, carbon dioxide, propane, methane introduce reactive species in the plasma system.

Commercial use of plasmajets came after Gage (13) had developed the constricted arc torch. In a gas stabilized arc, all or part of the arc column is contained in a nozzle or chamber as shown in Figure 32. The flowing gas medium passes through the arc discharge, absorbing a significant portion of the input energy. The jet or plasma gas exits through the chamber orifice or nozzle. Plasmajets produced in different ways have different efficiencies with respect to conversion of input power into heat. Hence, it is important to select a design which provides high efficiency of energy conversion.

In the transferred arc plasmajet, the arc does not end at the nozzle but continues on to the workpiece. The workpiece is connected to the power source as shown in Figure 32. Resistance heating of the extended arc as it strikes the workpiece furnishes about 2/3 of the heat produced.

4.2 Establishing a Directionally Stabilized Plasmarc

A quasi-electrode is installed between a non-consumable electrode and the crucible or another electrode. An arc is struck between the quasi-electrode and the main torch electrode. The arc is surrounded by an annular gas stream. A portion of this gas stream is directed into a cold wall nozzle which then acts as an arc stabilizer. The ionization of a portion of the gas then provides an extremely stable arc path.

Various types of gases differ widely in their capability to dissipate electrical energy as heat energy in the plasmarc. The energy of dissociation and the energy of ionization of a given gas determine the voltage drop across a given length of plasmarc at a given temperature.

In plasmarc, the arc is shrouded. It has a certain rigidity compared to the unshielded arc as in vacuum arc remelting. It is not extinguished by any magnetic field formed, nor is it deflected by the effects of the movement of cathodic and anodic spots.

In comparision to the arc formed by non-consumable electrode, plasmarc can be longer and therefore the spattering of the melted metal onto the electrode may be restricted. If the non-consumable electrode is made of tungsten, contamination of the melted metal by tungsten is minimized through specialized nozzle designs.

The gas flowing through the nozzle becomes united with the arc so that the profile of the effluent can be shaped by changing the geometry of the nozzle.

In the plasmarc, the voltage can be raised by lengthening the arc, while the current is maintained at a constant level. The electrical power can be increased in this fashion. As a result, high heat flux per unit surface area of the plasma flame is obtained along with marked increase in the flame temperature. It is estimated by many researchers that using argon, plasma flame temperatures in excess of 10,000°C may be obtained.

4.3 Influence of Plasma Torch Operating Parameters on the Thermal Characteristic of the Plasmarc

The gas is heated by the energy released in the arc column.

When the arc current is increased, the temperature and the power transmitted through the gas increase within certain ranges of current adjustment. The efficiency is unaffected.

As the length of the arc increases, the temperature and power of the gas increase. The heating efficiency reaches a maximum. After this maximum is reached, the efficiency decreases because the power of the arc is wasted in the nozzle cooling water.

The gas flow rate controls the mean mass temperature of the plasma effluent.

In the heating of a charge in a crucible, the plasmajet acts as a local surface heat exchange source. The energy of the plasmarc is transmitted to the heated body as a result of induced, convective and radiative heat exchange.

In a plasma torch of the transferred arc type, the electrode must be efficiently cooled. The constriction necessary to stabilize the arc and to attain high temperatures is achieved by

surrounding the arc with cold walls capable of withstanding high heat flux and/or surrounding the arc with a cold liquid or gas. The gas is forced to flow into the arc to form the thermal plasma.

4.4 Plasma Melting Studies

Plasmarc melting may be defined as melting and refining in furnaces using directionally stable and directionally controllable electric arcs. The phrase "directionally controllable" is used to describe an electric arc column in which the longitudinal axis coincides with the direction of current flow.

Power dissipation in such "stiff" arc column is controllable to provide a variable voltage drop across the arc. Thus, power input can be varied at constant current levels. The melt rates can be correspondingly increased or lowered by varying voltage drop.

At Schlienger, Inc., the production scale plasma primary melting and plasma drip melting work of this program was done under an argon atmosphere at slight positive pressure.

The argon operation of plasma melting was dictated by the characteristics of the available power source rather than any other process limitations.

Since it was not possible to conduct some of the planned studies of process plasma melting parameters at Schlienger, Inc., a sub-scale plasma melting facility was assembled and operated in order to generate information regarding torch operation using a variety of gases and mixtures of gases.

The sub-scale plasma torch operating and melting setup designed, built and operated for the above purpose is as shown in Figure 34. This system consisted of the following accessories:

1. A dish-shaped water-cooled copper crucible with attached bottom electrode.

2. A water-cooled shell and a water-cooled top cover.

3. A Linde type MAT-9B plasma torch riding on a slide.

4. Plasma torch coupled to a 300 KVA AC-DC power source.

5. A gas dispensing system for obtaining flow rates in the range 1 S.C.F.M. to 12 S.C.F.M.

6. A high pressure (200 psi) torch cooling water pumping system.

The current capabilities of the power source for DC operation was 800 amps at 380 volts and for AC operation 1000 amps at 300 volts.

The current voltage characteristics of the Linde type MAT-9B torch using different plasma gases are as indicated in Figure 35.

During operation of the plasma torch with argon, high stability of the plasmarc was achieved at current inputs above 400 amps. When arc current is increased, the temperature and power of the gas both increase. Nozzle erosion increases as the current input is increased at constant arc column length using argon gas.

The 90 argon, 10 hydrogen mixed gas provided high stability of the plasmarc at current inputs above 600 amps. As the amount of hydrogen mixed with argon is increased, the voltage and amperage characteristics tend to assume an approximate straight line relationship.

Power input with 80 argon 20 hydrogen gas mixture can be varied by increasing or decreasing either the voltage or the current.

Studies of plasmarc voltage variation as a function of flow rate of different gases have been conducted. Data of these studies are summarized in Figure 36. These data indicate that plasma torch power source requirements, especially the operating voltage, increase drastically when small amounts of hydrogen are mixed with argon in the torch gas.

The curves in Figure 36 further indicate that except in the case of pure argon, increase of torch gas flow causes a rise in arc voltage and the total power dissipated in the plasmarc.

The effect of increase in argon gas flow in the torch at first raises the voltage and power, but this voltage rise levels off quickly. Too high flow rate of argon causes instability in arc voltage and flaring of the plasma effluent upon impingement on the charge or the transfer electrode.

Several attempts were made to operate the sub-scale plasma torch using AC power. However, serious difficulties were encountered in transferring the plasmarc. The arc was deflected to the furnace shell because of magnetic field effects generated in the narrow section of the furnace shell. This problem could not be readily corrected prior to termination of the technical efforts planned in the current program.

4.5 Miscellaneous Plasma Melting Studies

The hot-wall plasma melting furnace can be used for recycling certain non-ferrous scrap, for example, aluminum, aluminum alloys, high conductivity copper, copper alloy, nickel and nickel alloys.

The copper skull crucible in the Schllenger production scale plasma furnace was lined with a high alumina castable refractory to a thickness of about 2 inches at the bottom allowing for an opening for the transfer electrode and 1 inch thick at the top. Aluminum scrap was gradually charged and an ingot of 128 pounds was cast after about 35 minutes of melting at 500 KW. This weight represented a ratio of about 0.95 of cast to melted metal.

Plasma melting of copper in the hot-wall crucible was also done using various forms of copper scrap. It was noted that copper melted quite rapidly and a casting of 300 pounds was made. The plasma melted copper exhibited the electrical conductivity characteristics similar to that of high conductivity copper produced by other techniques.

It was apparent from the above studies that relatively high power efficiencies could be obtained in plasma melting a variety of non-ferrous metals and alloys.

4.6 Reduction of Metal Oxides

Plasma reduction of chromium oxide was done using a mixed gas consisting of argon and methane and a layer of special slag cover on the melt. This experiment was conducted as follows:

Charge - Armco iron - 10 lbs.

Cr_2O_3 - 8 lbs.

Slag - 2 lbs. made up of $CaF_2/CaO/SiO_2$

Current - 530 amps

Voltage - 130 Volts

Gas Mixture - 100 CFH argon + 15 CFH methane

The Armco iron charge was first melted using argon plasma heat. The chromium oxide was then charged on top of the molten iron followed by the slag. Methane was introduced into the argon plasma gas. At the end of 50 minutes the melt was cooled and the resultant alloy analyzed for chromium enrichment. The alloy contained 2.3 percent chromium and the carbon content of the alloy was less than 50 ppm.

This experiment indicated the possibility of metal oxide reduction during plasma melting through the use of reducing gases.

5.0 FEATURES AND SPECIFICATIONS OF A PRODUCTION SIZE PLASMARC MELTING FURNACE SYSTEM

In the design of a plasmarc melting furnace, certain variables have to be initially defined. These are as follows:

1. Size of ingot to be made
2. Type and size of feed material
3. Method of ingot production -
   (a) Withdrawal
   (b) Casting

In order to give as wide an applicability as possible, this design report will cover a furnace set up to melt 14 inch diameter ingots by the withdrawal method with some remarks about means of readily converting to the casting type method of ingot production. Experience has shown, however, that the latter method is feasible only with a refractory lined crucible.

The feeding system will also be of the convertible type capable of utilizing scrap and/or virgin materials up to 4" square and also readily convertible to drip melting 6" diameter electrodes.

5.1 Melting and Feeding Chamber

The melting chamber consists of a double walled, water-cooled enclosure 7' in outside diameter, not including extensive external bracing required to make the assembly structurally sound. The melting chamber itself is integrally attached to the material feeding chamber which is of the same diameter but not water cooled. One end of the melting chamber consists of a water-cooled, dished head while the other end of the melting chamber again consists of a water-cooled, dished head, but includes an opening to enable the feeding mechanisms to enter the chamber through an appropriate cooling shield. The bottom of the melting chamber is designed to mate with the removable withdrawal and/or casting chamber.

The melting chamber also includes the following features:

(a) A large water-cooled track-mounted door assembly which can carry the casting crucible and water jacket and associated tilting mechanism. The door assembly is round in shape and when the door is retracted from

the furnace chamber, it allows ample space for a man to walk into the furnace chamber erect for cleanout and maintenance.

Although the chamber is cylindrical in shape, there is sufficient flat floor space within the enclosure to enable solid footing for workers.

(b) Plasma torch mounting flange. The plasma torch mounting flange is also water cooled and permits mounting of the plasma torch in a vertical position.

(c) Casting chamber mounting flange. Directly below the electrode mounting flange is the mounting flange for the casting and/or withdrawal chamber which is designed to enable the adaptation of a variety of casting modes to the basic melting chamber. This opening is positioned to enable static casting or withdrawal melting.

(d) Viewing ports. Auxiliary viewing ports are provided to enable monitoring of melt conditions at strategic locations other than that permitted by the optical viewing system.

(e) Vacuum and blowout port. The vacuum port is located in a position where it will see the minimum in radiated heat and condensible vapor from the melt. This is in a quadrant below the top lip of the melting crucible.

The blowout port is located in the end head of the melting chamber facing the exterior (blowout pit) of the building.

(f) Feeding chamber. The feeding chamber consists of a cylindrical tank 8' in diameter by 133" in length. As stated above, this chamber is a continuation of the melting chamber with a water-cooled bulkhead separating the two. At a position approximately 120" from the centerline of the crucible at the top of the chamber is located a 36" diameter nozzle upon which the secondary feeding mechanism mounts. This assembly is also heavily ribbed on the outside to withstand not only the extreme forces under vacuum melting conditions, but also to maintain an internal pressure to 65 psi.

(g) The primary feeder consists of a rotary drum which can be positioned longitudinally over a distance of 60". Aside from the longitudinal and rotary movement imparted to the feeding mechanisms, it can also be inclined in a variety of positions to various feeding

parameters. When in the feeding position, a heavy chute at the rear extremity of the feeder can receive material continuously from the secondary feeder to provide a continuous supply of material to the crucible. During periods when the secondary feeder is being recharged, the speed of the primary feeder can be altered to provide continuous material supply or the speed of the secondary feeder can be increased prior to emptying to supply a surge capacity sufficient to cover the time needed for the reloading cycle.

(h) Access door. The access door to the feeding chamber allows entry into the chamber for cleanout, maintenance or unplugging of the feeder nozzle, should such a problem occur. This door is also of sufficient size to permit complete removal of the primary feeder through the opening. The door is rectangular in shape and is held closed by ten heavy-duty swing clamps. In the event it is desired to drip melt electrodes, these can be loaded directly into the primary feeder by opening the access door and inserting an eight inch diameter pipe into the primary feeder. This pipe is bolted directly to the nozzle flange. The electrodes to be melted are then inserted in the same manner. Rotation of the primary feeder then causes the electrodes to advance slowly into the melting chamber.

5.2 Secondary Feeder

The secondary feeder shall consist of a chamber of sufficient capacity to contain a feeding can 20" in diameter by 10' in length. This can is placed in the chamber in an inclined position in such a manner so that when it is rotated, material is fed from its open end into a bell valve housing which directs the material through a funnel to the primary feeder.

The features of this equipment are as follows:

(a) Rotary drive. The rotary drive which permits feeding of material from the can to the primary feeder is coupled to an appropriate speed reduction mechanism powered by a variable speed DC motor. Complete rotational speed control is enabled with this equipment and adjustment is controlled from the furnace control panel.

(b) Isolation valve. To enable reloading operations while the furnace is melting, a plunger type isolation valve is provided at the feeding end of the chamber. This valve seals directly on the feeding chute and functions well even though the surface may be quite rough and dirty. Actuation is by an air cylinder.

(c) The secondary feeder can be loaded through a small end flange which incorporates the rotary drive for the feed can. The feeding cans can be pre-filled and stored in either a horizontal or vertical position and are satisfactory for feeding a wide variety of material.

5.3 Casting Chamber

The casting chamber shall be fastened by clamping to the bottom flange of the melting chamber and consists of a cylindrical vessel having sufficient diameter and length to accommodate ingot molds or an ingot withdrawal mechanism.

(a) The withdrawal mechanism consists of a hydraulic cylinder which is bolted to the outside of the casting chamber. The cylinder rod enters the casting chamber through a set of vacuum seals and scraper rings. A water-cooled plug is mounted to the cylinder rod. This plug is designed to allow insertion of an ingot stub of the same alloy as the one to be melted. The ground connection is also made through the withdrawal ram.

5.4 Crucible Assembly

Option A - Withdrawal

The crucible assembly is a one-piece forged or cast copper sleeve.

The water jacket is of stainless steel construction and incorporates accommodations for a stirring coil within the jacket assembly. The whole assembly is mounted on a structural frame within the furnace structure.

Option B - Casting

(a) The crucible is a one-piece welded or cast copper structure. The crucible incorporates a bottom contact plug to insure proper grounding of the skull. Grounding is accomplished using a 4" block of the material to be melted. The crucible is 22" OD and 20" in depth tapering to a bottom diameter of 20".

(b) Water jacket. The water jacket is of stainless steel construction and incorporates accommodations for a stirring coil within the jacket assembly. If a high flux density coil is required, the need for a larger diameter water jacket may be necessary. It is not advisable to place a coil on the outside of the jacket on a casting crucible due to the presence of metal splatter and radiation. The water jacket is mounted on a single trunion to enable easy removal of the assembly from the furnace for cleaning and maintenance.

Power input to the crucible is through the mounting flange.

5.5 Torch Drive

(a) The drive is mounted on a Universal quill slip which consists of a vacuum ball joint held in an appropriate water-cooled housing or socket. The quill slip or ball joint is positioned by two hydraulic cylinders which permit X & Y location of the equipment mounted on the quill slip flange.

(b) Mounting flange for the quill slip consists of an elongated cover plate which makes a vacuum seal with the top opening in the melt chamber, located in a position to enable vertical mounting of the electrode drive mechanism.

(c) The actuating mechanism for the electrode drive is mounted to the top flange on the quill slip. This mechanism consists of a servo controlled cylinder anchored at rod end to the mounting plate and at the cylinder base to the electrode mounting flange. The electrode mounting flange also is located by a set of guide tracks to enable alignment and act further as a torque arm for the cylinder mounted electrode mounting flange. The assembly as above described allows a vertical movement of 48" which

coupled with a full 15° X & Y movement allows for complete coverage of crucible with sufficient stroke for clearance of the crucible and water jacket during pouring operations.

(d) Other features:

(1) The X & Y cylinders are of large diameter to permit precise control of position in a smooth manner.

(2) All parts of the mechanism subject to splatter, condensate and radiation from the crucible are shielded for maximum protection.

(3) The Universal quill slip can handle an electrode structure to 9" OD with the appropriate shielding for the same.

(4) Insulation. The electrode drive assembly is insulated to enable operation with operating voltages of 500 V DC. All hydraulic lines and other attached controls are electrically isolated.

5.6 Miscellaneous Equipment

(a) Argon supply. Due to the rather large consumption of argon during plasma melting, a bulk type liquid argon storage tank should be installed. Using torches up to one megawatt a facility supplying argon at pressures up to 200 lbs. and flow rates of 2500 S.C.F.H. is fully adequate. These systems are available on a rental basis.

(b) Hydraulic system. The hydraulic unit should be capable of a pressure of 2000 psi and flow rates of up to 15 GPM.

The hydraulic unit has the following interlocks with corresponding indicators on the control panel.

1. Oil level
2. Oil pressure (for each critical circuit)
3. Oil temperature
4. Water

Water flow to the heat exchanger is not interlocked as this valve is modulated by oil temperature and since

the oil reservoir has a sufficiently high capacity and cooling surface, no cooling water flow is required for the hydraulic system for long periods of time, especially when cold weather is encountered.

(c) Water requirements. Minimum plant water requirements would be as follows:

1.	Power supplies	80 GPM
2.	Vacuum pumps	8 GPM
3.	Hydraulic system	10 GPM
4.	Bus bar	6 GPM
5.	Plasmarc cooling system	150 GPM
6.	Furnace chamber	85 GPM
7.	Crucible cooling	130 GPM
8.	Casting chamber	50 GPM
9.	Spare	5 GPM

The water manifold consists of an open sight bosh with individual return lines for each water-cooled circuit. Flow switches and shutoff valves are also incorporated in the bosh assembly. All flow switches have readout indicators on the control panel.

Closed circuit water system. The closed circuit water system is for torch cooling only. It should include the following:

1. 500 gallon stainless steel storage tank
2. Pump rated at 200 PSI at 150 GPM
3. 1,000,000 BTU/hr. tube type heat exchanger
4. 20 micron 150 gallons/minute stainless steel water filter
5. Interlocks
   a. Pressure set at 200 PSI
   b. Flow set at 80 gallons/minute
   c. Water level
   d. Water temperatures set at 55°C
6. Argon cover gas system
7. Steel frame and base
8. All piping, valves and fittings necessary to enable adequate operation of the system. All pipe, fittings and valves are to be either copper or brass.

5.7 Vacuum System

(a) The vacuum system shall consist of two Stokes Model 1724 mechanical booster pumps arranged with a vacuum manifold

to enable both pumps to pump down the basic furnace chamber and feeding chamber during initial pump down cycle. Included with the vacuum system is the following equipment:

1. Two model 1724 Stokes Vacuum Pumps
2. Filters:
   a. Main line filter connected to vacuum line from melting chamber
   b. Fiberglass throw-away filters located in mold chamber and material feed chamber
   c. Fiberglass filter located in vacuum line to secondary material feeder
3. Valves. All valves are to be air actuated butterfly type valves. Valving shall permit isolation of each pump from the vacuum system and also enable interchangeability whereas one pump can carry out all functions of the entire system if necessary.
4. Piping. Piping shall be a schedule 40 steel pipe with flange and "O" ring joints as required to allow disassembling and cleaning. Dresser slip-on pipe flanges may be used where appropriate.
5. Pressure control system. When operating under pressure control mode, the bypass valve on the main vacuum line will be modulated to keep the furnace pressure within preset limits.
6. Breaker panel. A breaker panel is provided for all auxiliary equipment as follows:
   a. Closed circuit water system
   b. Hydraulic system
   c. Vacuum system
   d. Controls
   e. Secondary feeder drive
   f. Stirring coil power supply

5.8 Controls

The controls are broken into the following functions:

(a) 4-pen TI recorder for recording of voltage, amperage, electrode position and pressure.

(b) Remote power supply panel including individual manual power supply controls, SCR, failure circuits and indication of all other power supply interlock systems.

(c) Data Trak. Room is allotted in the auxiliary control panel for addition of a data trak programmer for electrode positioning if this option is desired.

(d) Argon controls. Argon controls are included on a panel containing flow meter, control valves and pressure interlocks for setting of argon supply as required for melting operations.

(e) Water interlock panel. All cooling water interlocks displayed on one panel with each circuit indicated green when flow is correct and red under restricted or no-flow conditions.

(f) Crucible and electrode control panel. This panel includes the following:
1. Crucible tilt meter
2. Crucible tilt control
3. Electrode X-Y control
4. Electrode position indicator (vertical)

(g) Power controls. The power control panel includes the following equipment:
1. All units on off
2. Current set level under automatic mode
3. Totalizing ammeter
4. Voltage meter

(h) Torch control panel. The torch control panel includes a voltage type controller with reference voltage set, mode selection switch, servo amplifier, servo amplifier output meter, reference voltage meter and error voltage meter. Also included is an emergency stop. The mode switch has the following settings: "Automatic", "Position", "Manual" and "Off."

