Recent Improvements in the Economics of Plasma Melting

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Abstract: In recent years, plasma melting has become an important technique in the production of titanium and its alloys. Continuing development work has enabled improvements in the econimics of plasma melting which are applicable to production operations.

Background: Improvements in plasma processes for melting reactive and refractory metals have substantially affected both the cost of melting and the properties of the melted metal.

Economic factors discussed below include melt rate, power cost, consumables, yield and raw material cost. The melt rate achievable has a strong effect on the cost of melting. Labor costs are almost independent of melt rate; thus doubling the melt rate reduces the labor cost per pound almost a factor of two. Increasing the melt rate usually also reduces the specific power cost. Consumables include plasma gas consumption, torch replacement parts and maintenance of furnace equipment. Final product yield depends on surface finish, chemistry uniformity, shrinkage porosity, evaporation loss and ingot shape. Raw material costs can be reduced if the process permits achieving product quality standards while feeding lower cost material, e.g. dirtier material.

Quality factors also affect economics of the total process, even if they may not change melting cost per pound. A reduced grain size

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or greater freedom from inclusions affects down-stream processing cost and customer acceptability, thus changes in these are also important.

Technology Improvements Since 1986: One of the most striking improvements in the rate of melting titanium was the substitution of helium for argon as the plasma torch gas. This was first tried at Oregon Metallurgical Corporation in their PASER (Plasma Arc Single Electrode Remelt) furnace, made by Retech. Data on the effects of arc gas, pressure and current in a lab-size furnace were presented at the 1986 Pittsburgh Vacuum Metallurgy Conference(1). When melting titanium at pressures near atmospheric, the melt rate with helium was about twice that with argon at the same torch current and standoff. The difference between argon and helium in specific power to melt is less than for the melt rate, since arc voltage is greater in helium than in argon.

Subsequent to the 1986 study, additional work on the effect of furnace pressure on melt rate showed that reducing the furnace pressure from 1100 millibar to 200 millibar, in helium at constant current, reduced the melt rate when standoff was held constant, but increased the melt rate when voltage (and thus power) was held constant(2). Data from the two papers is replotted in figure 1.

It is believed that the pronounced difference between helium and argon in melt rate results from the factor of ten ratio in molecular weights; helium's low molecular weight results in much higher thermal conductivity and decreased radiation loss. This low molecular weight also results in a higher torch gas flow rate with helium at similar pressure and geometry.

At the 1987 Electron Beam meeting in Reno (3), successful use of a gas recirculation system for the RP-250T torch was reported. Using a makeup flow rate of 6%, the cost of the helium flowing through the melt torch was reduced from \$134/hr (48 Nm^3/hr x \$2.82/Nm^3) to \$8/hr. The melt rate was 198 kg/hr and the power to the melt torch was 270 kW (290 kW including power supply losses). Thus power cost to melt at \$.10/kWh was 14.8¢/kg. Gas cost would have been 68¢/kg without recirculation and only 4.1¢/kg with recycle and 6% makeup. Table 1 below gives data for production size furnaces on the importance of gas cost with respect to power cost as affected by recycling.

TABLE 1 - GAS RECYCLE ECONOMICS

	CONSOLIDATION MELT	HEARTH MELTING
NUMBER OF TORCHES	1	3
MELT RATE kg/hr	700	700
TOTAL POWER, kW	800	2000
TOTAL GAS FLOW RATE Nm^3/hr	70	210
MAKEUP FLOW RATE Nm^3/hr	2.1	6.3
GAS COST/POWER COST* - NO RECYCLE EUR. / U.S.	7.0/3.5	8.4/4.2
GAS COST/POWER COST* - RECYCLE** EUR./U.S.	0.2/0.1	0.25/0.12

* Assuming $1Nm^3$ He costs 80 x 1 kWh in Europe, 40 x 1 kWh in U.S.
**Assuming 3% makeup

Subsequent work with a number of production systems has shown that the makeup rate for such systems averages 2% to 3%. However, if feed stock has perceptible moisture or contains hydrided scrap, the hydrogen concentration in the recycle gas can build up to levels where hydrogen content of the ingot is too high. Then, addition of hydrogen removal equipment to the gas recycle system is desirable. Figure 2 shows the elements of a helium recycle system which removes particulates, hydrogen and water.