(i) Torch functions and hydraulic panel. This panel includes control of the hydraulic pump and indicates all hydraulic interlocks in the same manner as the water interlock panel. Also included on this panel are the controls for the closed circuit water system and the control for the torch and its associated interlocks.

(j) Vacuum map. The vacuum panel includes a schematic layout of the vacuum system, a gauge for operating in the 0 to 1000 torr range. Start and stop of vacuum pumps and actuation of valves is also included in this panel.

(k) Feeder controls. The feeding control panel shall include controls for both the primary and secondary

feeder. This panel will consist of a separate box mounted on the main control panel and shall include the following:

1. Primary feeder location readout
2. Primary feeder position control
3. Primary feeder rotational control
4. Primary feeder inclinator control
5. Secondary feeder rotational control
6. "On-Off" switch for each feeder control system

5.9 Optical System

Optical system is designed to furnish as close as possible a full size image of the melt zone. The optics are placed in a position which enables observation of melting and feeding. This geometry permits the optimum in viewing with a single lens system for maximum clarity and relationship of all components of the melting system. The optical system can also be arranged in other configurations and, if necessary, a split lens system can be incorporated. Final selection of lenses and location of the viewing screen from the operator's pulpit is determined by the final furnace layout.

5.10 Plasma Torch Power Supply

The plasma torch power supply is a 1000 KW DC unit rated at 250 volts and 4000 amps. The power circuit utilizes water-cooled thyristors in each leg of a six phase rectifier circuit to provide the adjustable voltage required.

The basic control scheme consists of a rapid response current regulator which will provide continuously adjustable constant current output up to the rated current of any DC voltage from zero to rated.

A block diagram of the power supply system is shown in Figure 37. The input power requirement is three phase, 480 volts at 1500 amps. A capacitor bank provides the necessary power factor correction. The three phase primary contactor can be activated from the control console and is connected to the interlock and protective circuits.

A 1300 KVA three phase water-cooled transformer is used to step down the line voltage to 283 V AC which supplies the SCR stacks. Each SCR cell is protected by a current limiting fuse. The entire power supply is provided with suitable safety interlocks and protective circuitry and any fault condition is displayed on the control console.

6.0 MERITS OF PLASMA MELTING PROCESS IN COMPARISON TO OTHER ESTABLISHED SPECIAL MELTING PROCESSES

In this section, out of the many uses of plasma heat in metallurgical applications, only the use of plasma as thermal energy for melting metals, superheating metal and slag melts will be examined. Plasma melting as an industrial process is still in its infancy in the U.S.A. Therefore, an appraisal of the plasma melting process can be made based largely on the information developed in this program and that obtained from overseas sources.

The several methods of plasma melting can be conveniently divided into two groups. The first group includes methods of preparing liquid metal of certain quality using a variety of charge materials. The casting of the plasma processed metal is done outside the furnace in conventional manner. This group includes methods proposed by Linde (4), VEB Edelstahlwerk Freital (10), Daido Steel (7), Mellon-Schlienger (this program), using either DC or AC operated plasma torches with and without tungsten electrodes.

The second group includes methods of remelting-refining and progressive solidification of the melt in short water-cooled copper sleeves by ingot withdrawal. This group includes plasmarc remelting as developed in the U.S.A. by Schlienger for this program effort, Soviets at Paton Institute (5), Ulvac in Japan (8), Daido Steel, Japan (14).

Plasma melting process installations not cited in this section are those operated on a very small scale in the U.S.A. and elsewhere.

Plasma melting furnaces operating on a method in the first group have limitations on ingot weight and metal quality since melting is performed in refractory crucibles.

Plasmarc furnaces based on ingot withdrawal can be successfully used for scrap consolidation as well as for consumable electrode remelting. Plasma furnaces of the second group are therefore dual duty melting devices.

A special feature of the plasma remelted ingots is the grain structure with dendrites orientated parallel to the ingot axis. This type of structure provides ingot metal of exceptional homogeneity. The plasma drip melted metal is in many ways superior to that produced in vacuum arc remelting and electroslag remelting furnaces.

Plasmarc remelting produces ingots of low inclusion content and high yield of metal since hot topping can be easily accomplished.

However, the withdrawal cast ingot tends to have somewhat rougher surface than electroslag ingots made in stationary molds.

Simultaneous deoxidation of remelted metal can be conducted in plasmarc furnaces using hydrogen or other reducing gas. Also, nitrogen alloying during remelting can be done in plasma drip melting furnaces operated at elevated pressures.

Plasma furnaces of the first group (refractory lined crucibles) can be used (a) for melting high quality low-carbon steels and alloys containing large amounts of chromium, nickel, cobalt; (b) for recycling scrap of non-ferrous metals and alloys and scrap of high-speed steel; (c) as a substitute melting furnace for preparing electrodes of various alloys for remelting purposes.

A comparison of various primary melting methods applicable to certain specialty metals and alloys is given in Table 28. Plasma heat is used as primary heat source in one case and auxiliary heat source in another case.

Table 29 provides a comparison of group two or remelting methods using various forms of electric arc heat.

In summation, plasma furnaces of both the first and second groups -- especially the dual duty unlts -- are likely to be the melting tools of the specialty metals industry with a promising future.

Multitorch plasma melting units are expected to have uses in the titanium and other reactive metal castings manufacturing industries and also for the manufacture of directionally solidified castings.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

7.1.1 Plasmarc melting process using a single plasmatorch can be used to satisfactorily consolidate superalloy and titanium alloy scrap of various shape, size, and forms into a semi-fused remelt type electrode but not a homogeneous ingot.

7.1.2 The special material feed system designed, constructed, and operated for feeding various types of scrap and the consumable electrode, functioned satisfactorily for feeding scrap and lump charge materials but not the consumable electrode.

7.1.3 Since the consumable electrode could not be continuously fed into the plasmarc, the ingot solidification process had many interruptions. Therefore, forgeable quality, full size ingots were not made within the program time schedule.

7.1.4 Evaluations of the pilot scale plasmarc remelted ingots produced in this program indicated material characteristic trends as follows:

(a) Excellent chemical homogeneity

(b) Excellent structural homogeneity including freedom from large inclusions, stringer-type inclusion cluster, and segregation

(c) Highest yield of material - virtually no shrinkage cavity in the ingot hot top.

(d) Uniform mechanical properties

7.1.5 Plasmarc remelting coupled with ingot withdrawal provides a unique ingot structure with dendrites oriented parallel to the ingot axis. The molten metal pool produced by plasmarc heat application tends to be shallow and flat in shape which gives rise to the pronounced unidirectional grain orientation in the solidified ingot.

7.1.6 An inference drawn from above conclusions is that plasma heat application using multiple torch systems may be useful in the titanium casting and turbine blade casting industries for the manufacture of metallurgically superior cast components.

7.2 Recommendations

Plasmarc melting systems presently available in this country have not reached maturity to serve as viable production systems in the specialty metals industry. This program effort has disclosed certain major benefits which could be derived through application of plasmarc heat for melting and casting specialty metals and alloys. Further developmental work in the plasmarc heating devices, plasma heat application in melting and castings systems is required to create improved technology.

8.0 REFERENCES

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2. R. M. Gage, "Method for Furnacing Conductive Materials", U.S. Patent 3,147,330, September 1, 1964.

3. R. J. Baird, "High Voltage Arc Plasma Generator", U.S. Patent 3,194,941, July 13, 1965.

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8. S. Kashy, S. Nishino and C. Hayashi, "A Plasma Electron Beam Heating Source", Japan Vacuum Eng. Co., 1966. (Also private communications with Dr. C. Hayashi, September 1971, June 1973.)

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10. H. Fiedler, W. Lachner, G. Belka and F. Müller, "Results of Plasma Melting", Proceedings of the Fifth International Symposium on Electroslag and Other Special Melting Technologies, Pittsburgh, October 16-18, 1974 (Proceedings - March 1975).

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12. "Plasma Processes in Metallurgy", JPRS Publication 61321, 26 February 1974. (Translation of a Russian Language Book, Edited by B. E. Paton, Kiev, U.S.S.R.)

13. R. M. Gage, "Arc Torch and Process", U.S. Patent 2,806,124, September 10, 1957.

14. "Plasmarc Progressive Casting System", private communication, Daido Steel Company, Nagoya, Japan, April 1973.

Figure 1

600 kg Plasma Induction Furnace (Daido Steel)
(Shown in Teeming Position - Launder is in an Enclosed Box Flushed with Argon).

Figure 2

Surface Appearance of GFM Forged,
Plasma Induction Melted and Cast Ingots of Inconel 718.

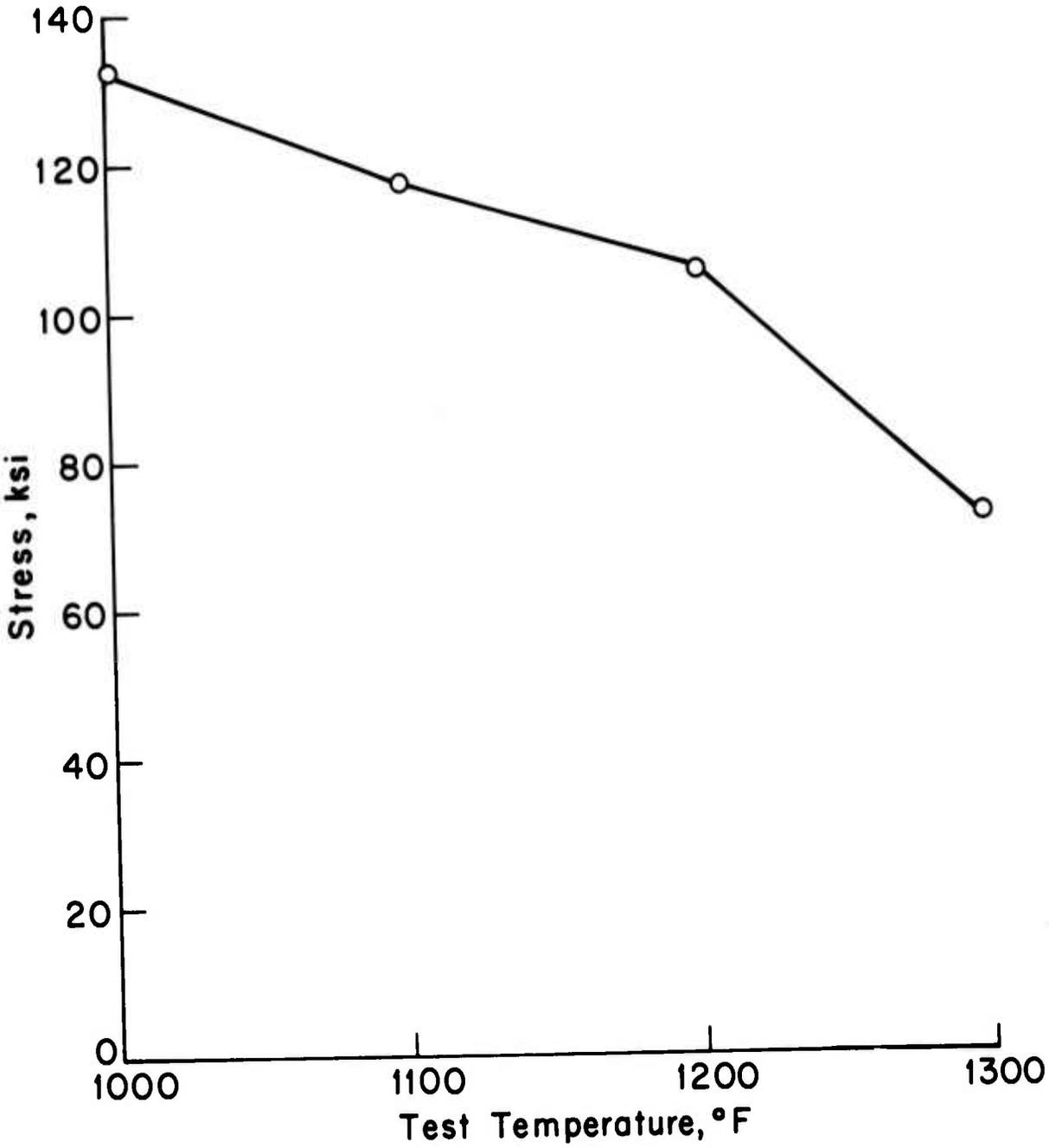
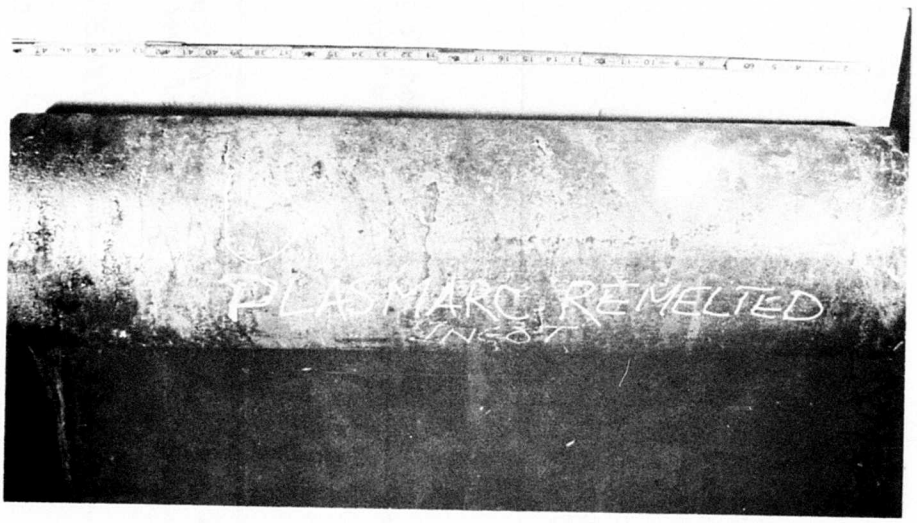


Figure 3

Plot of 100 Hour Stress Rupture Data for
Plasma Induction Melted and Forged Inconel 718 Alloy.

4(a)



(b)

Figure 4

(a) Hot Top Surface of Plasmarc Remelted Austenitic Steel Ingot.

(b) Surface Condition of Plasmarc Remelted Austenitic Steel Ingot by Continuous Ingot Withdrawal from Water-Cooled Copper Mold.

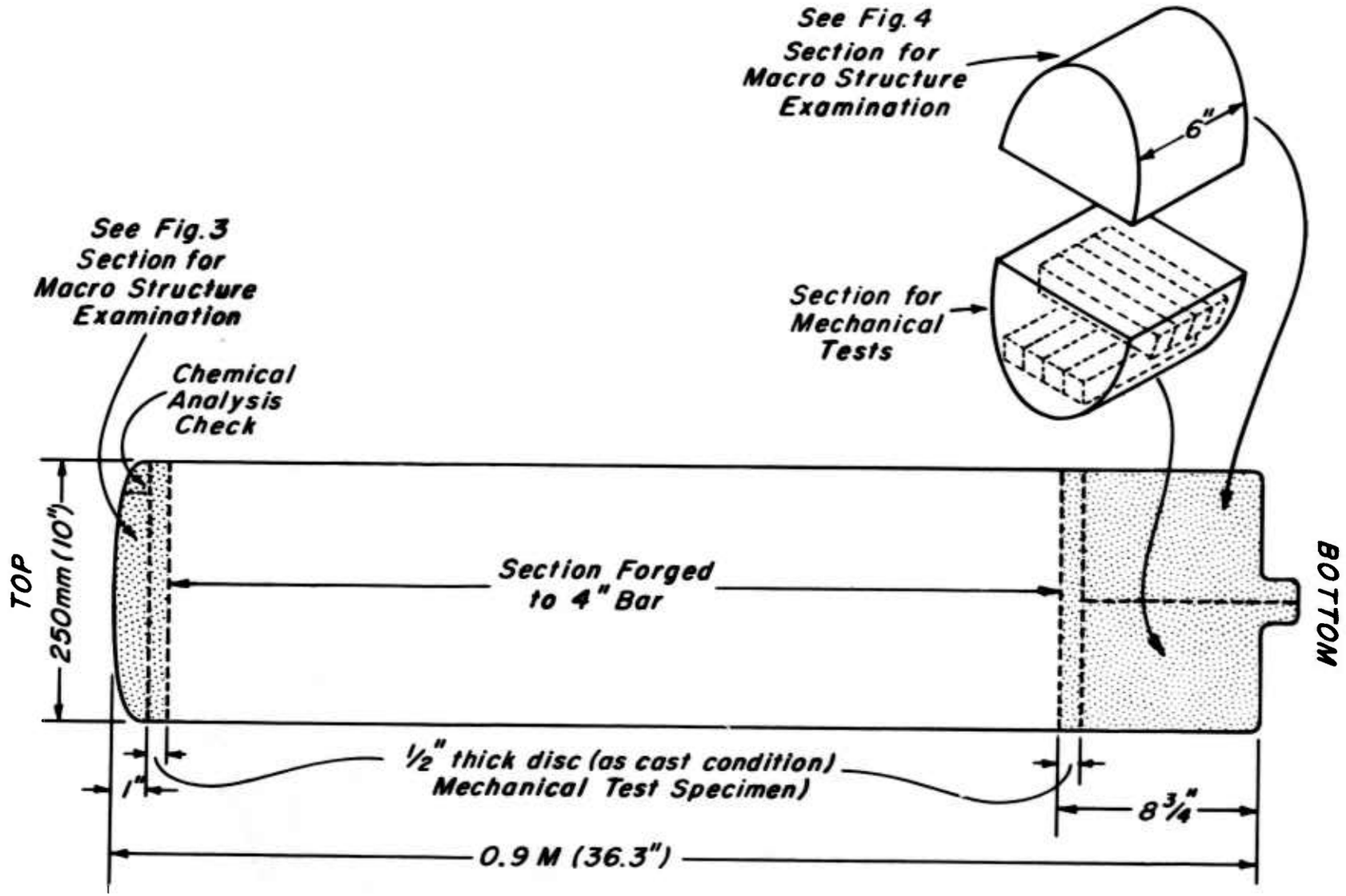


Figure 5

Plan of Sectioning Plasmarc Remelted Austenitic Steel Ingot for Macrostructure Evaluation and Mechanical Test Specimen Extraction.

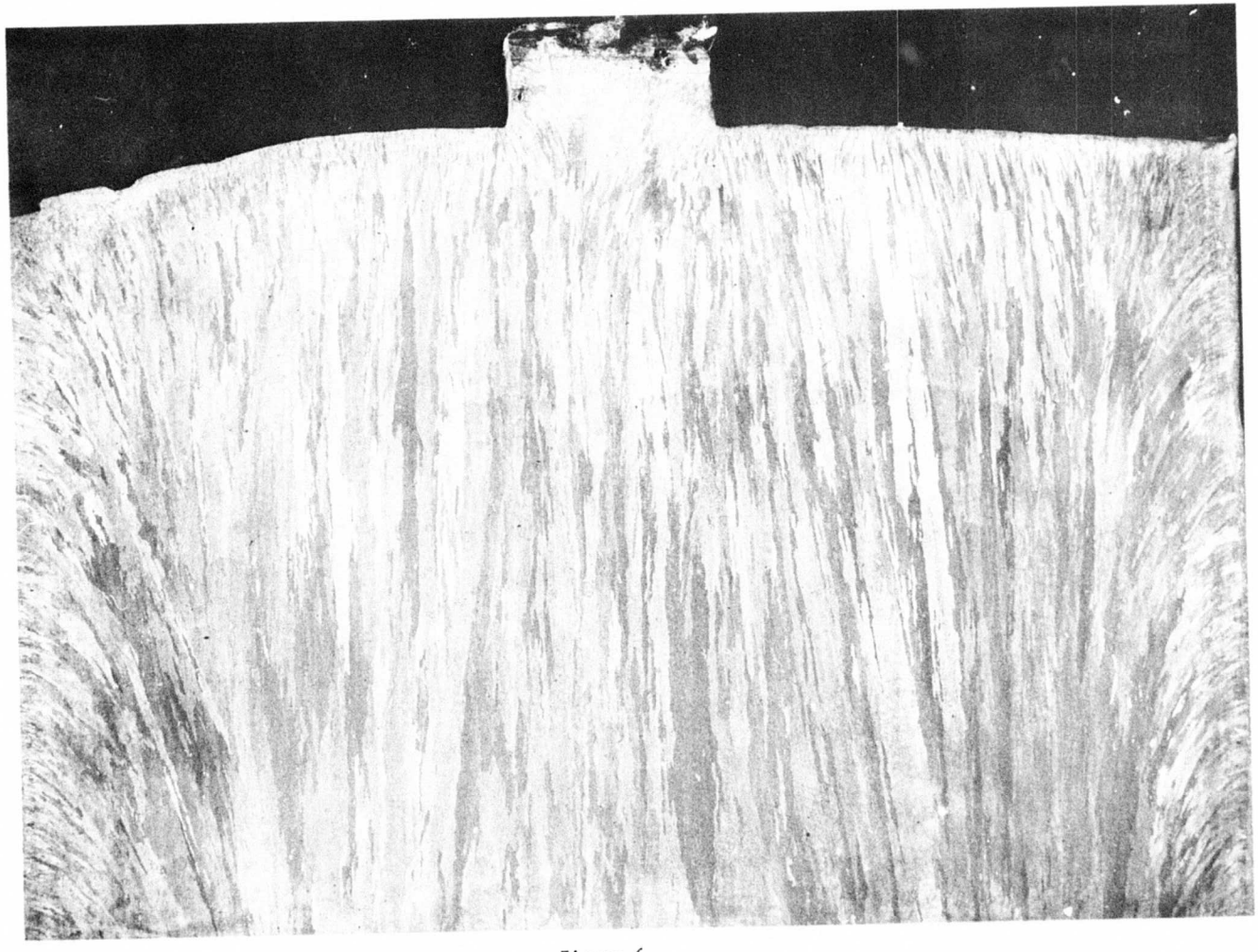


Figure 6
Plasmarc Remelted Austenitic Steel Ingot Bottom -- Macrograph Shows Vertical Section Through Ingot Center.

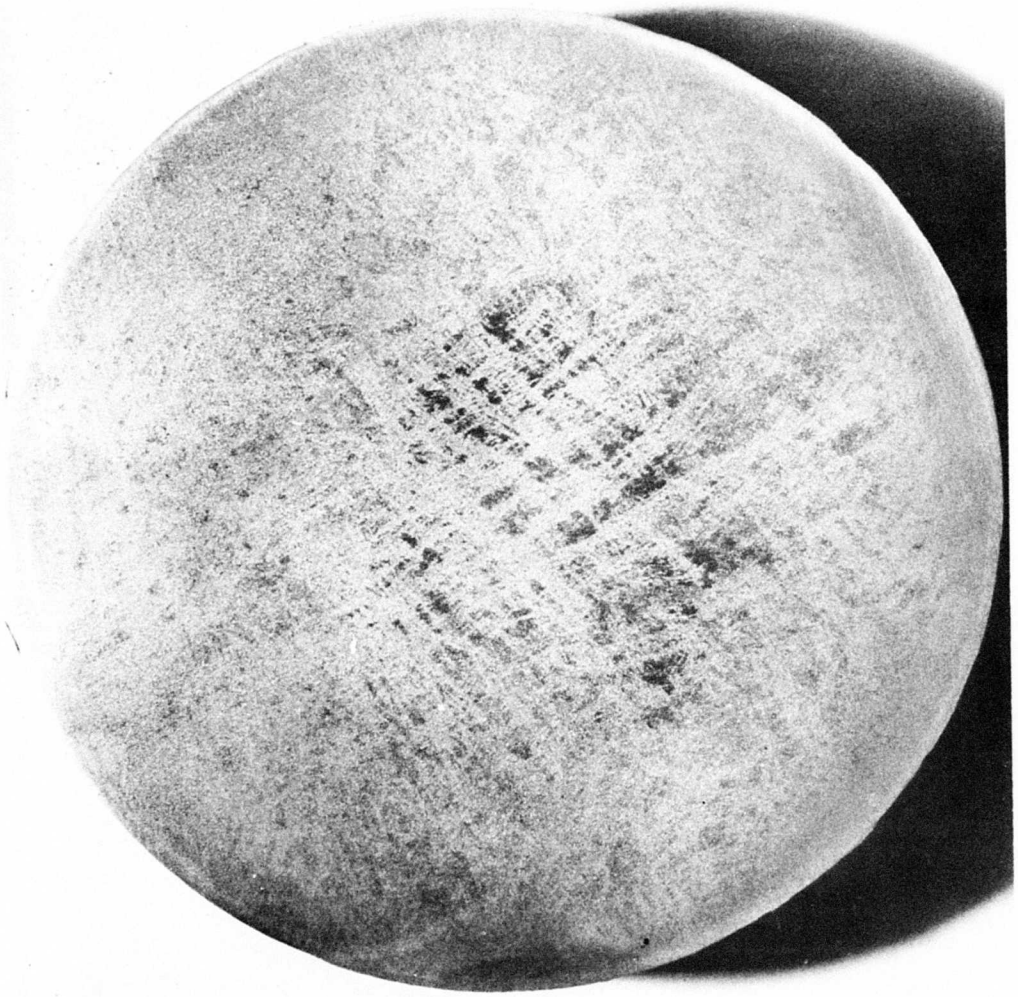


Figure 7

Cross-Sectional Macrostructure of the Forged Four-Inch Bar from the Plasmarc Remelted Austenitic Steel Ingot.

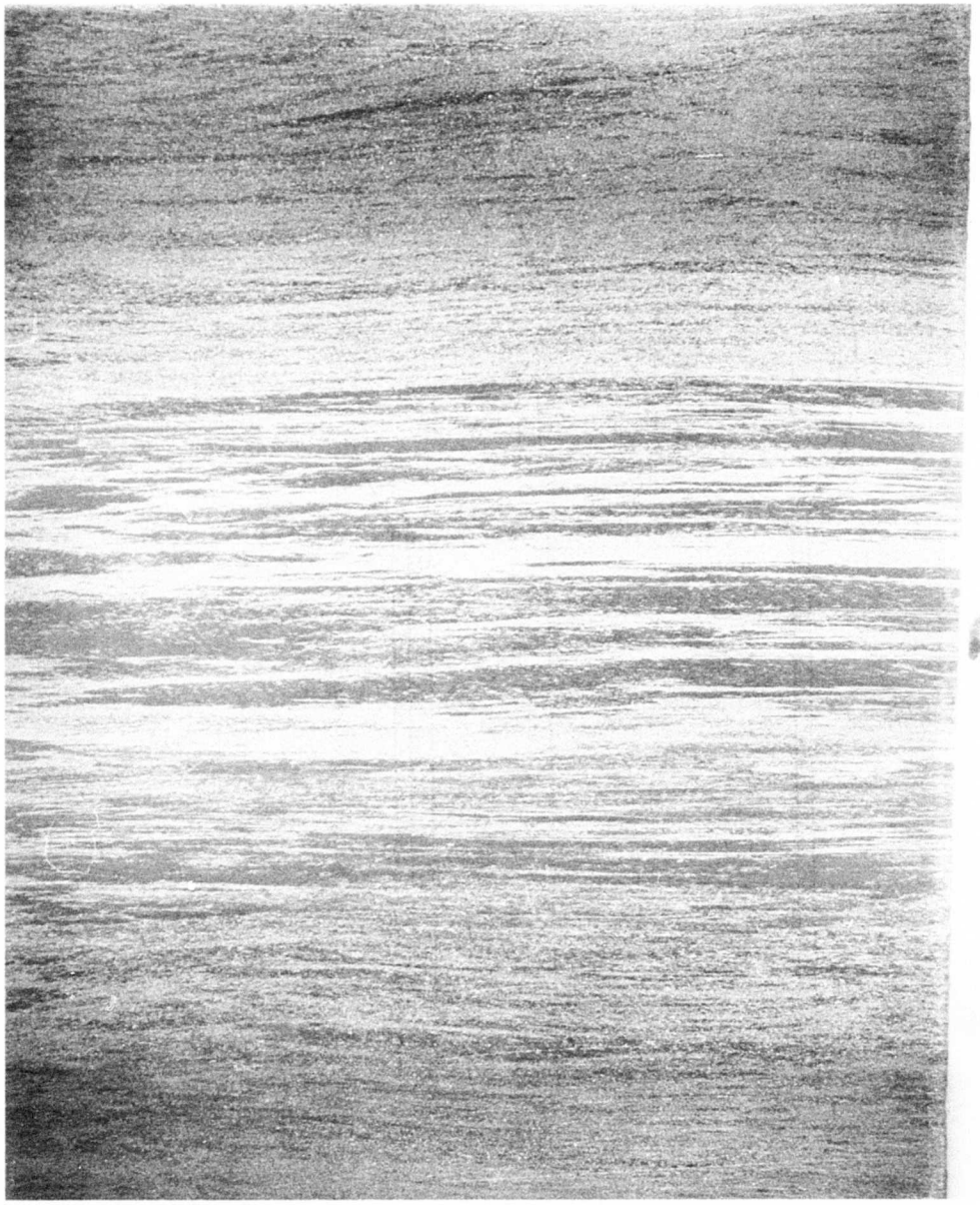


Figure 8

Macrostructure of a Longitudinal Section of the Forged Four-Inch Bar from the Plasmarc Remelted Austenitic Steel Ingot.

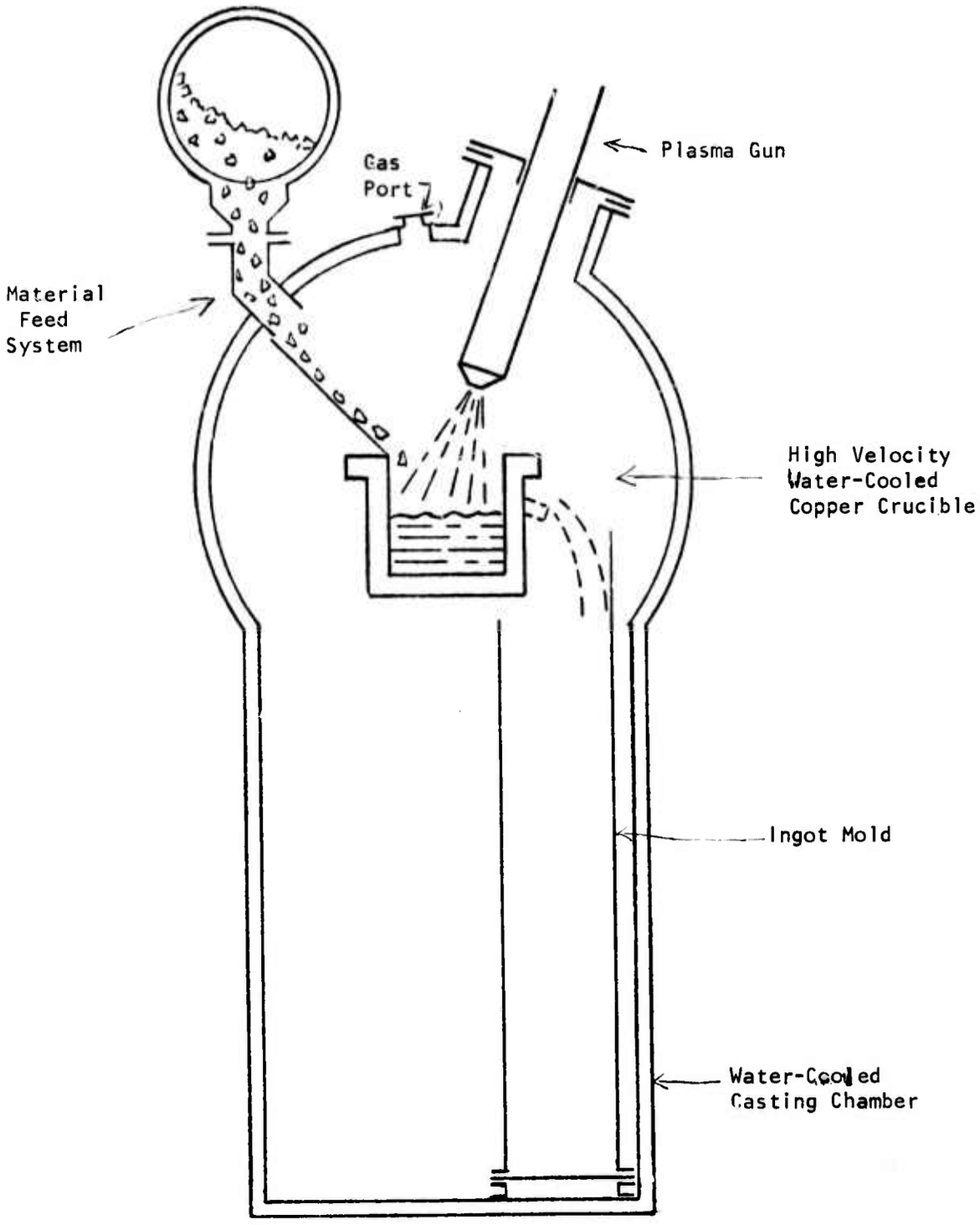


Figure 9

Schematic of Schlienger Rotary Non-Consumable Electrode Melting System Converted for Conducting Plasma Melts.

Figure 10

Photographs of Plasmarc Melted Ingots
Made in a Cold-Wall Crucible Using
Inconel 718 Scrap and Other Charge Materials.

[Shallow Melt (Top Photo)]
[Unfused Scrap at Ingot Bottom (Bottom Photo)]

Figure 11

Plasma Drip Melted Ingot Made from Inconel 718 Electrode in a 20-Inch Diameter Cold-Wall Mold. (230 lb. Ingot)

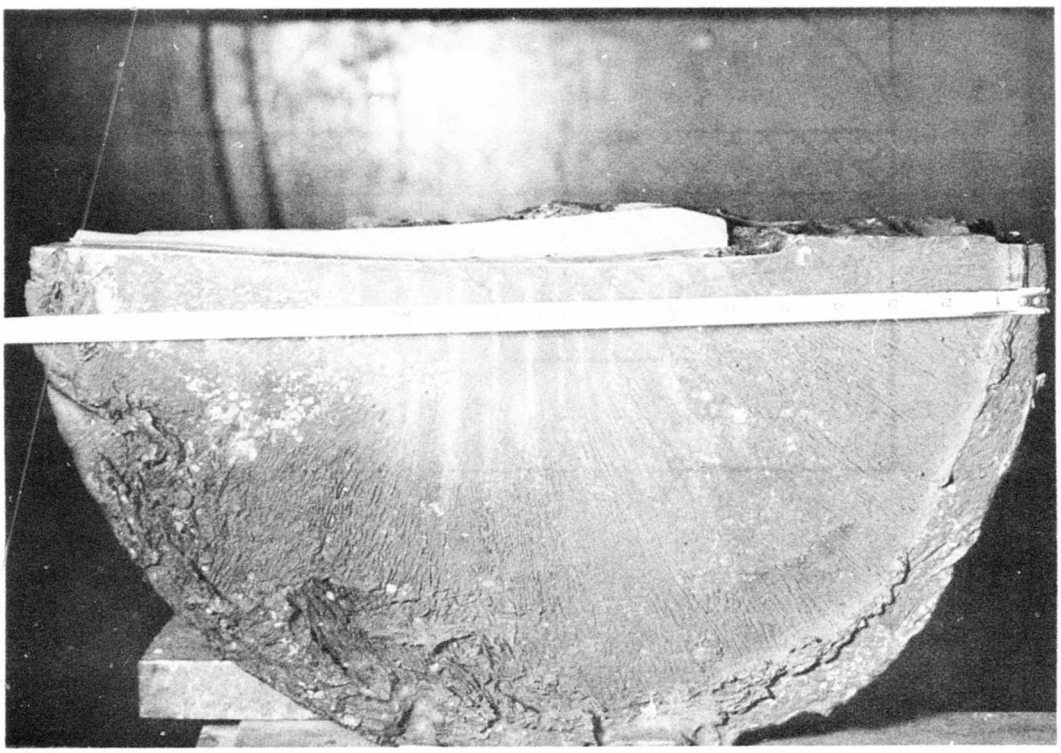


Figure 12

Plasmarc Melted Inconel 718 Ingot (600 lbs.).
(Ingot Top Surface Shows No Shrinkage Cavity.)

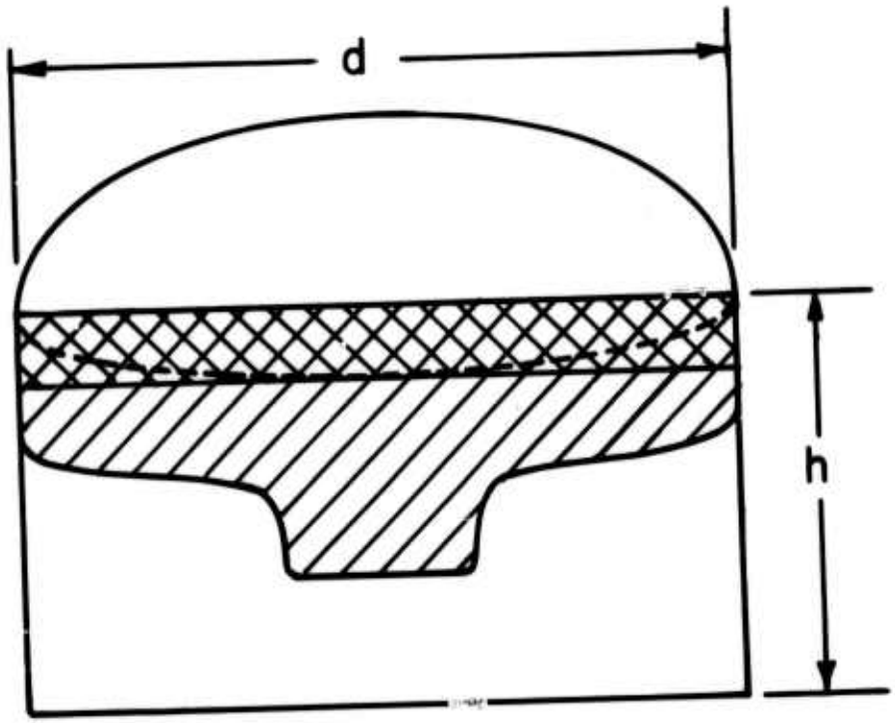


Figure 13

Plan of Sectioning Plasmarc Melted
20-Inch Ingot of Inconel 718.

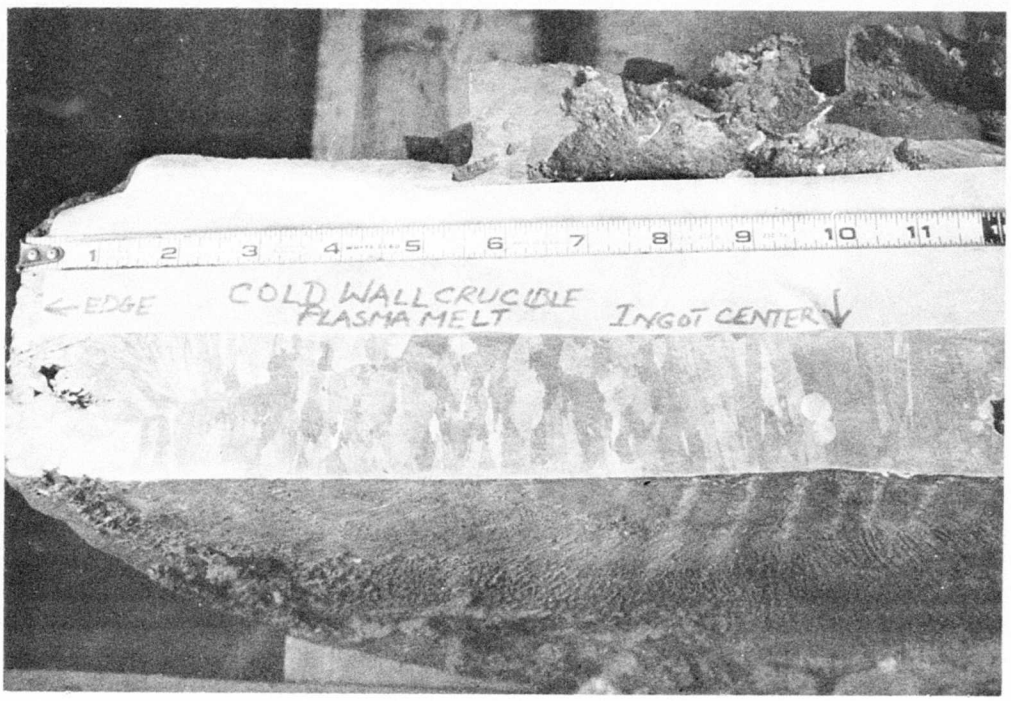


Figure 14

Macrostructure of a Vertical Section Through the Center of Plasma Melted Inconel 718 Ingot in a Cold-Wall Crucible. (Note Vertical Orientation of the Grains Even in the Center of the Ingot.)