Electrode lifetime with hollow electrodes has been increased by some refinements in electrode configuration and gas injection geometry. Lifetime for the production size RP-600T are typically 200 to 300 hours at 2500 to 3000 amperes. Lifetime with the pilot-size RP-250T at 1200 to 1500 amperes was initially 15 to 20 hours, but has been increased to at least 80 hours. Similar refinements of the RP-75T electrode have increased its life from 8 hours to more than 30 hours, occasionally 75 hours.

The yield of forgeable ingot from plasma hearth melted material depends on surface smoothness (laps or variations in ingot diameter may have to be machined), presence of solidification voids (sometimes found on the centerline about half an ingot radius below the top surface if power is shut off abruptly) evaporation losses and on whether any ingots are rejected for being outside chemical or inclusion specifications.

An investigation carried out jointly by Pratt & Whitney Division of UTC and Retech (4) brought out important parameters for achieving smooth surfaces. The work showed that surface quality with helium was much better than with argon. Subsequent production experience has show that surface finish of withdrawn ingots can be comparable with the best practice with stationary cast ingots (as in VAR). The 1990 program (4) showed that selection of optimum parameters resulted in an rms roughness of only 125 micrometers.

Shrinkage voids have been found on axis about half the ingot radius below the top surface when casting has been abruptly stopped and the ingot torch current has been simultaneously abruptly changed to zero. However, a hot-top achieved by reducing the power of the ingot torch more gradually (i.e. two minutes for an eight inch diameter ingot) prevents void formation. Such voids obviously increase yield loss.

Plasma melting was noted prior to 1986 as a low evaporation loss process (5). Development and production tests confirm that even multi-hearth plasma melting results in evaporation loss rates for titanium alloys of less than 1%. The low evaporation rate both has a direct effect on production cost, and constitutes a "hidden" economic factor that can have a significant impact on process development cost.

In general, it is difficult to gauge alloy losses that occur in a vacuum melt. This difficulty is compounded as the alloy system becomes more complex and the constituent requirements are tightened. Typically multiple melts are required for each alloy in order to determine the appropriate amount of "sweetening" to account for process losses of the volatile constituents. In addition, melting techniques must often be carefully designed and meticulously followed, since even relatively small deviations from steady state may result in compositional inhomogeneities.

Since plasma melting occurs at significantly higher pressures, the loss of volatile constituents is drastically reduced. For most titanium and zirconium alloys, the composition of the ingot accurately reflects the composition of the raw materials fed. Plasma's positive pressure capabilities allow the successful production of such materials as niobium aluminides. Plasma's ability to produce one of a kind melts, in spec, has been repeatedly demonstrated. This represents a significant cost saving when trying to bring a new alloy to market.

Since compositional control is de-coupled from molten metal residence times, process fluctuations due to such items as variations in feed rate have little or no effect on the compositional integrity of the produced ingot. As a result generic melt practices may be successfully used for a wide variety of alloys. This factor in conjunction with the ease of attaining in spec chemistry provides a significant economic advantage in situations where a diverse alloy mix and one of a kind "specials" are expected.

Using electromagnetic stirring in conjunction with plasma melted ingot withdrawal results in finer grains in the ingot. Benefits include less tendency to crack during forging operations, i.e. higher yield. In addition, improvements in homogeneity and micro-alloying have been reported.

Current practice for rotating grade titanium alloys uses cold-hearth melted (either plasma or electron beam) ingots which are subsequently melted once in a consumable electrode furnace. A significant cost saving is achievable if the VAR step can be omitted. As noted above, reducing the hydrogen content in the gas recirculation system permits making single process ingots which fully meet all specs and which represent a substantial improvement over the prior three-step VAR process in freedom from inclusions, reduced grain size and improved micro-homogeneity (i.e. no freckles).

WHAT LIES AHEAD: Further improvements in plasma processing of reactive and refractory metals are expected. Several possibilities have been verified at development scale, but only a small amount of production experience has been gained. Four primary items are listed here.

Round cornered slabs have been made by plasma, and offer the possibility of reduction in down-stream processing cost and yield improvement.

Powder made from alloys melted in plasma and bottom-poured may permit significant broadening of available alloy chemistries, due to the characteristics of rapidly solidified metals. Even with conventional chemistries, improvements in alloy cleanliness are attainable.

Extension to nickel-base alloys should permit the same advantages of fine grain and good micro-homogeneity shown for titanium alloys.

Hollow rounds have now been made with plasma, following the electron beam example, and should offer some cost advantages when making tubular shapes.