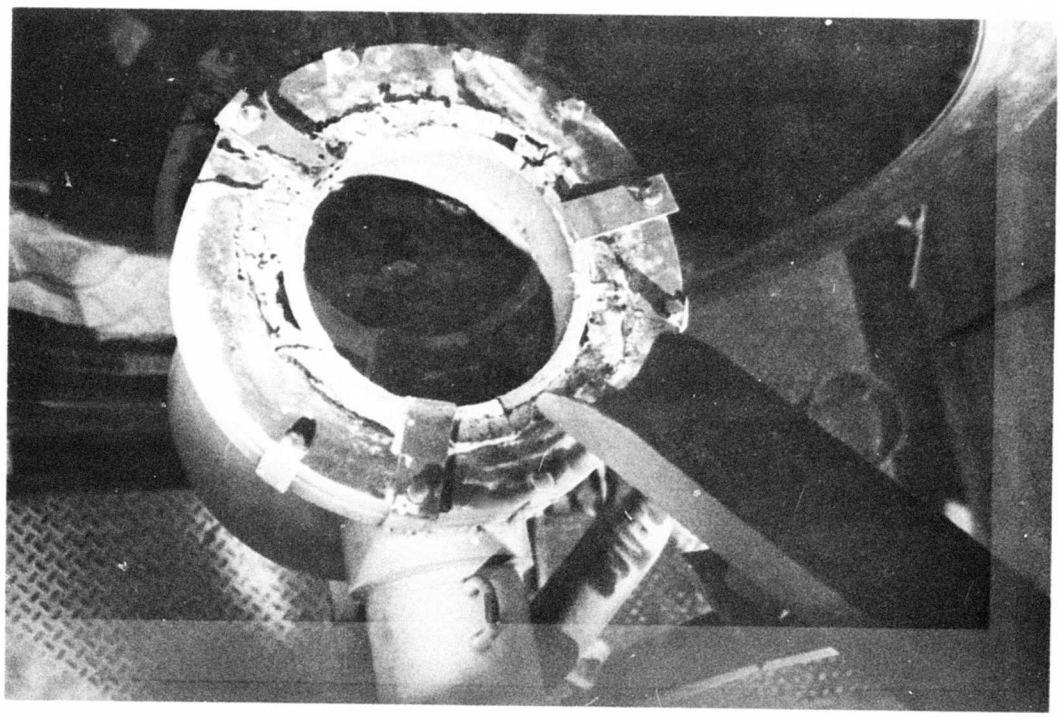
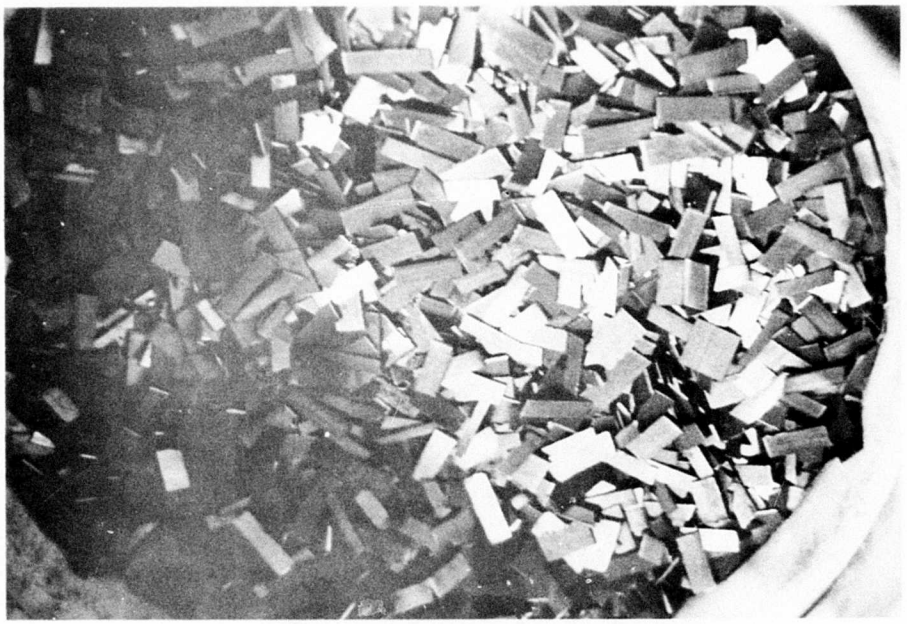
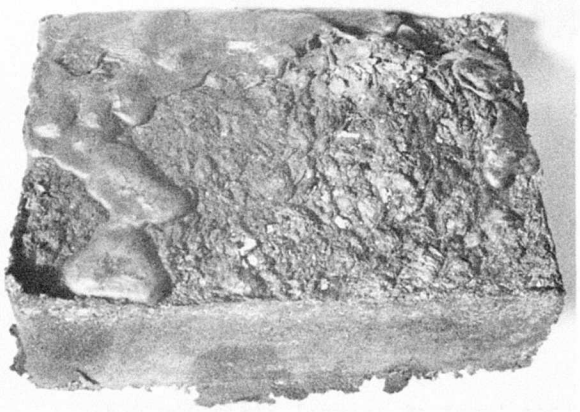


Figure 15

Photograph Showing Zirconia Liner
Fitted Inside the Cold-Wall Mold.



16(a)



16(b)

9" x 12" x 4" Thick Slab

Figure 16

(a) Sheet Clippings of Inconel 718 Charged into 15-Inch Diameter Hot-Wall Crucible for Plasmarc Melting.

(b) Slab Ingot Made by Pour-Casting Plasma Melted Inconel 718 from Hot-Wall Crucible.

Figure 17

Plasmarc Melted Ingot of Inconel 718 Alloy Made in Hot-Wall Crucible. (Charge - Heavy Scrap, Master Alloy and Ferroalloys) (680 lb. Ingot)

Figure 18

Photograph of Plasmarc Melted Ingot of Inconel 718 Produced from Sheel Clippings in a Hot-Wall Crucible. (15-Inch Diameter Approximately 600 lb. Ingot.) Note Complete Melting Only in Top 5 to 6 Inch Section of the Ingot.

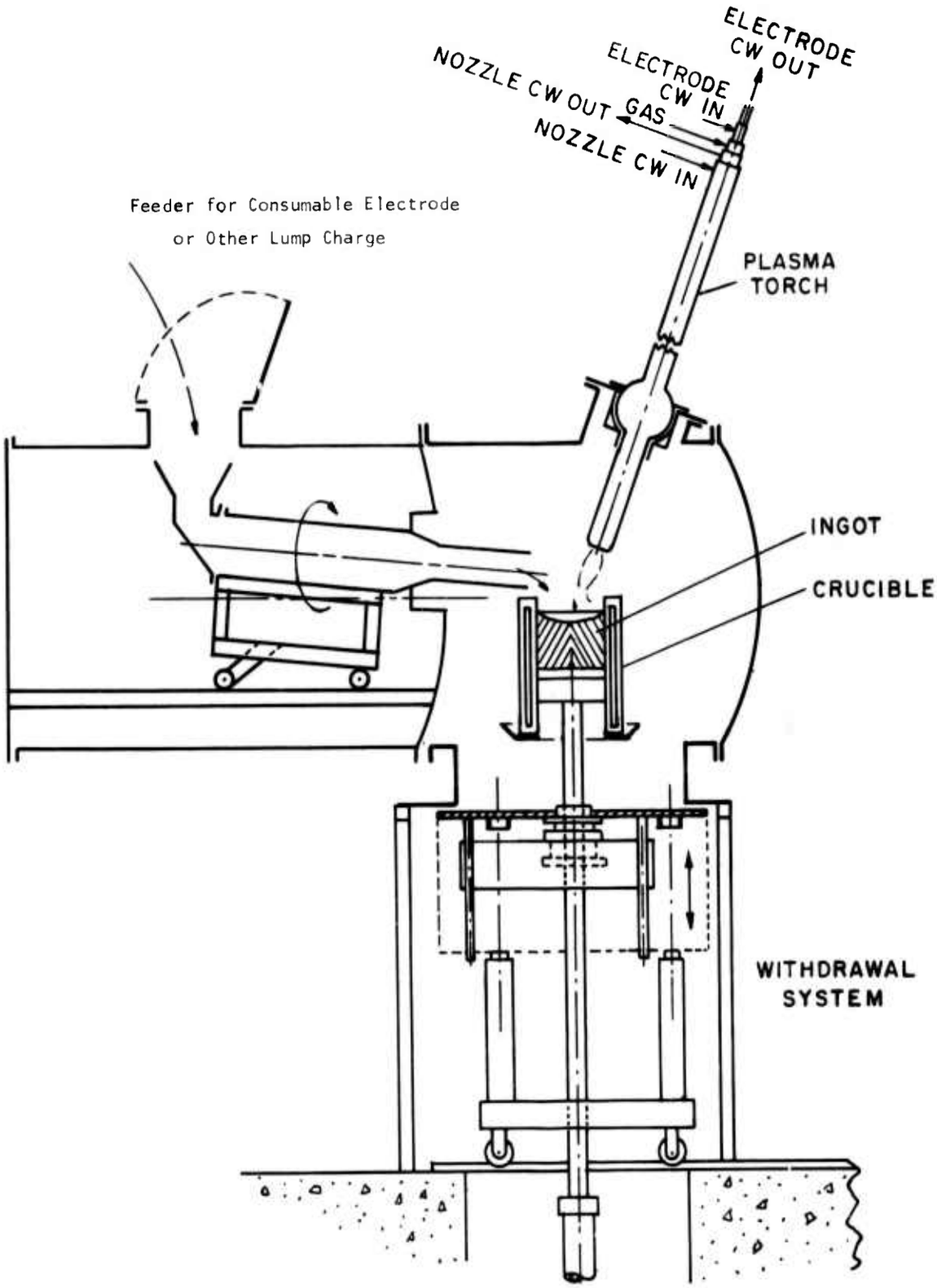


Figure 19

Schematic of Dual Duty Plasma Melting Equipment Showing Material or Electrode Feed System and Ingot Withdrawal Through a Sleeve Mold.

Figure 20

Photograph of Plasma Melted-Withdrawal Cast, 520 Pound Ingot of Inconel 718 Made From Sheet Clippings. (Scrap Consolidation into an Electrode for Consumable Remelting.)

Figure 21

Plasmarc Melted Ingots of Maraging Steel -- A Scrap Consolidation to Make Electrodes for Remelting. (Ingots Shown are 14 Inch Diameter, Approximately 1,000 lbs. and 670 lbs.)

(a)

← Ingot Top

← Ingot Bottom

Bottom Deformities →

(b)

→ Ingot Axis Directions

← Surface Laps

Figure 22

(a) First Plasma Drip Melted 13.5 Inch Diameter, 750 Pound Ingot of Inconel 718 Using 6 Inch Diameter Electrode.

(b) A Close-Up View of the Types of Surface Defects in the First Plasma Melted-Withdrawal Cast Ingot of Inconel 718.

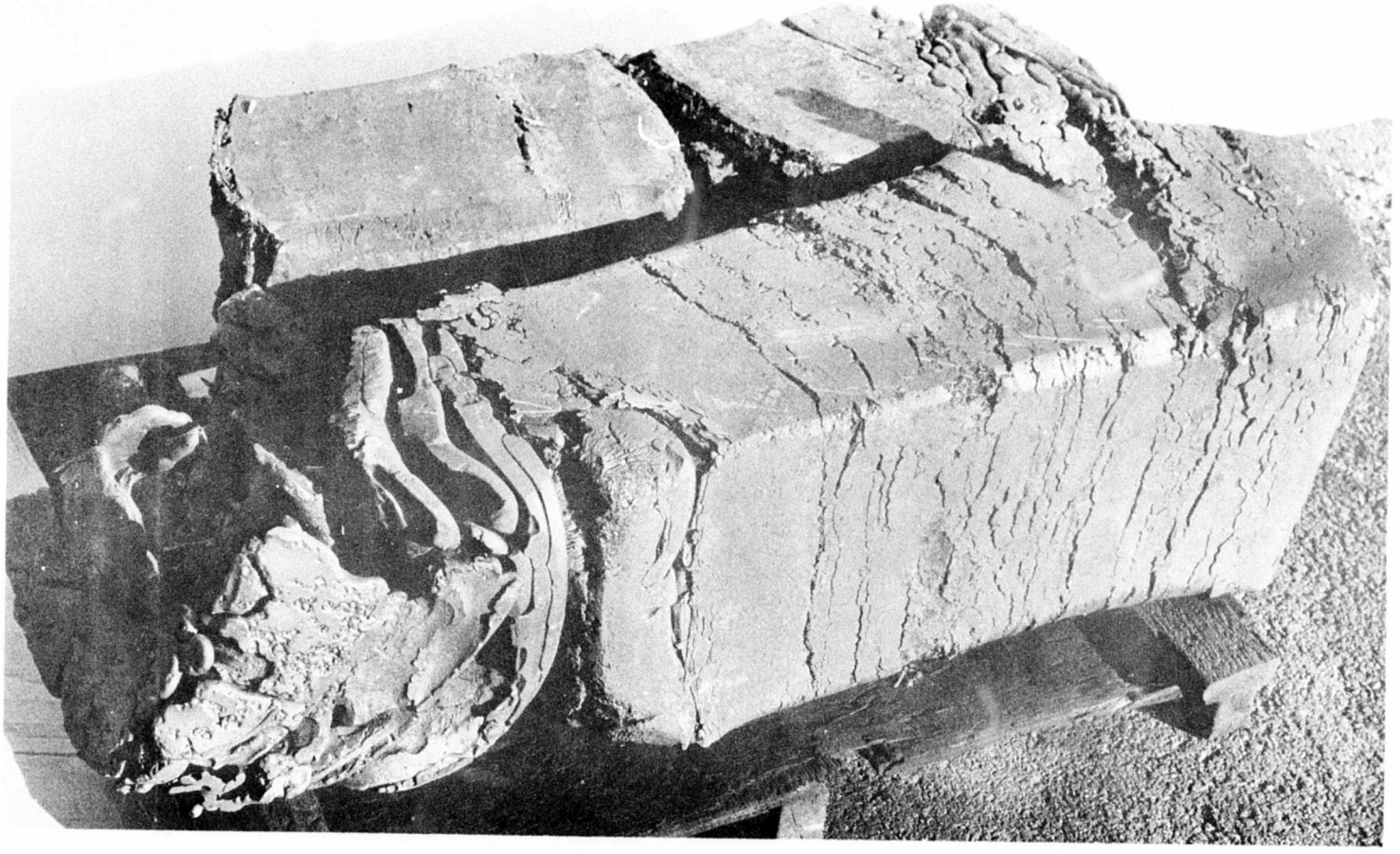
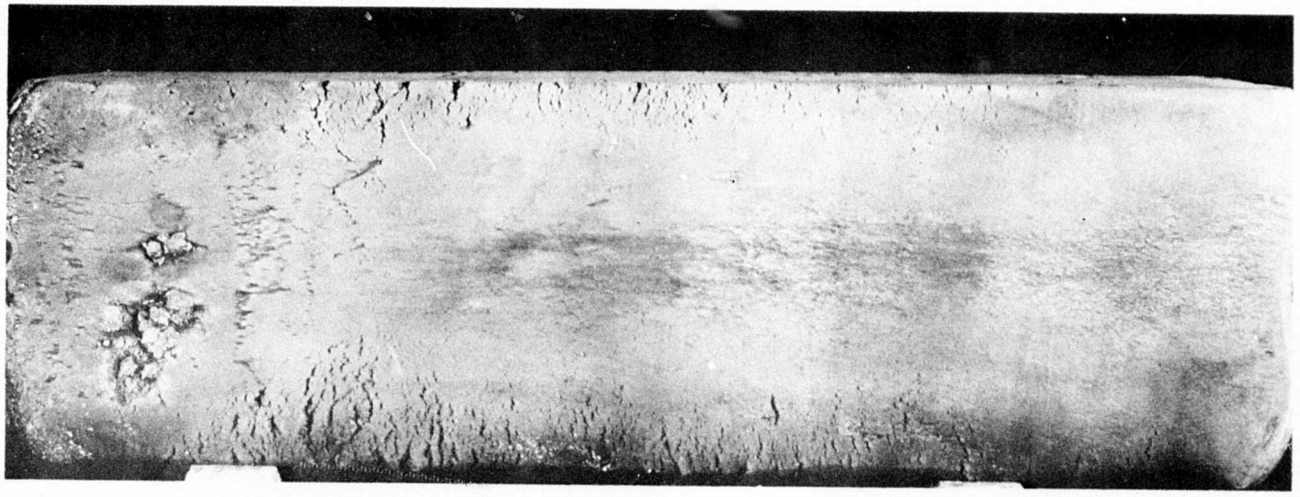
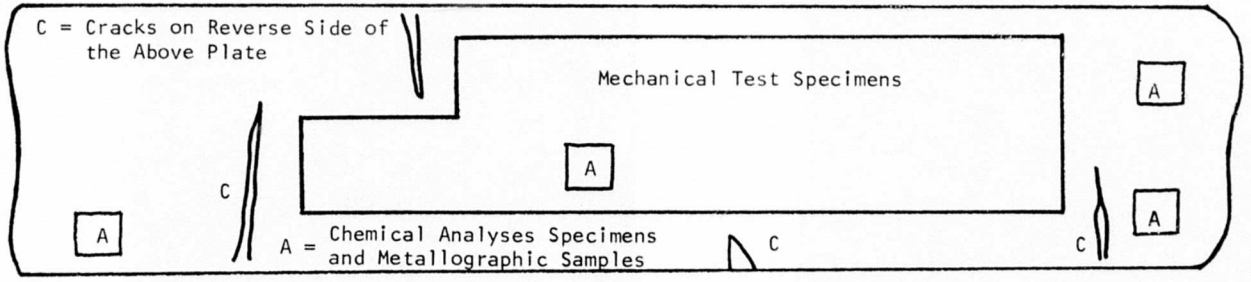


Figure 23

Press Forged Plasmarc Drip Melted Ingots of Inconel 718.
(Severe Cracks Seen are at Melt Interruption Locations in the Starting Ingot.)



(a)



(b)

Figure 24

(a) Press-Forged 1-1/4 Inch Thick Plate Produced from Plasma Drip Melted and Press Cogged Ingot of Inconel 718.

(b) Specimen Extraction from the 1-1/4 Inch Plate of Plasma Drip Melted Inconel 718.

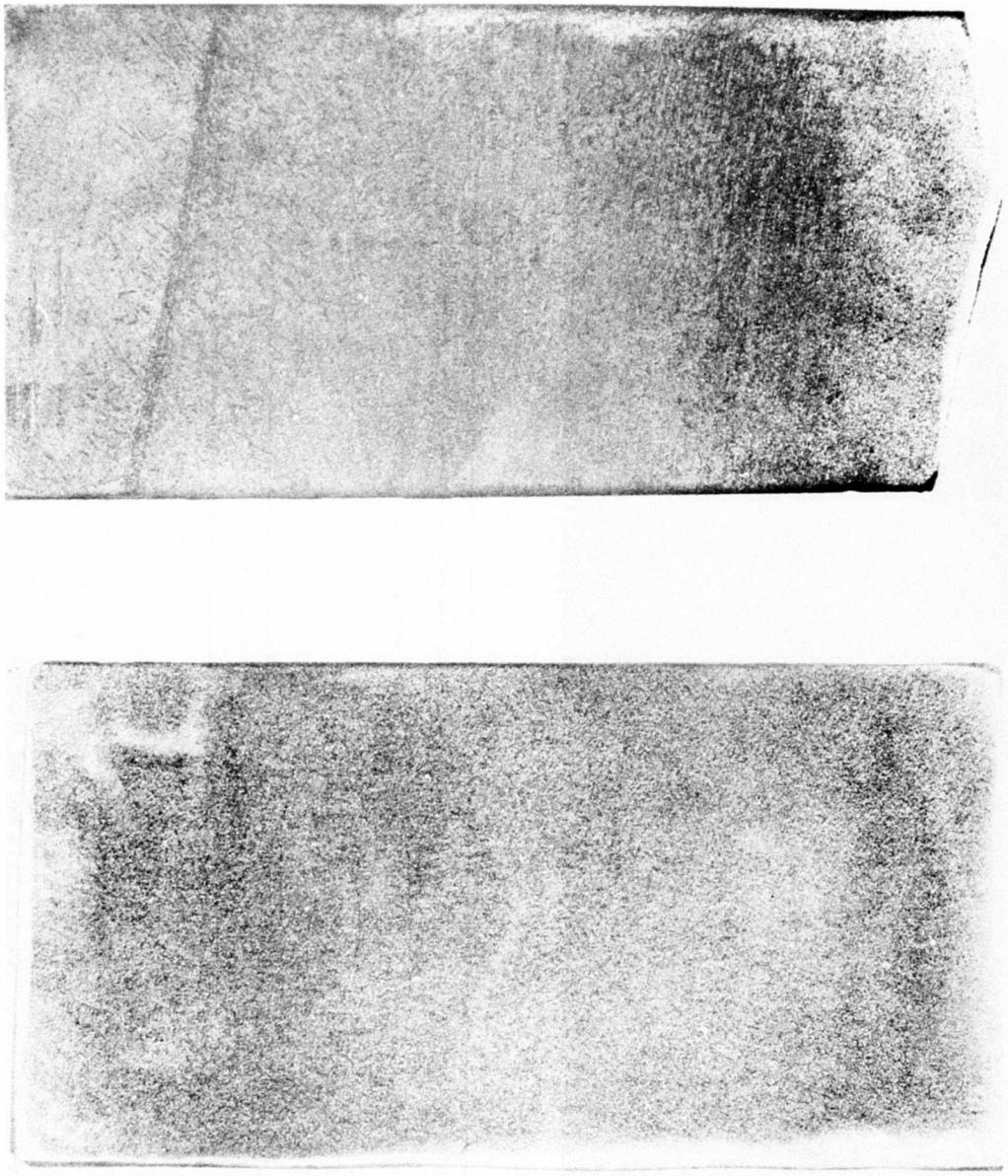


Figure 25

Macrostructural Features of Forged Plasma Drip Melted Inconel 718, Showing Very Clean, Fine Grained Material.

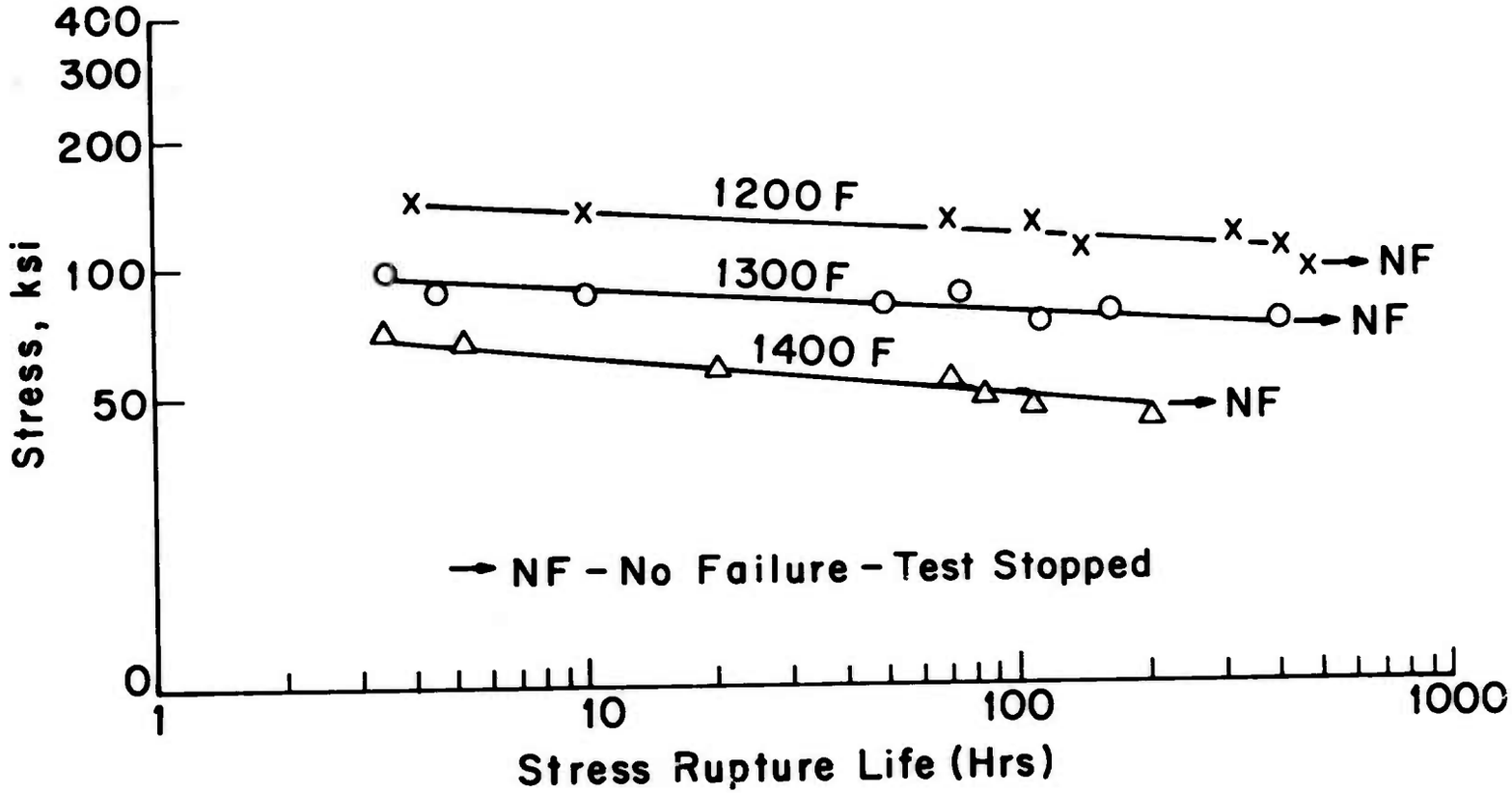


Figure 26

Stress Rupture Data for Plasma Drip Melted and Forged Inconel 718.

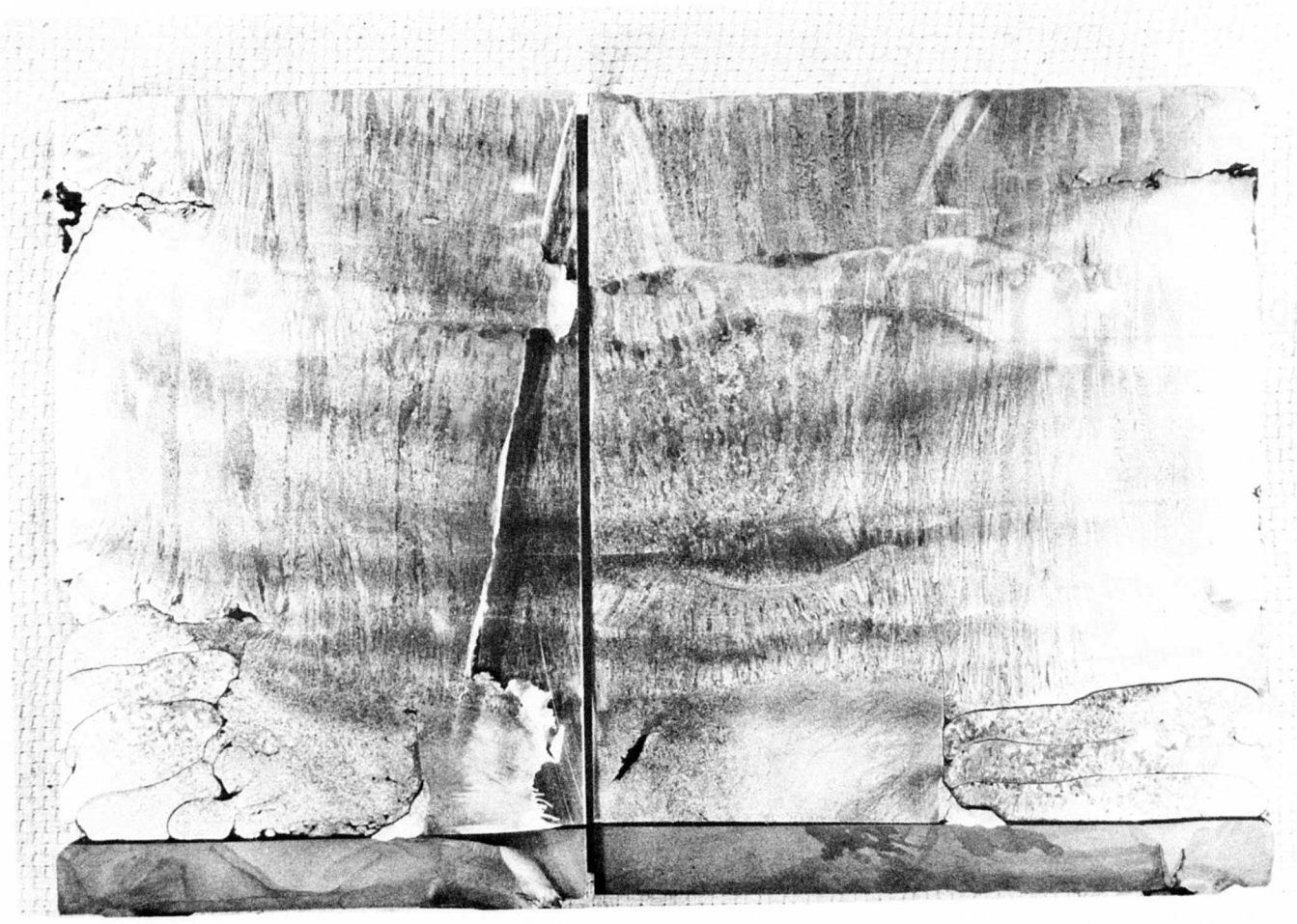


Figure 27

Macrostructural Features Observed in Plasma Drip Melted Ingot of Inconel 718 (Bottom Section).
(Ingot Shown is 13.8 Inch Diameter, 8 Inch Long Section Excluding 1 Inch Thick Bottom Contact Plates.)

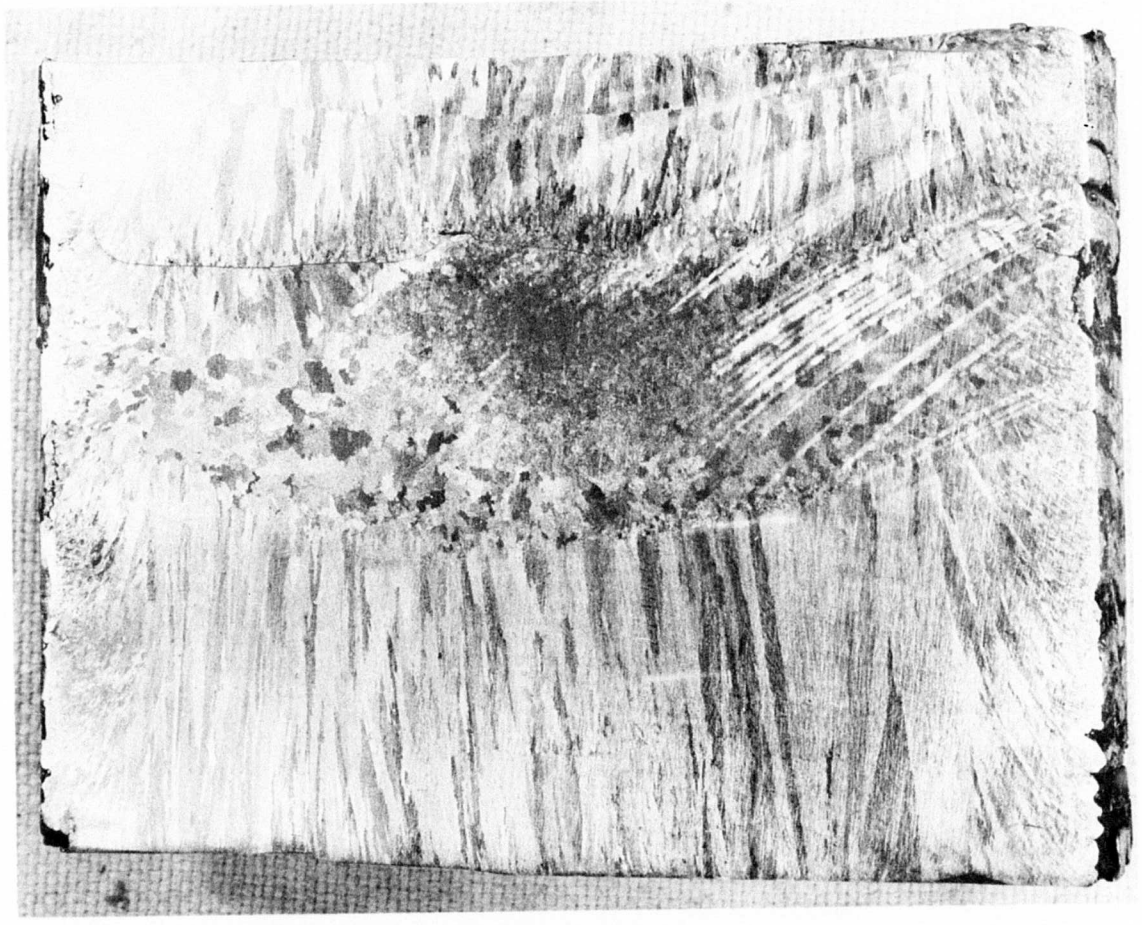


Figure 28
Macrostructural Features Seen in Plasma Drip Melted Ingot of Inconel 718 (Top Section).
(Ingot Section Shown is 13.8 Inch Diameter, 9 Inch Long Section.)

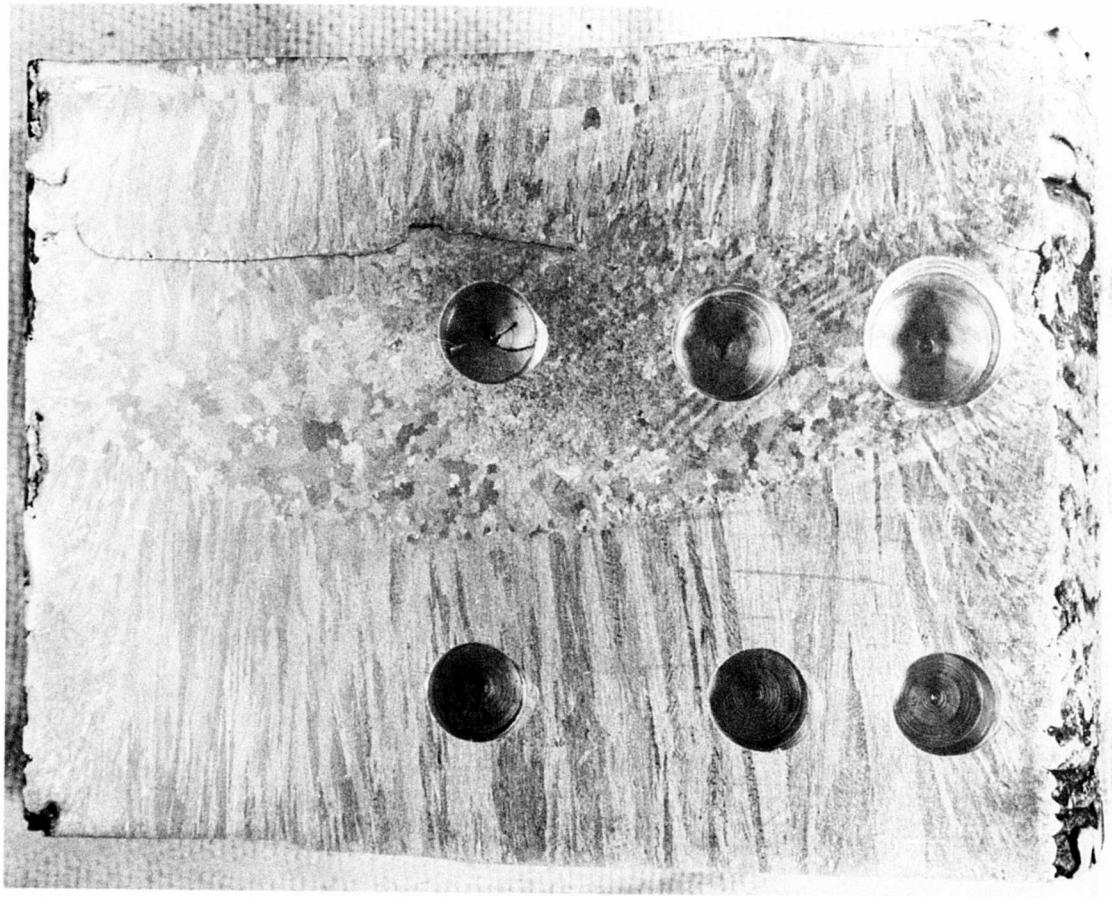


Figure 29

Picture Showing Locations in the Plasma Drip Melted Ingot of Inconel 718 of Chemical Analyses Samples.

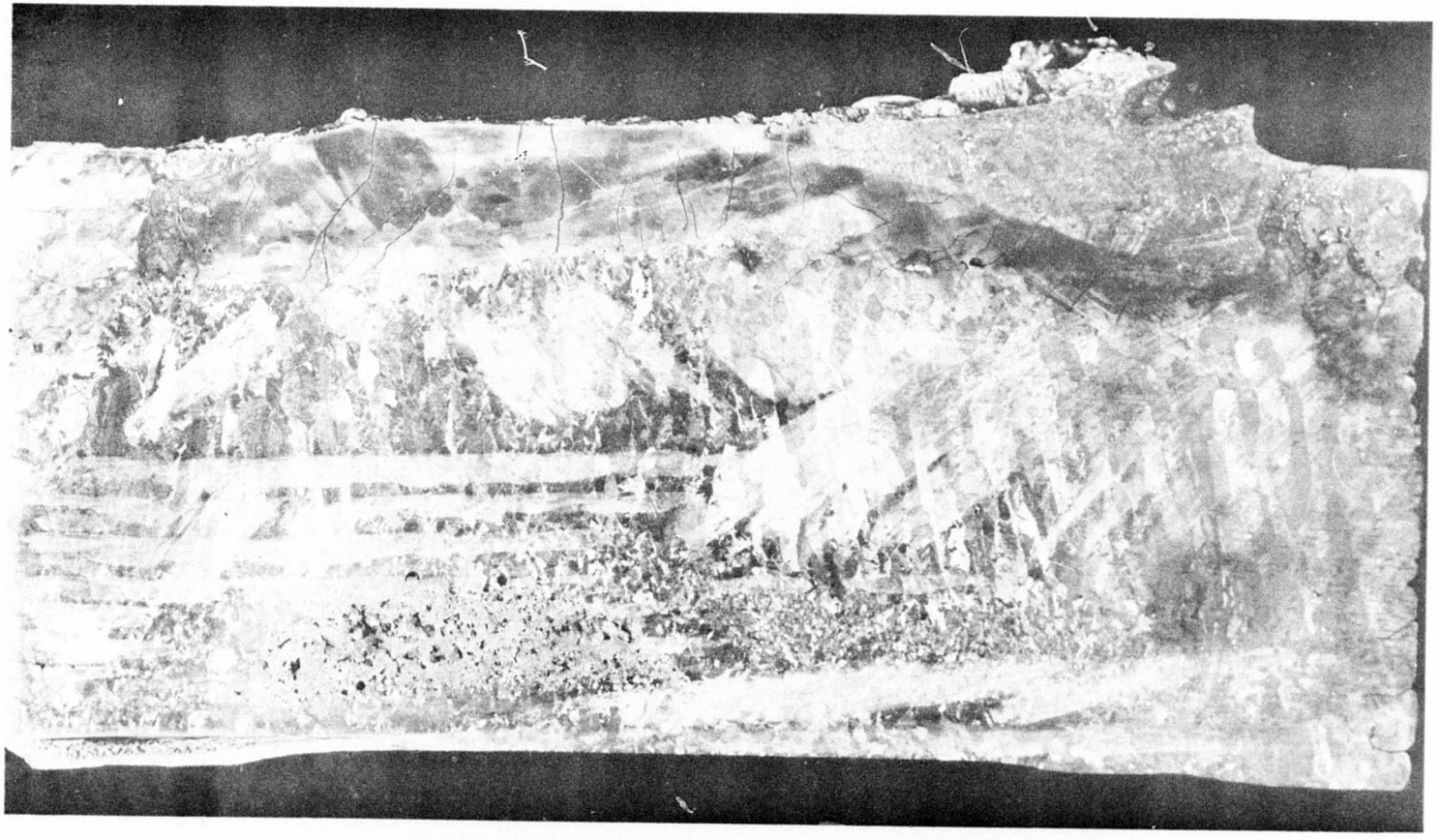


Figure 30

Macrostructural Features Seen in a Plasma Drip Melted C.P. Titanium Ingot. (13.8 Inch Diameter, 12 Inch Long Ingot Section. Charge Material was Isostatically Compacted Sponge Electrode and Loose Sponge.)

Figure 31

Plasma Drip Melted, 14 Inch Diameter, 18 Inch Long Ingot of Titanium-6Al-4V Alloy. (Blue Coloration Due to Iron Contamination.)