REFERENCES

1.) R. C. Eschenbach, "Lab Scale Plasma Melting Furnace," 1986 Vacuum Metallurgy Conf. on Specialty Metals Melting and Processing, Pittsburgh, PA, June 9-11, 1986

2.) R. E. Haun, R. A. Lampson "The Effect of Chamber Pressure on Melt Rate in Plasma Arc Melting," 1991 Vacuum Metallurgy Conf., Pittsburgh, PA, September 9-10, 1991

3.) M. P. Schlienger, R. C. Eschenbach, "Recent Developments in Plasma Melting of Reactive and Refractory Metals," Electron Beam Melting & Refining, Reno, Nevada, November 8-10, 1987

4.) D. R. Malley, R. C. Eschenbach, M.E. Schlienger, "Control of Plasma Hearth Melted Ingot Surfaces," 10th ICVM, Beijing, China, June 11-15, 1990

5.) R. C. Eschenbach, G. Herman, "Plasma Melting of Reactive Metals," Vacuum Metallurgy Conf. on Specialty Metals Melting & Processing, Pittsburgh, PA, June 11-13, 1984

$$1/T=1/S+(\lambda/c_2)\ln(\varepsilon/\varepsilon_s) \quad (5)$$

T : Temperature measured by thermocouple(True temperature)
S : Temperature measured by radiation thermometer
ε_s : Emissivity used for the measurement by a radiation thermometer
ε : Emissivity of surface
λ : Wavelength for measurement(650nm)
c_2 : The 2nd radiation constant(1.4388×10^{-2} m·K)

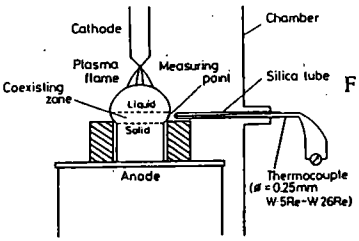

Figure 3. Scheme for temperature measurement of molten titanium surface by a thermocouple.

Temperature measurement of titanium vapor by spectroscope

Figure 4 shows a schematic diagram of an apparatus for spectroscopic analysis. Spectroscopic analysis was carried out through the window of 30mm in diameter. A titanium sample was melted by Ar arc plasma. By the use of a convex lens of 30mm in diameter and 60mm in focal distance, an image of plasma flame enlarged by four times was projected on a screen with a pinhole of 0.9mm in diameter. Only light which passed through the pinhole was analyzed by a spectroscope. The wavelength range of 325nm to 450nm was used for analysis. The analysis was conducted at the four points of 0.75, 1.50, 2.25 and 3.00mm in distance from molten titanium surface along the plasma flame axis, as shown in Figure 5. The analyzing point was chosen by the motion of convex lens.

The temperature of titanium vapor can be determined from the intensity of spectral line by the use of equation (6) shown below.

$$\log(I_n\lambda_n/A_{nm}g_n)=(-5040/T)E_n+\text{Const.} \quad (6)$$

I_n : Intensity of spectral line n
λ_n : Wavelength
A_{nm} : n-to-m transition probability
g_n : Statistical weight of excited state n
T : Arc temperature(vapor temperature)
E_n : Excitation energy

If the local thermal equilibrium(LTE) is realized in the plasma flame, $\log(I_n\lambda_n/A_{nm}g_n)$ is linearly proportional to E_n. Temperature of the titanium vapor therefore can be determined from the slope of the straight line.

Results

Emissivity of molten titanium

The surface temperature of solid and liquid in the coexisting zone has been measured to be around 1830K by a radiation thermometer and 1940K of the melting point by a thermocouple respectively. Because the temperature measured by a thermocouple is considered to be true temperature, emissivity has been calculated by using equation (5). The emissivity of molten titanium is determined to be 0.33.

Surface temperature measurement of molten titanium

After confirming that the plasma flame was stable, i.e., arc voltage and current were constant, surface temperature was measured by a radiation thermometer in the wavelength of 650nm. The radiation thermometer covered the temperature range of 1173K to 3273K and was able to measure the temperature of the small region of about 0.4mm in diameter.

The upper half of the titanium sample was melted and became hemisphere-shaped, as shown in Figure 2. In the figure, d and $\triangle\theta$ are the distance and the angle between measuring point and the top of molten titanium respectively, ϕ is the angle between bottom of molten part and axis, R is the radius of molten part, h is the height of non-molten part and r is the diameter of sample before melting. The top sometimes was not on the axis.