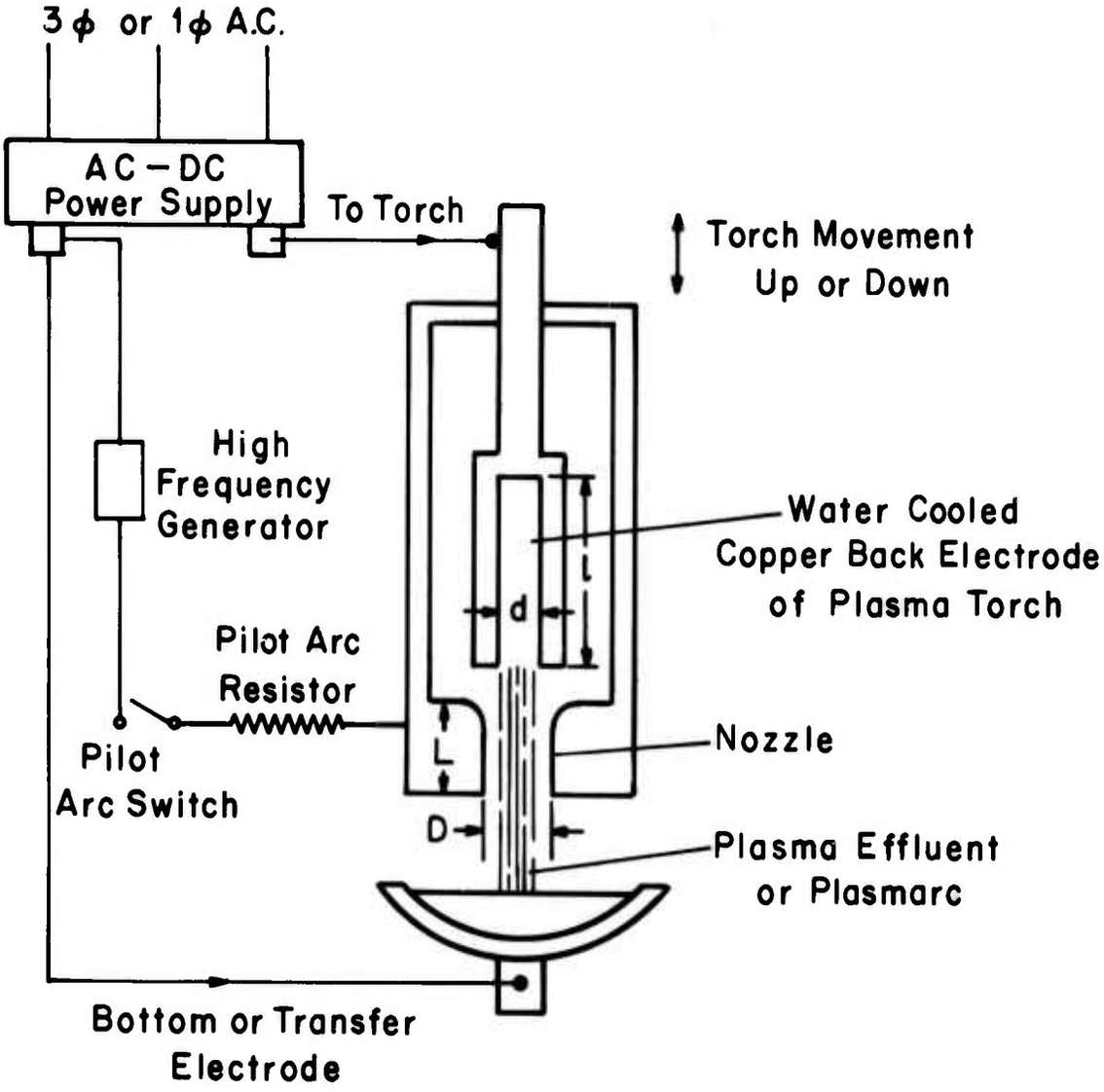


Figure 32

A Schematic Diagram Showing the Essential Components of Linde MAT-9B Type Plasma Torch and Electrical Power Connections Between the Plasma Torch and Workpiece (Melting Receptacle).

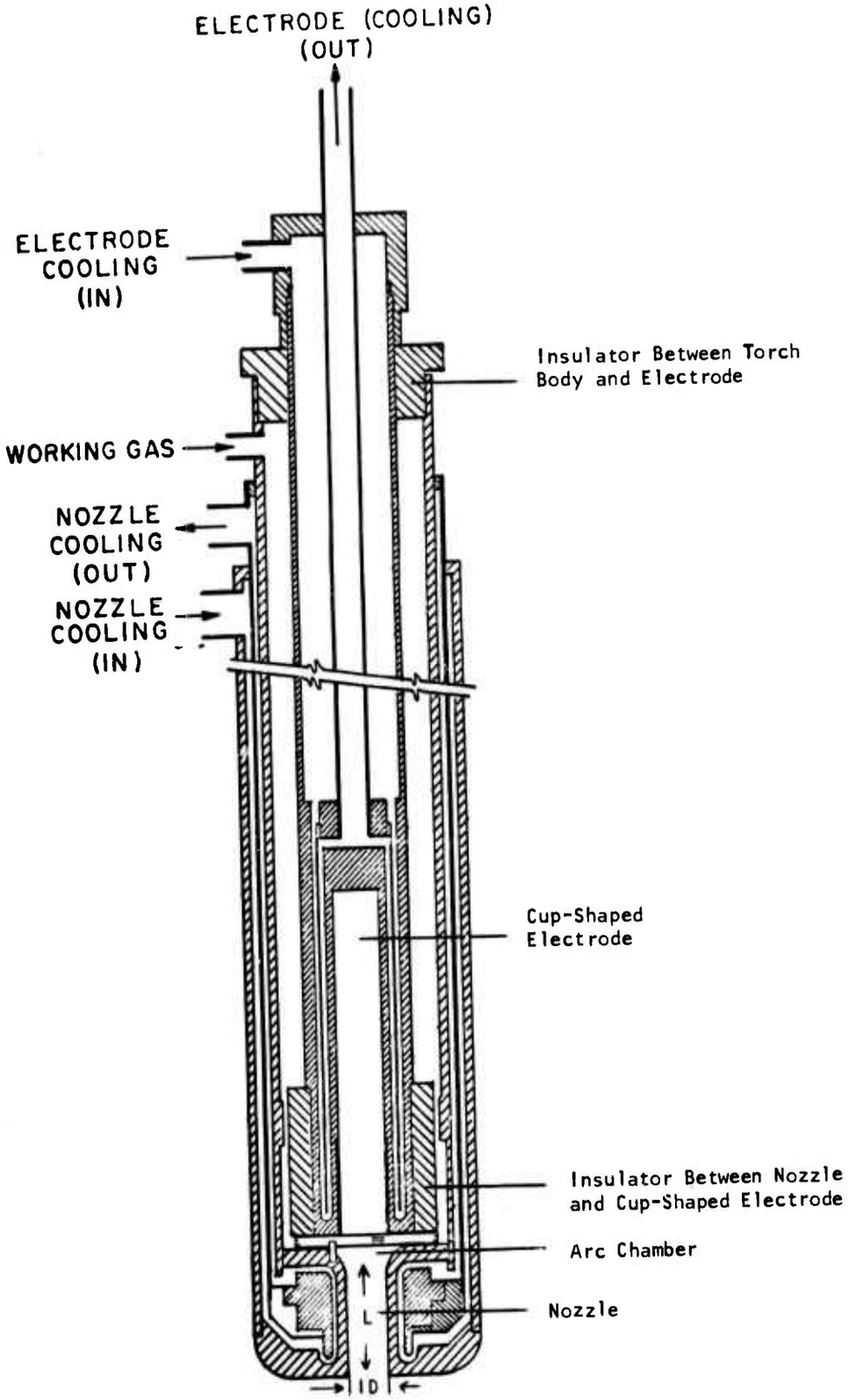


Figure 33

A Schematic Diagram of Linde Type MAT-9B Plasma Torch.

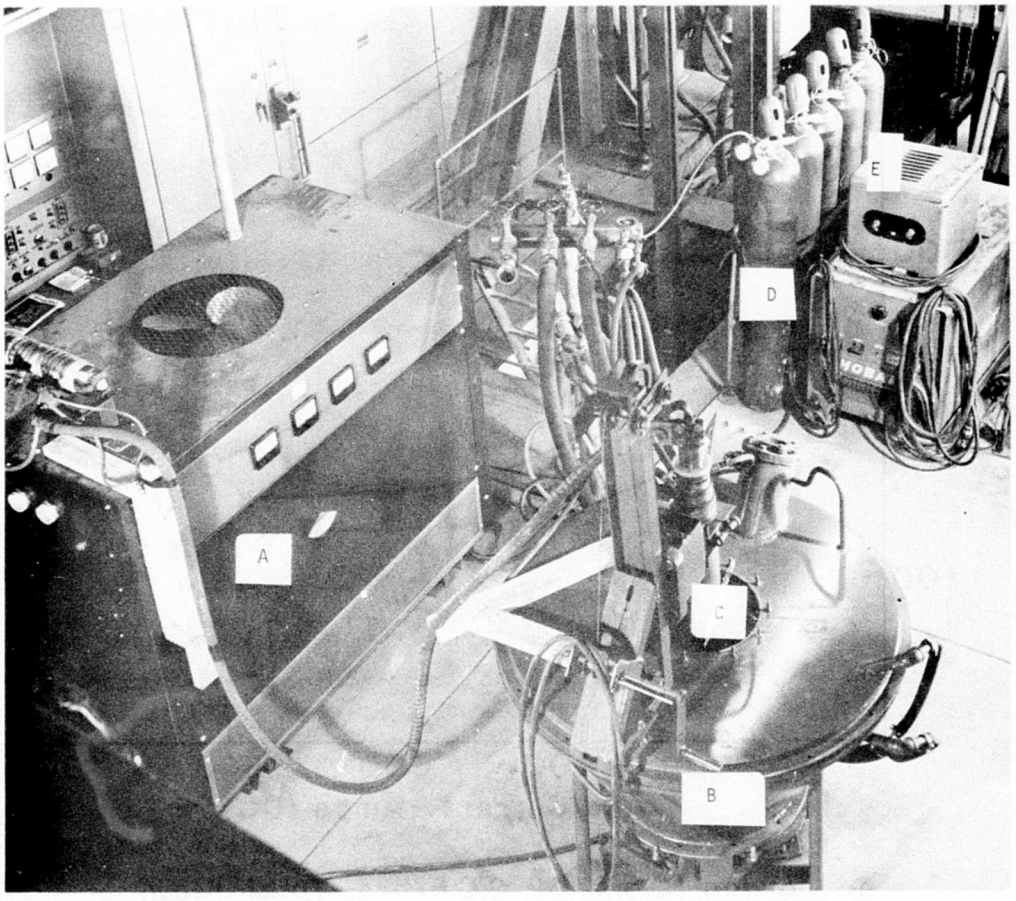
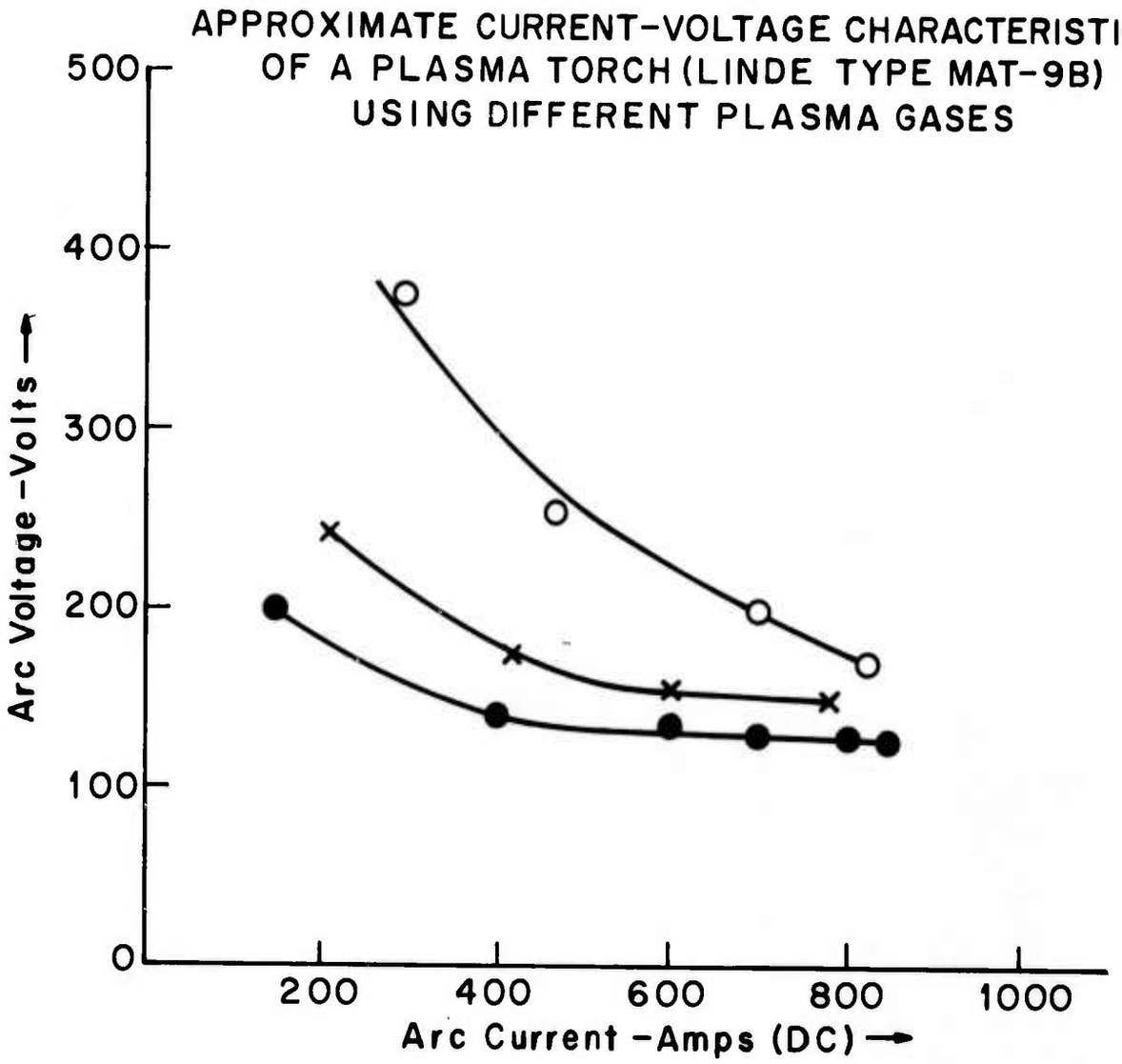


Figure 34

Sub-scale Plasma Melting System.

a. 300 KVA, AC-DC Power Supply
b. Furnace Enclosure (Water Cooled)
c. Plasma Torch
d. Torch and Furnace Gas Supply
e. High Frequency Pilot Arc Starter

Figure 35



● Argon 100% 42 S.C.F/hrs. Torch Flow

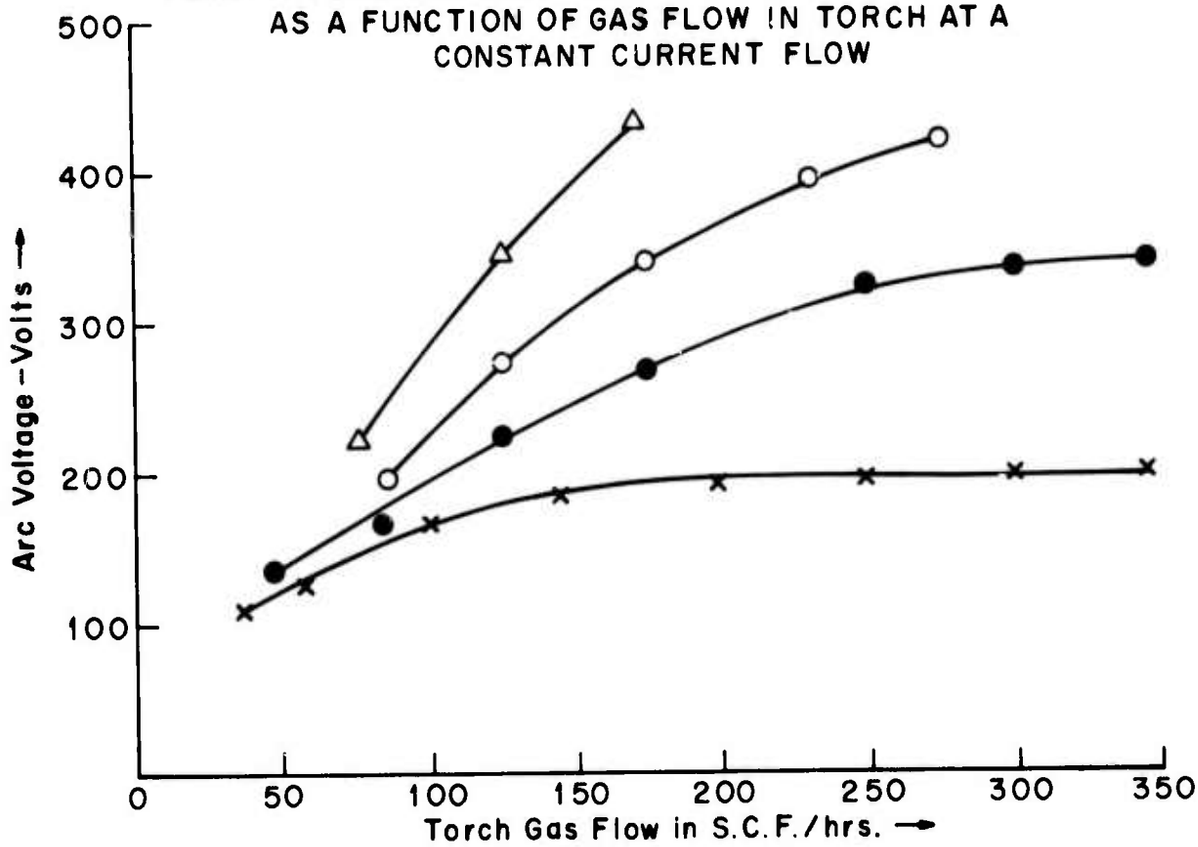
× 90:10 Argon-Hydrogen Mixture-65 S.C.F/hr.

○ 65:35 Argon-Hydrogen Mixture 108 S.C.F/hr.

Furnace Chamber Filled With Argon
Plasma Torch Nozzle-3/4 inch I.D.
Back Electrode-1 inch I.D. 6 5/8 inch Length

Figure 36

PLASMA TORCH OPERATIONAL PARAMETERS-ARC VOLTAGE AS A FUNCTION OF GAS FLOW IN TORCH AT A CONSTANT CURRENT FLOW



△ 80:20 Argon-Hydrogen Mixture in Torch
○ 92:8 Argon-Hydrogen Mixture in Torch
● 100% Argon in Torch. 100% Nitrogen-130 S.C.F./hr. in Furnance Chamber.
× 100% Argon in Torch

100% Argon at 110 S.C.F/hr. in Furnace Chamber Except Where Noted Otherwise

700 Amp DC Current Flow in Torch-(3/4 inch I.D. Nozzle (1 inch I.D.-6 5/8 inch Long Hollow Copper Electrode)

LINDE TORCH-MAT-9B

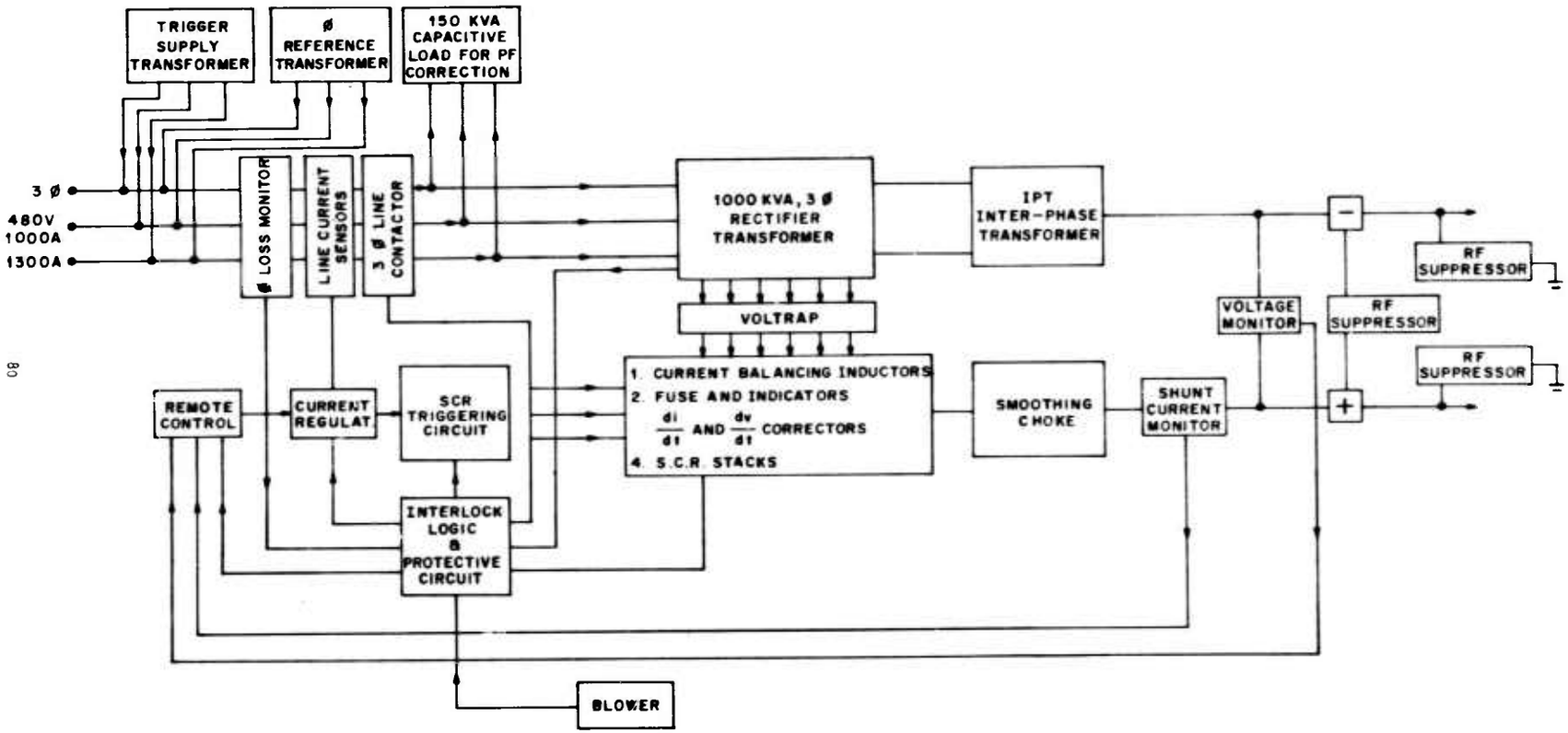


Figure 37

A Block Diagram of the Plasma Torch Power Supply System.

TABLE 1

PLASMA INOUCTION MELTING LOG FOR IRON-BASE SUPERALLOY A-286
(Oaido Steel - 600 Kg Furnace)

	Time	Operation	Temp. °C	Chemical Composition (% Wt.) C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Ti	Al	B	O (ppm)	N	H	Weight of Molten Steel	Remark
A-286	8° 37'	IF on																			
	10° 30'	FCrL4 118.7 kg																			
	11° 07'	MO FSi 2.5 kg																			
	11° 10'	NO1	1570	.012	.38	.07	.008	.018	.06	27.77	15.12	1.27	---	---	---	---	172	.018			
	11° 39'	Comp. Control Al 2.0 kg Ti 11.8 kg																			
68	47'	NO2	1590	.040 .039	.48	1.54	.005	.016	.072	26.08	14.96	1.21	.29	2.22	---	---	---	.008			Ti Recovery 88%
	12° 08'	Comp. Control FB 0.15 kg											V, Ti, Al - no addn.								
	17'	8.0 kg NO3	1565	.037	.54	1.74	.011	.016	.08	---	15.04	1.20	.34	2.12	.21	.0070	76	.006		486 kg	Ti Oxidation Rate .003%/Min.
	19'	Tap																			
		In Ingot Case															53				Overall Recovery - 94%

Memorandum: Comp. Control - Chemical Composition Control

TABLE 2

PLASMA INDUCTION MELTING LOG FOR NICKEL-BASE SUPERALLOY INCONEL 718
(Daido Steel - 600 Kg Furnace)

	Time	Operation	Temp. °C	Chemical Composition (% Wt.) C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	Ta	Ti	Al	O (ppm)	N	H	Weight of Molten Steel	Remark
Inconel 718	12° 25'	IF on																			
	13° 28'	M0																			
	35'	N01		.049	---	---	---		---	---	---	---	---	---	---	---	40				
	50'	FCrL4 150 kg																			
	14° 17'	N02	1575	.030	.24	.11	---	.012	---	56.86	20.18	3.07	---	---	---	---	140				
	42'	Comp. Control																			
	45'	FNb 41 kg																			
	51'	MTi 5.42 kg																			
	56'	N03	1600	.040	.47	---	---	.013	---	52.66	17.51	3.07	4.73	---	.88	.07	60				
	15° 20'	FCrL4 5.3 kg																			
		Ni-Mg 0.3 kg																			
	28'	N04	1570	.049	.49	.30	.005	.013	.05	---	18.13	2.94	---	---	.76	.52	40			520 kg	
		Tap																			
		In Ingot Case															37				Overall Recovery - 95.5%

Memorandum: Comp. Control - Chemical Composition Control

TABLE 3

ALLOYING ELEMENT RECOVERY IN PLASMA INDUCTION MELTED ALLOYS
(Daido Steel Data)

Element	Yield of Alloy Addition (%)
C	100
Si	99
Mn	98
Cr	100
Al	96.5
Ti	95.5
V	100
B	95.0
Nb	97.0

TABLE 4

CHEMICAL ANALYSES INCLUDING GAS CONTENT OF PLASMA INDUCTION MELTED A-286

Ingot No.	C	Si	Mn	P	S	Ni	Cr	Mo	V	Ti	Al	B
M 3142	.04	.91	1.89	.012	.026	25.71	15.32	1.31	.36	3.04	.25	.007
M 4128	.03	.65	1.70	.017	.015	25.46	15.35	1.27	.30	2.28	.17	.007
M 4129	.04	.86	1.80	.012	.014	25.42	15.26	1.28	.49	3.07	.31	.007
M 4130	.04	.81	1.92	.008	.012	25.85	15.27	1.28	.49	3.09	.29	.006
M 4131	.04	.82	1.95	.006	.013	25.36	15.16	1.27	.54	3.04	.31	.006

TABLE 4 (Continued)

CHEMICAL ANALYSES INCLUDING GAS CONTENT OF PLASMA INDUCTION MELTED A-286

Ingot No.		Oxygen	Nitrogen	Hydrogen
M 3142	Top	32 ppm	40 ppm	< 1 ppm
	Bottom	28 ppm	43 ppm	< 1 ppm
M 4128	Top	30 ppm	42 ppm	--
	Bottom	26 ppm	41 ppm	--
M 4129	Top	28 ppm	38 ppm	--
	Bottom	30 ppm	36 ppm	--
M 4130	Top	22 ppm	34 ppm	--
	Bottom	20 ppm	32 ppm	--
M 4131	Top	20 ppm	31 ppm	--
	Bottom	20 ppm	33 ppm	--

TABLE 5

ROOM TEMPERATURE AND ELEVATED TEMPERATURE TENSILE DATA FOR PLASMA INDUCTION MELTED AND REMELTED A-286

Test Temp.	Yield 0.2% Offset KSI	Tensile KSI	Elongation %	Red of Area %
ESR Ingot 1017-05 - PI Electrode 4131				
RT	116.4	168.0	25.5	40.5
400°F	103.4	158.0	21.5	39.5
750°F	105.0	150.0	22.0	41.0
920°F	111.3	144.0	20.5	38.5
1020°F	110.5	142.0	23.0	38.5
1100°F	106.0	140.0	23.5	43.0
1200°F	108.0	132.0	29.0	43.0
1300°F	93.0	114.0	27.0	38.0
PI Electrode - Forged in a GFM Machine to 3" Bar				
RT	99.5	150.2	24.0	38.0
1100°F	96.4	138.0	22.0	36.0
1200°F	93.0	128.0	25.0	37.0
1300°F	89.5	111.0	24.0	33.0

Heat Treatment

1800°F - 1 hr. - OQ
1650°F - 2 hr. - OQ
1300°F - 16 hr. - AC

TABLE 6

CHEMICAL ANALYSES OF INCONEL 718 SCRAP USED IN THE PLASMA INDUCTION FURNACE MELTS AND THAT OF THE RESULTANT ALLOY INGOT

Elements	Scrap	Melt 5405	Ingot 5405	Melt 5406	Ingot 5406
C	0.037	.10	.08	.08	.06
Mn	0.04	.30	.19	.30	.19
Si	0.006	.003	.003	.004	.004
Cr	17.99	17.73	17.75	18.14	17.90
Fe	18.96	18.50	18.97	18.93	19.07
Co	0.14	0.29	0.26	0.30	0.26
Mo	3.02	3.07	3.09	2.99	3.05
Nb + Ta	4.87	5.13	4.90	5.14	4.93
Ti	1.06	1.20	1.08	1.12	1.00
Al	0.46	0.68	0.46	0.51	0.38
B	0.003	0.006	0.01	0.005	0.01
Ni	53.19	53.40	52.80	52.80	52.62

TABLE 7

TRACE ELEMENT AND GAS ANALYSES DATA OF INCONEL 718 SCRAP CHARGE AND RESULTANT PLASMA INDUCTION MELTED INGOTS (S-5405 AND S-5406).

Element	Specification Maximum Limit (PPM)	PI-Ingot S-5405 (PPM)	PI-Ingot S-5406 (PPM)	Sheet Scrap S4 (PPM)	Bar Scrap S3 (PPM)	Castings S1 (PPM)
Ag	10	0.5	1.1	0.2	0.4	0.3
Pb	Class A 5 Class B 3	7.3***	5.3	0.3	2.0	0.3
Bi	1	3.0	4.6	< 0.1	0.1	< 0.1
Te	Class A 5 Class B 3	< 0.1	< 0.1	0.1	0.1	0.1
Tl	1	< 2	< 2	< 1	< 1	< 1
Pb+Bi+Te +Tl	10	13.10	12.10	< 2	< 4	< 2
O	50	16	14	-	-	-
N	50	160	150	-	-	-
As	100	34	23	12	17	17
Se	100	0.1	0.3	0.1	0.8	0.2
Ga	100	11	11	4.6	9.0	7.8
(Cu (Nb (Ta	1000) 500) 500)					
H	25	4.1	-	-	-	-
Li	25	-	-	-	-	-
Be	25	-	-	-	-	-
F	25	-	-	-	-	-
Na	25	-	-	-	-	-
Mg	25	-	-	-	-	-
Cl	25	-	-	-	-	-
K	25	0.4	0.6	0.1	0.5	0.2
Ca	25	34**	18	2.8	4.1	5.8
Sc	25	1.3	1.5	0.02	0.02	0.02
V	25	170	290	100	90	240
Zn	25	9.7	8.2	0.9	3.2	2.0
Ge	25	6.7	5.5	3.3	6.8	5.6
Br	25	-	-	-	-	-
Rb	25	1.0	1.0	0.4	0.4	0.9
Sr	25	0.8	1.2	0.1	0.3	0.2
Y	25	0.6	0.4	0.3	0.9	0.4
Zr	25	11	11	1.1	180	1.5
Ru	25	< 3	< 3	≤ 2	≤ 2	≤ 2
Rh	25	n.d.*	n.d.	n.d.	n.d.	n.d.
Pd	25	18	18	2	5	5
Cd	25	1.0	2.0	0.4	0.8	0.9
In	25	0.9	0.3	< 0.5	< 0.5	< 0.5
Sn	25	35	22	14	22	16
Sb	25	11	6.4	5.6	5.1	8.7

TABLE 7 (Continued)

Element	Specification Maximum Limit (PPM)	PI-Ingot S-5405 (PPM)	PI-Ingot S-5406 (PPM)	Sheet Scrap S4 (PPM)	Bar Scrap S3 (PPM)	Castings S1 (PPM)
I	25	-	-	-	-	-
Cs	25	< 0.02	< 0.02	0.05	0.05	0.05
Ba	25	< 0.1	< 0.1	< 0.1	1.0	< 0.1
La	25	< 0.1	< 0.1	< 0.05	<u>35</u>	< 0.05
Ce	25	< 0.1	< 0.1	< 0.5	<u>120</u>	< 0.5
Pr	25	< 0.2	< 0.2	0.1	13	0.1
Nd	25	< 0.3	< 0.3	1	33	1
Sm	25	< 1	< 1	0.5	0.5	0.5
Eu	25	< 2	< 2	3	3	3
Gd	25	n.d.	n.d.	n.d.	n.d.	n.d.
Tb	25	n.d.	n.d.	n.d.	n.d.	n.d.
Dy	25	n.d.	n.d.	n.d.	n.d.	n.d.
Ho	25	n.d.	n.d.	n.d.	n.d.	n.d.
Er	25	n.d.	n.d.	n.d.	n.d.	n.d.
Tm	25	n.d.	n.d.	n.d.	n.d.	n.d.
Yb	25	n.d.	n.d.	n.d.	n.d.	n.d.
Lu	25	n.d.	n.d.	n.d.	n.d.	n.d.
Hf	25	< 2	< 2	< 2	< 2	< 2
W	25	<u>280</u>	<u>170</u>	<u>39</u>	<u>45</u>	<u>74</u>
Re	25	9	15	10	10	10
Os	25	< 5	< 5	15	15	15
Ir	25	< 7	< 7	3	3	3
Pt	25	< 2	< 2	< 2	< 2	< 2
Au	25	< 1	< 1	< 0.5	< 0.5	< 0.5
Hg	25	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Th	25	n.d.	n.d.	n.d.	n.d.	n.d.
U	25	n.d.	n.d.	n.d.	n.d.	n.d.

Every element -- mass spectrum analysis data (except O, N and H).

Sheet Scrap - Approximately - 1/8" Thick
Bar Scrap - 0.32" Diameter

*Not detected

**Underlined (double) are values exceeding the specification maximum

TABLE 8

MECHANICAL PROPERTY DATA FOR PLASMA INDUCTION MELTED AND CAST INCONEL 718 (HEAT S-5405 EVALUATED IN PHASE I OF THIS PROGRAM)

Type of Test	Material Condition	Testing Temp.	Spec. Orien.	UTS KSI	0.2 YS KSI	Elong. %	RA %	Life HRS	BHN
Tensile	Cast	RT	L	176.4	137.9	23.0	38.8		
		RT	T	169.0	131.6	20.0	23.0		
		1200°F	L	149.5	122.3	18.0	35.5		
		1200°F	T	137.6	113.3	18.0	29.8		
		1300°F	L	131.6	112.9	17.0	20.8		
		1300°F	T	124.5	106.4	10.0	20.2		
		1400°F	L	109.7	90.5	8.0	11.5		
		1400°F	T	99.4	83.5	10.0	17.4		
Stress Rupture	Cast								
160 KSI		1000°F	L			24.0	27.0	BL[1]	
160 KSI		1000°F	T			21.0	28.4	BL	
110 KSI		1200°F	L			4.0	7.7	44.8	
110 KSI		1200°F	T			6.0	14.5	8.0	
100 KSI		1200°F	L			N-B[2]	N-B[2]	43.4	
100 KSI		1200°F	T			2.0	13.1	35.1	
75 KSI		1300°F	L			6.0	10.1	37.9	
75 KSI		1300°F	T			4.0	8.5	25.2	

Note: Mechanical test specimens of this table were heat treated as follows: 1750°F/1 hr/AC + 1325°F/8 hr/FC to 1150°F/8 hr/AC

[1] Broke on loading

[2] Notch brittle

TABLE 9

MECHANICAL PROPERTY DATA FOR PLASMA INDUCTION MELTED AND FORGED INCONEL 718 (HEAT S-5406 EVALUATED IN PHASE I OF THIS PROGRAM)

Type of Test	Material Condition	Testing Temp.	UTS KSI	0.2 YS KSI	Elong. %	RA %	Life HRS	BHN
Tensile	Wrought	RT	192.2	174.8	18.8	29.2		423
		RT	196.1	172.3	19.2	27.9		
		1200°F	168.0	148.8	21.6	30.8		
		1300°F	139.2	123.5	19.3	28.8		
		1400°F	121.8	109.3	16.9	22.3		
Stress Rupture	Wrought							
110 KSI		1200°F			9.0	26	108	
110 KSI		1200°F			8.0	29	132	
75 KSI		1300°F			6.0	14	61	
75 KSI		1300°F			5.0	13	42	

Note: All test specimens received conventional heat treatment: 1750°F/1 hr/AC + 1325°F/8 hr/FC to 1150°F for 8 hr/Ac.

TABLE 10

INFORMATION RELATIVE TO THE PLASMARC REMELTED HIGH NITROGEN AUSTENITIC NICKEL-CHROMIUM STEEL PROCURED FROM THE U.S.S.R.

Ingot Production Source - "ELECTROSTAL"
Grade of Steel - PD 722
Net Weight - 336 Kg
Ingot Diameter - 250 mm
Ingot Length - 0.9 in.

Ingot Metal Chemical Analysis

Elements in %	Producer's Report	Mellon Check Report
C	0.02	0.016
Si	0.20	0.18
Mn	6.52	6.57
S	0.009	0.008
P	0.013	0.013
Cr	20.30	20.25
Ni	7.00	7.01
Mo	2.46	2.43
Nitrogen	0.48	0.40

Nitrogen Analysis (in Wt. Percent) From Top and Bottom Ingot Locations

	Edge	1/3 Rad.	2/3 Rad.	Center
Ingot top	0.45	0.48	0.44	0.43
Ingot bottom	0.40	0.41	0.40	0.38

Nitrogen Analysis (in Wt. Percent) of Samples from Forged Bar of This Ingot

Top end	0.41	0.40
Middle	0.42	0.38
Bottom end	0.42	0.39

TABLE 11

ROOM TEMPERATURE TENSILE TEST RESULTS FOR PLASMARC REMELTED HIGH NITROGEN AUSTENITIC STEEL
(Cast Condition)

Specimen No.	Specimen Location in Ingot	Tensile Strength psi	.2% Offset Yield Strength psi	.02% Offset Yield Strength psi	Elongation, %	Reduction in Area %
1-T1	Bottom	86,773	46,092	42,084	50.0	50.7
1-T2	Bottom	86,972	45,090	42,084	51.0	47.8
1-T3	Bottom	92,929	49,898	46,464	54.0	51.3
2-T1	Top	88,176	46,693	43,086	54.0	59.2
2-T2	Top	86,868	48,484	46,464	55.0	63.0
2-T3	Top	87,975	49,098	46,092	55.0	70.5
1-L1	Bottom	98,196	51,903	46,092	57.0	71.4
1-L2	Bottom	101,603	51,703	48,096	58.0	63.3
1-L3	Bottom	92,985	51,302	48,096	55.0	69.5
2-L1	Top	100,200	52,905	48,096	56.0	69.2
2-L2	Top	94,949	50,505	46,464	54.0	68.8
2-L3	Top	101,402	52,304	48,096	55.0	69.9

L - Longitudinal

T - Transverse

TABLE 12

ROOM TEMPERATURE TENSILE TEST RESULTS FOR PLASMARC REMELTED HIGH NITROGEN AUSTENITIC STEEL (Wrought Condition)

Specimen No.	Specimen Location in Ingot	Tensile Strength psi	.2% Offset Yield Strength psi	.02% Offset Yield Strength psi	Elongation, %	Reduction in Area %
A5-T1	Bottom	109,218	71,743	---	23.0	45.4
A5-T2*	Bottom	90,981	78,156	---	6.0	19.6
A10-T4	Bottom	122,444	80,961	---	30.0	51.3
A10-T5	Bottom	120,641	78,757	---	35.0	46.6
A11-L2	Bottom	125,651	80,160	---	43.0	68.7
A11-L3	Bottom	129,058	80,961	---	42.0	73.3
B4-T2	Top	128,256	86,172	---	30.0	44.2
B4-T3	Top	126,052	87,975	---	27.0	47.2
B7-L4	Top	127,454	86,172	---	40.0	70.5
B7-L5	Top	137,074	98,196	---	38.0	70.5
B7-L6	Top	143,486	105,811	---	37.0	67.7
B7-T3	Top	134,268	98,196	---	35.0	51.3

*Broke because of lap or seam

L - Longitudinal

T - Transverse

TABLE 13

IMPACT TEST RESULTS FOR PLASMARC REMELTED HIGH NITROGEN AUSTENITIC STEEL (Cast Condition)

Specimen Code	Speciman Location	Testing Temperature	Energy ft-lbs
L1-1	Top - Edge	RT	203.0
L1-2	Top - Center	RT	57.0
L1-3	Top - Mid Rad.	RT	70.5
T1-1	Top - Center	RT	59.0
T1-2	Top - Edge	RT	64.5
L4-1	Bottom - Mid Rad.	RT	68.5
T2-2	Bottom - Mid Rad.	RT	74.5
T4-1	Bottom - Edge	RT	83.5
L2-1	Top - Edge	-40°F	141.0
T2-1	Top - Edge	-40°F	54.0
T5-1	Top - Center	-40°F	46.0
L3-2	Bottom - Edge	-40°F	138.0
L5-1	Bottom - Center	-40°F	91.0
T3-2	Bottom - Center	-40°F	65.0
L4-2	Top - Center	-100°F	32.0
T6-1	Top - Center	-100°F	44.0
L3-1	Bottom - Edge	-100°F	109.0
L6-1	Bottom - Center	-100°F	62.0
T3-1	Bottom - Edge	-100°F	25.0
T4-2	Bottom - Center	-100°F	11.0

L - Longitudinal specimens

T - Transverse specimens

Top - Ingot top

Bottom - Ingot bottom

TABLE 14

IMPACT TEST RESULTS FOR PLASMARC REMELTED
HIGH NITROGEN AUSTENITIC STEEL
(Wrought Condition)

Specimen Code	Specimen Location	Testing Temperature	Energy ft-lbs
A4T2	Top - Center	RT	46.0
A8T5	Top - Edge	RT	65.0
A12L2	Top - Mid Rad.	RT	194.0
L6	Top - Edge	RT	224.0
B5T2	Bottom - Edge	RT	49.0
T3	Bottom - Center	RT	46.0
B6T2	Bottom - Mid Rad.	RT	52.0
T3	Bottom - Center	RT	58.0
B7L1	Bottom - Edge	RT	216.0
L2	Bottom - Mid Rad.		181.0

T - Transverse

L - Longitudinal

TABLE 15

CHEMICAL ANALYSES OF INCONEL 718 SCRAP USED AND THAT OF THE RESULTANT PLASMA MELTED INGOT

Elements	Scrap	PM Ingot
Mo	3.05	3.05
Ta	.011	.012
Nb	4.90	4.89
Cu	.013	.012
Ni	53.33	53.32
Co	.12	.13
Fe	18.94	18.93
Mn	.051	.049
Ti	.93	.93
Si	.12	.12
Al	.38	.38
Cr	18.00	18.01
B	.0031	.0031
C	.040	.041
S	.008	.007
P	.009	.008

TABLE 16 - A

LOGS OF INCONEL 718 PLASMA MELTS MADE IN HOT-WALL CRUCIBLE

Charge - 805 lbs. Inconel 718 - chunks, clippings and master alloys

November 30, 1973

Heat 103

Current	Voltage	KW	Time Min.	KWH
1500	150	225	5.625	21.13
2550	170	433.5	6.750	48.57
2800	170	476	64.575	512.33
1500	135	202.5	7.425	24.96
	Total for Melt		84.375 Min.	606.99 KWH

Total Charge Wt. = 805 lbs.