In order to measure the distribution of surface temperature, the positions of measuring points were represented by $\triangle\theta$. $\triangle\theta$ was calculated from d by the use of equations (1)~(4) shown below.

$$V = \pi R^3(2-3\cos\phi+\cos^3\phi)/3 \quad (1)$$

$$V = V_0(l_0-h)/l_0 \quad (2)$$

$$r = 2R\sin\phi \quad (3)$$

$$d^2 = 2R^2(1-\cos\triangle\theta) \quad (4)$$

Here V is volume of molten part, V_0 and l_0 are volume and height of sample before melting respectively. d was measured by the use of the circular mark calibrated by a scale in a finder of the radiation thermometer.

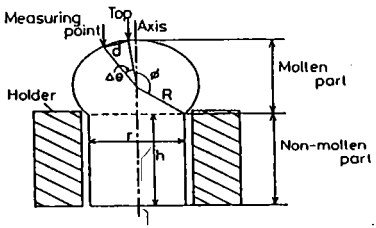

Figure 2. Cross section of melted sample.

Determination of emissivity of molten titanium surface

Determination of the emissivity of a molten titanium surface was performed by measuring the temperature of the same point using both a radiation thermometer and a thermocouple. Figure 3 schematically shows an apparatus for temperature measurement of molten titanium surface by a thermocouple. The thermocouple was W•5Re-W•26Re of 0.25mm in diameter and could measure temperatures below 2623K. The size of hot junction was about 1mm in diameter. A silica tube was used for protection and insulation of the thermocouple.

Determination of emissivity was carried out at a point of solid and liquid coexsiting zone, which was not directly in contact with plasma flame. After the temperature was measured by the radiation thermometer, the hot junction was contacted on surface at the same point. The emissivity (ε) can be determined by substituting the two temperatures measured by the two manners into the equation (5) which was derived from Wien's radiation equation.

We report surface temperature and vapor temperature of titanium melted by DC argon arc plasma. Surface temperture of molten titanium is measured by a radiation thermometer. For this measurement, emissivity of molten titanium is determined. Temperature of titanium vapor is determined from the intensity of spectral line of titanium vapor measured by a spectroscope.

Experimental

Melting by DC arc plasma

A DC transfered arc plasma generator was prepared, in which tungsten rod of 3mm in diameter and 50mm in length was used as cathode and water-cooled copper plate of 30mm in diameter and 1mm in thickness as anode, as shown in Figure 1. The chamber was made of cylindrical transparent quartz glass of 50mm in inner diameter and 250mm in length. Argon, which was dehydrated by calcium chloride, and silica gel was introduced into the chamber at the flow rate of 300ml/min.

The sample was a titanium cylinder, about 3g in weight, 8mm in diameter and 13mm in height, and mounted in an alumina tube on copper plate. The alumina tube was 9mm in inner diameter, 17mm in outer diameter, and 8mm in height. It was used to hold the shape of molten titanium.

A radiation thermometer was fixed at a distance of 10cm from the sample and a thermocouple in a glass tube was fixed horizontally near the sample.

DC voltage of about 115V was applied between electrodes. DC arc plasma was ignited by pilot arc sparked from the cathode tip with a high frequency starter. Then the plasma was generated between the tungsten cathode and the titanium sample. While the plasma irradiated the sample, electric current and voltage were about 27A and 15V respectively and electric power was consequently about 400W. Arc length was about 3mm.

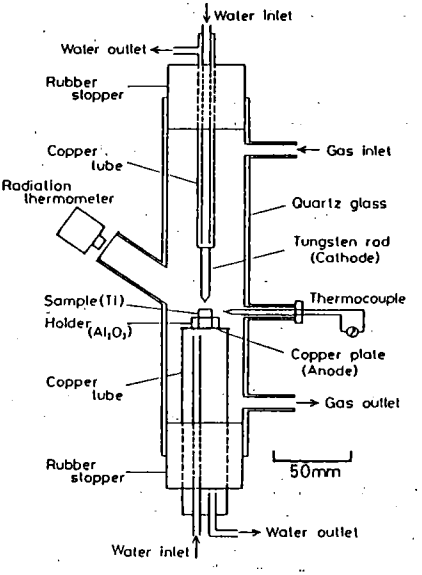

Figure 1. Schematic diagram of plasma generator.