Power Consumption/Ton = 1510 KWH

TABLE 16 - B

PLASMA MELT

November 28, 1973

Heat 104

Current	Voltage	KW	Time Min.	KWH
1500	150	225	3.50	11.7
2100	180	380	6.15	39.0
2600	190	495	2.85	23.5
2800	190	530	2.55	22.6
3000	190	570	1.75	16.6
	Total for Melt		16.80 Min.	113.4 KWH

$$\text{KWH/lb.} = \frac{113.4}{670} = 0.17 \text{ KWH/lb.}$$

TABLE 17

A SUMMARY REPORT OF PLASMARC MELTING AND INGOT WITHDRAWAL SYSTEMS CHECK-OUT OPERATIONS

During the month of May several melts were made to check out the plasma torch and the withdrawal system. The first run of any duration was made on May 8, 1974. A listing of the melting parameters is given below.

Time	Amperage X 10^{-3}	Voltage	Argon Flow Rate CFM
0:00	1	130	18
0:10	1.5	150	18
0:20	2	145	18
0:28	1	137	Turned plasma off. Fed some material.
0:37	Turned back on at 1000 amps and slowly increased to 2000 A.		
0:47	2	150	18
0:47	Turned off again to feed more scrap. Turned back on at 0:51.		
0:51	2	140	18
0:57	2	160	18
1:01	Power supply blew a fuse. Terminated melt.		

The total weight of maraging steel melted during the above run was 230 lbs.

Several further melts were made to check out the plasma torch. Operating parameters were from 145-165 volts and current up to 2500 amps with Ar flow rates up to 30 CFM. During the runs which were of a total duration of 1 hour 47 minutes approximately 6-1/2" of ingot were melted.

Another melt using the following parameters was made on the same ingot.

0	Pilot arc		12
0:01	.7	140	20
0:02	1	145	20
0:03	2	150	27
0:09	2.5	155	27
0:31	2.5	165	29

Terminated melt after 2 hours 45 minutes.

TABLE 17 (Continued)

The total amount of material melted in these last two runs was approximately 1050 lbs.

One more test run was made in order to finish melting all of the available maraging steel. The total duration of this run was 1 hour 50 minutes.

After initial startup the operating parameters were set at 2000 amps, 150 volts, 25 CFM argon for 11 minutes. Then the current was increased to 2500 amps, the voltage to 165 volts and the argon flow rate to 29 CFM for the remainder of the melt.

A total of 725 lbs. was melted.

Both the torch and the withdrawal system appeared to be operating satisfactorily in these last two melts.

TABLE 18

A LISTING OF PLASMA MELTING STOCK SUPPLIED TO SCHLIENGER, INC.

1.	Inconel 718 Sheet Clippings	2002 lbs.
2.	Incoloy 600	682 lbs.
3.	CP Titanium Sponge	300 lbs.
4.	Ti-6Al-4V Sponge, Master Alloy Mix	322 lbs.
5.	Inconel 718 - 6 Inch Diameter Electrode	785 lbs.
6.	Inconel 718 - 6 Inch Diameter Electrodes	1985 lbs.

Test Melt Stock

Maraging Steel Scrap 2103 lbs.

TABLE 19

MELT LOG OF PLASMA MELTED AND WITHDRAWAL CAST INGOT FROM INCONEL 718 SHEET CLIPPINGS

(June 1974, Schlienger, Inc.)

Weight of Ingot - 520 lbs.

Dimensions - 13.85 Inch Diameter 12.5 Inch Long

Ingot Casting Method - Melt-Ingot Withdrawal

Melting Conditions

Time	Voltage	Amp x 10^{-3}	Argon (S.C.F.M.)
0:00	Initiated pilot arc		8-16
0:01	150	1.5	25
0:02	150	2.0	29
0:12	160	2.5	30
Steady melting continued			
2:06	Melt terminated		

Ingot Condition: Surface appearance overlapped metal layers

Disposition: Unsuitable for direct forging

TABLE 20

CHEMICAL ANALYSES OF INCONEL 718 SHEET CLIPPINGS AND OF THE RESULTANT PLASMARC MELTED 14 INCH DIAMETER WITHDRAWAL CAST INGOT OF INCONEL 718 ALLOY

Elements	Scrap	Ingot Bottom	Ingot
C	0.047	0.056	0.050
Mn	0.050	0.059	0.06
Si	0.12	0.10	0.10
S	0.008	0.007	0.008
P	0.009	0.010	0.09
Cr	17.99	17.96	17.91
Fe	18.96	19.10	18.62
Co	0.14	0.10	0.10
Mo	3.02	3.07	3.01
Nb + Ta	4.97	5.01	4.99
Ti	0.93	0.91	0.92
Al	0.46	0.41	0.39
B	0.003	0.0028	0.003
Cu	0.01	0.01	0.01
Ni	53.19	53.16	53.13
O_2	0.0014	0.0029	0.0021
N_2	0.008	0.010	0.007

TABLE 21

MECHANICAL PROPERTY DATA FOR PLASMA PLUS ELECTROSLAG REMELTED* INCONEL 718 ALLOY

Type of Test	Material Condition	Testing Temp.	Spec. Orien.	UTS KSI	0.2 YS KSI	Elong. %	RA %	Life HRS
Tensile	Cast	RT	L	180.2	143.8	21	36.0	
		RT	T	181.8	142.6	20	33.1	
		1200°F	L	158.8	131.2	18	30	
		1200°F	T	146.2	124.3	19	29.8	
		1300°F	L	133.6	118.2	16	21	
		1300°F	T		Broke in threads			
	Wrought	RT	L	196.8	179.2	20	31	
		RT	T	192.6	176.4	19	29.5	
		1200°F	L	170.4	153.8	20.6	30.2	
		1300°F	T	143.8	126.2	19.8	27.8	
		1400°F	L	124.2	113.4	15.6	21.8	
Stress Rupture	Wrought							
110 KSI		1200°F	T			5.8	8.0	56
110 KSI		1200°F	L			5.2	8.2	48
75 KSI		1300°F	L			7.1	10.8	37

Heat Treatment - Solution anneal 1750°F for 1 hour, AC, duplex age at 1325°F for 8 hours, furnace cool to 1150°F and holding at 1150° for a combined total aging time of 18 hours.

*Inconel 718 sheet clipping scrap consolidated into 13.8 inch diameter electrode by plasmarc melting in a withdrawal crucible and the electrode subsequently electroslag remelted into a 16 inch diameter ingot.

TABLE 22

MELT LOG OF PLASMA DRIP MELTED 13.5 INCH DIAMETER, 750 POUND INGOT OF INCONEL 718 ALLOY

Time	Amp X 10^{-3}	Voltage	Argon (S.C.F.M.)
June 10, 1974			
11:45	2.5	165	29
12:19	2.5	165	29
June 11, 1974			
10:16 to 10:18	Initiate pilot arc and arrive at the following operating parameters.		
10:18	2.5	150	30
10:24	2.5	175	30
10:33	2.25	215	30
10:49	Shut off as ingot would not withdraw.		
June 19, 1974			
10:51	Initiate pilot arc.		
10:53	2.0	165	25
11:00	2.3	180	28.5
11:47	Power off.		
3:35	2.5	175	29
4:00	Power off. Would not withdraw.		
June 26, 1974			
10:46	1.5	130	20
10:53	2.0	180	28
11:02	2.5	175	29
12:16	2.0	150	29
12:20	1.5	150	29
12:23	1.0	140	29
12:25	Power off.		

TABLE 23

MELT LOG OF PLASMA DRIP MELTED 13.5 INCH DIAMETER, 350 POUND INGOT OF INCONEL 718 ALLOY

Time	Amp X 10^{-3}	Voltage	Argon (CFM)
July 1, 1974			
10:30	2.5	160	29
10:38	Shut down. Would not withdraw.		
08			
July 2, 1974			
8:13	Pilot arc.		
8:15	2.0	155	16
8:23	2.5	165	29
8:38	Started raising torch.		
8:42	2.5	180	29
8:55	2.5	170	29
9:14	2.5	200	29
9:28	Shut down because of feeding problems. Electrode fed back instead of forward. Opened furnace and reversed electrode.		
75			
1:50	Pilot arc.		
1:52	1.5	130	25
1:56	1.5	130	29
2:03	2.15	200	29
2:08	2.4	200	29
2:17	2.5	200	29
2:24	2.5	180	29
2:40	2.5	200	29
3:00	2.5	180	29
3:20	2.5	180-190	29
3:52	2.5	180	29
3:54	Stub of electrode fell into pool.		
4:00	2.5	160	29
4:10	2.5	170	29
4:20	Terminated melt.		
2:30			

Total melt time 3.38 hours
= 3 H 23 min.

TABLE 24

MELT LOG OF PLASMA DRIP MELTED 13.5 INCH DIAMETER, 794 POUND INGOT OF INCONEL 718 ALLOY

July 22, 1974

Time	Voltage	Amp X 10^{-3}	Argon (S.C.F.M.)
1:57	Established pilot arc		
1:58	150	2.0	29
2:14	150	2.5	29
2:45	Terminated melt. Electrode would not feed.		

July 23, 1974

8:45	Established pilot arc.		
8:46	130	1.5	29
8:48	150	1.5	29
8:53	165	2.0	29
8:56	165	2.5	29
9:00	200	2.0	29
9:17	200	2.3	29
9:47	Arc extinguished.		
9:47 to 10:05	Established and lost arc. 3 times. Arc extinguished each time attempts were made to extend the column.		
10:05	170-180	2.5	29
10:25	Terminated because of inability to extend arc column.		

July 23, 1974

3:30	Established pilot arc.		
3:31	160	2.0	29
3:38	200	2.5	29
3:40	Arc extinguished.		
3:50	Established pilot arc.		
3:51	160	2.0	29
3:53	165	2.5	29
	Arc extinguished when attempt was made to lengthen arc column.		

July 24, 1974

12:45	Initiated pilot arc.		
12:46	125	1.5	29
12:51	140	2.0	29
12:53	155	2.5	29
1:07	185-190	2.0	29
1:12	200 (app.)	2.5	29
1:51	Terminated. Feeder quit rotating. Also found a hole in the Argon line leading to the torch.		

TABLE 24 (Continued)

Time	Voltage	Amp X 10^{-3}	Argon (S.C.F.M.)
July 26, 1974			
4:38	Initiated pilot arc.		
4:39	130	1.5	29
4:40	Arc blew out.		
4:41	Initiated pilot arc.		
4:42	140	1.5	25
4:46	160	2.0	28
4:48	165	2.5	29
4:54	Lost arc column too long.		
4:55	Initiated pilot arc.		
4:56	160	2.0	29
4:58	160	2.5	29
5:00	190	2.5	29
5:03	200	2.5	27
5:50	Lost arc.		
5:51	Initiated pilot arc.		
5:51	200 (app.)	2.5	29
6:00	Lost arc.		
6:02	Initiated pilot arc.		
6:03	200 (app.)	2.5	29
	Both voltage and current very unstable.		
6:21	Terminated - feeder would not rotate.		

TABLE 25

CHEMICAL ANALYSES OF PLASMA DRIP MELTED ELECTRODE OF INCONEL 718, RESULTANT INGOT AND FORGED PLATE

Elements	Electrode	Ingot	Forged Plate	
C	0.048	0.005	0.005	
Si	0.13	0.12	0.12	
Mn	0.06	0.05	0.05	
S	0.006	0.004	0.003	
P	0.008	0.008	0.007	
Cb + Ta	5.11	5.09	5.04	
Fe	19.80	19.92	19.90	
W	0.04	0.04	0.04	
Cr	18.33	18.32	18.35	
V	0.04	0.04	0.03	
Ni	51.98	51.66	51.60	
Mo	3.00	3.02	3.01	
Co	0.09	< 0.10	< 0.10	
Cu	0.04	< 0.05	< 0.05	
Al	0.60	0.59	0.58	
Ti	1.00	0.99	0.99	
B	0.004	0.038	0.038	
N_2	0.010	0.008	0.008	
O_2	0.008	0.026	0.023	
Sn	14 PPM	5 PPM	5.6 PPM	Mass Spectral Analysis (Daido Steel)
Pb	4.8 PPM	2 PPM	2 PPM	
Bi	3.8 PPM	< 1 PPM	< 1 PPM	
As	23 PPM	5 PPM	4 PPM	
Sb	5.6 PPM	3.8 PPM	4 PPM	

TABLE 26

MECHANICAL PROPERTY DATA FOR PLASMARC DRIP MELTED AND FORGED INCONEL 718

ASTM Grain Size 6/7

Type of Test	Test Temp.	UTS KSI	0.2% YS KSI	Elong. %	RA %	Life HRS
Tensile	RT	189	168	16	26	
	1200°F	169	146	18	28	
	1300°F	146	121	19	22	
	1400°F	103	88	21	26	
Stress Rupture						
110 KSI	1200°F			9		116
75 KSI	1300°F			8		93
50 KSI	1400°F			4		88
After 1250°F, 50 KSI Exposure for 200 Hours						
Stress Rupture						
90 KSI	1200°F			10.5	15	136 (NF)
100 KSI	1200°F			10.0	15.5	116 (NF)
After 1300°F, 50 KSI Exposure for 100 Hours						
90 KSI	1200°F			15.5	26	106 (NF)
110 KSI	1200°F			18.8	23	61
100 KSI	1200°F			19.0	24	92

Additional Stress Rupture Data Plotted in Figure 26.

Heat Treatment: 1800°F/1 hr/AC + 1325°F/8 hrs. furnace cool to 1150°F/8 hrs. AC.

TABLE 27

CHEMICAL ANALYSES DATA FOR PLASMA DRIP MELTED INGOT OF INCONEL 718 ALLOY

(Cast Condition - Ingot Section as Shown in Figure 29)

		Plasma Drip Melted Ingot					
		Columnar Grain Section			Equiaxed Grain Section		
Elements	Electrode	Edge	Mid-Radius	Center	Edge	Mid-Radius	Center
C	0.08	0.076	.076	0.077	0.078	0.075	0.081
Si	0.36	0.36	0.35	0.36	0.37	0.34	0.37
Mn	0.30	0.24	0.24	0.24	0.24	0.24	0.24
S	0.004	< .001	< .001	< .001	< .001	< .001	< .001
P	0.008	0.004	0.004	0.003	0.004	0.003	0.004
Cr	18.14	18.07	18.12	18.12	18.13	18.15	18.10
Ni	52.80	51.94	52.10	52.05	52.12	51.80	52.08
Co	0.30	0.27	0.27	0.27	0.28	0.27	0.28
Fe	18.93	Bal	Bal	Bal	Bal	Bal	Bal
Mo	2.99	3.00	3.00	3.00	3.00	2.96	3.00
Cb	-	5.03	5.03	5.01	5.03	4.80	5.02
Ta	0.05	0.08	0.07	0.08	0.09	0.09	0.09
Cb + Ta	5.14	-	-	-	-	-	-
Ti	1.12	1.11	1.07	1.08	1.12	1.07	1.10
Al	0.51	0.49	0.47	0.50	0.50	0.54	0.57
Cu	0.04	0.06	0.04	0.05	0.06	0.07	0.05
B	0.0052	0.004	0.004	0.004	0.004	0.004	0.004
N_2 (PPM)	160	78	76	84	96	90	133
O_2 (PPM)	16	515	512	278	377	384	339
Ag (PPM)	1.1	< 1	< 1	< 1			
Pb (PMM)	5.3	2.3	2.2	2			
Bi (PPM)	4.6	2	2	1.8			
As (PPM)	23	5.2	5	4.6			
Se (PPM)	0.3	< 0.1	< 0.1	< 0.1			
Ga (PPM)	11	< 1	< 1	< 1			
Te (PPM)	< 0.1	< 1	< 1	< 1			
Tl (PPM)	< 2	< 1	< 1	< 1			

NOTE:

Trace element analytical results are for two samples from this ingot - not necessarily representing columnar or equiaxed grain area.

TABLE 28

COMPARISON OF VARIOUS SPECIALTY METAL PRIMARY MELTING PROCESSES

Melting Method Features	Hot-Wall Crucible Plasma Melting (PM)	Plasma Induction Melting (PIM)	Vacuum Induction Melting (VIM)	Electric Arc or Induction Furnace (EF or IF)
Operating Pressure (mm)	760+	760+	10^{-1}-10^{-3}	760
Atmosphere	Inert or Reactive Gas	Inert or Reactive Gas	-	Air/Inert gas
Crucible	Castable Refractory	Refractory	Refractory	Refractory
Slag Treatment	Possible	Possible	No	Electric arc - yes Induction - no
Materials to be Melted				
(a) Steels	All	All	Many	Many
(b) Superalloys	All	All	All	Some
(c) Al or Cu Alloys	All	All	Some	Some
(d) High vapor pressure metals and alloys	Many	Many	No	Some
Scrap	Yes	Yes	Repeated Charging Difficult	Yes - EF Some - IF
Melt rate of charge	Very high	High	Fairly high	Low - EF Fairly high - IF
Efficiency (Kg/KWH)	1.6-1.8 (Preliminary Estimate)	1.1-1.7	1.5-1.9	1.2-2.00

TABLE 28 (Continued)

Melting Method Features	Hot-Wall Crucible Plasma Melting (PM)	Plasma Induction Melting (PIM)	Vacuum Induction Melting (VIM)	Electric Arc or Induction Furnace (EF or IF)
Heat Source	Plasma	Induction + Plasma	Induction	Induction
Investment Cost	80% of VIM system	60% of VIM system	Medium	Small*
Operating Cost	> VIM	> VIM	Low	Low
Quality of Melt	= VIM	= VIM	High	Fair
Yield of Added Metal	High	High	High	Fair
Gas Content	Low	Low	Very low	Higher than in other processes

*Pollution control equipment not included.

TABLE 29

COMPARISON OF VARIOUS SECONDARY REFINING-CONSUMABLE ELECTRODE REMELTING PROCESSES

Melting Method Features	Remelting Methods* PDM	VAR	ESR	EB	PB
Pressure in Melt Chamber mm-Hg	Normal 50-760+ Also very high pressure	10^{-2}-10	760	10^{-5}-10^{-3}	10^{-3}-10^{-1}
Type of Atmosphere	Inert gas/ Reactive gas	-	Air or Protective gas	-	Small amounts of high purity argon in torch
Crucible	Ingot withdrawal	Stationary; Ingot withdrawal	Stationary; Ingot withdrawal; Moving mold	Ingot withdrawal	Ingot withdrawal
Heat Source	Plasmarc single torch or multiple torches	Electric arc	Resistance heating of flux	Single or multiple electron beam	Single or multiple plasma electron beam
Type of Current	AC or DC	DC	AC or DC	DC	DC
Maximum Ingot Size	Not reached; presently 14"ϕ	Appears to be around 60"ϕ	Reached to 90"ϕ; Maximum could be larger	Presently 33"ϕ	Presently 20"ϕ 12" x 40" slab
Types of Material Melted	Various	Consumable electrode	Various	Various	Various
Scrap Melting	Possible	Not possible	Probable	Possible	Possible
Superheating of Melt	Independently possible	Limited	Limited; Slightly better than VAR	Independently possible	Independently possible

TABLE 29 (Continued)

Melting Method Features	Remelting Methods*				
	PDM	VAR	ESR	EB	PB
Slag Refining	Possible	No	Yes	No	No
Impurity Evaporation	Good	Good	No	Excellent	Good
Gas Removal	Good/average	Good	Limited	Very good	Good
Ingot Solidification Control	Excellent; Independently controllable	Limited; Controlled through power input	Variable; Better than VAR	Very good; Independently controllable	Very good; Independently controllable
Ingot Yield (Total)	Good/average	Low	Good	Good/average	Good/average
Ingot Yield (Surface)	Average	Average/low	Good	Average	Average
Quality (Purity)	Higher	High	High	Higher	Higher
Initial Investment	Moderate	High	Moderate	Very high	Very high
Operating Cost	> VAR	Moderate	> VAR	High	High
Efficiency (Kg/KWH)	0.9-1.4 (Preliminary Estimate)	0.8-1.1	0.7-1.1	0.5-0.8	0.7-1.1

*PDM - Plasma Drip Melting;
VAR - Vacuum Arc Remelting;
ESR - Electroslag Remelting;
EB - Electron Beam Melting;
PB - Plasma Beam Melting.