5.1 Introduction

Previous chapters dealt with the first option of bulk utilization of these wastes (i.e. iron ore slime and bottom ash) towards constructional products in the form of bed filter materials and making bricks for domestic and industrial uses. The present chapter deals with the design and fabrication of laboratory scale transferred arc plasma (TAP) furnace to examine the feasibility for extraction of metals (i.e. Si & Al) from these solid wastes which may be the another option of their bulk utilization. A high temperature generating tool is required for reduction of industrial wastes containing mainly stable oxides like silica, alumina which needs a lot of energy (high temperature) for their reduction in the presence of reducing agents (Mandal and Sinha, 2014). Plasma is a known tool for generation of enormous heat energy, temperature ranging from 5000-8000 K (4727-7727 °C) which is useful to melt refractory metals and alloys (Edneral and Afanas' ev, 1979; Ettlinger et al., 1980; Feinman, 1987; Rains and Kadlec, 1970; Upadhya et al., 1986). Increasing attention towards applications of plasma smelting for mineral processing has been gaining popularity day by day (Alcock, 1980; Ettlinger et al., 1980; Moore et al., 1981). The amount of heat generation in plasma arc depends on types of current, current density, the ionizing behavior of different gasses, types of plasma, etc. (Inaba et al., 1998). Both types of current such as AC or DC could be used to form a normal arc as well as plasma arc (Arrabal et al., 2008; Inaba et al., 1998; Yao et al., 2008). Several researchers were studied about the heat distribution in different arc systems and showed that 72% total heat of DC arc is transferred into melt whereas 65% total heat is transferred in case of AC arc. In the case of laboratory experiments, DC plasma is widely used for simplicity, safety and more heat input to the metals (Stenkvist, 1985; Stenkvist and B. Bowman, 1987). The selection of plasma generating gas could be made as depending upon the need and their chemical effect on the work piece and electrodes (Glocker et al., 2000). The oxygen could be used for oxidizing, argon and nitrogen could be commonly used to provide neutral (inert) atmosphere whereas hydrogen could be used to maintain a reducing atmosphere around the melt (Kaneko et al., 1976; Rains and Kadlec, 1970). Generally, nitrogen plasma is being used for creating a neutral atmosphere around the melt as well as absorbing by the melt for manufacturing austenitic stainless steel where nickel is replaced partially or fully, because nitrogen gas is cheaper and readily available substitute of nickel (Sinha and Gupta, 1994, 1993). In the case of smelting reduction studies, nitrogen plasma is generally used to minimize the reoxidation of metals (Mandal and Sinha, 2016). Electrically generated gas plasma is well known to electric steelmakers in the form of an arc between graphite electrode and charge materials, called transferred arc plasma (Gauvin, 1989; Katou et al., 2001). The transferred arc gives higher current compared to non-transferred arc, but maximum power for both the arc is similar. The main difference between two arc systems is the energy density of the plasma gas generated in the respective arc. In the transferred arc, the energy density is 30 times higher than the non-transferred arc. Therefore, in the case of transferred arc plasma, the heat transfer to the metal is tremendously high. For that reason, the transferred arc is mostly used for metal and alloy melting (Glocker et al., 2000). Initially, plasma arc was generated in DC furnaces but nowadays, three phase AC plasma furnace is also feasible (Arrabal et al., 2008; Eschenbach et al., 1987; Neuschutz et al., 1985). In 1991, Takuma developed a DC plasma furnace to be used for melting the residue and has been conducting basic melting tests since 1993. The output production of that bench scale furnace having 300 kW capacities was 7.2 ton/day. In 1998, a new demonstration plant with 1710 kW output and 25 ton/day output were built, and tests have been continued with this new plant (Inaba et al., 1998; Katou et al., 2001). About the transferred arc plasma for smelting reduction studies in laboratory scale is not yet found elsewhere in the literature.

The main objective of this part of the present work is to design and fabricate a laboratory scale transferred arc plasma furnace in the laboratory and testing for its proper functioning. Indigenized furnace is to be characterized for its well worthiness by testing different operational parameters such as meltdown time, arc length, energy consumption, sound levels, electrode consumption, lining life etc. It could be utilized for smelting reduction studies to recover their valuable metals from solid wastes of metallurgical industry which will be the subject matter of the next chapter.

5.2 Design of transferred arc plasma (TAP) furnace in laboratory

To study the smelting reduction behavior of metallurgical solid waste, a furnace of two-kilogram steel melting capacity was designed and then fabricated indigenously in our laboratory. For designing of the furnace following important components were selected and considered in fabrication.

5.2.1 Selection of transformers

Selection of required capacity transformer for minimum 2 kg steel melting along with waste material is very important because it supplies current for required heat generation in the melting system. To operate a furnace of 2 kg steel melt capacity, along with 500 g waste materials at a temperature of 1873 K (1600°C) was found to be about 675 kcal heat energy requirement. Hence, to generate 675 kcal heat energy, nearly 9.8 kVA electrical energy would be needed (Riss and Khodorovsky, 1967). Considering nearly 60% energy losses, the total energy input should be around 16 kVA (Stenkvist, 1985; Stenkvist and B. Bowman, 1987). Keeping a good safety margin from a normal working load, a transformer should have a capacity of 30 kVA which could give power at 77, 81, 85, 89 and 93 volts settings. This transformer required a single phase AC power supply of 220 volts, which was provided by another transformer working on three phase 440 volts input power supply to the laboratory.

5.2.2 Electrode

The present unit belongs to transferred arc type system. While arcing, there is significant voltage drop at both anode and cathode surfaces. This is associated with high heat flux which tends to increase the electrode temperature in the region of the arc. Most of the material evaporates at the temperature needed to get current density for operating plasma. Therefore suitable cooling arrangements are required. Graphite rod is ultimate choice as an electrode material due to the feasibility of its use without cooling. The diameter of solid graphite electrode depends on current to be carried out and its material which possesses excellent electrical conductivity and high melting point (Fauchais et al., 1987). Eschenbach et al showed that the heating depends on the electrical resistivity and thermal conductivity of the graphite electrode (Fauchais et al., 1987). The diameter and current relationship for standard (200 kA/m^2) and superior (250 kA/m^2) grades of graphite electrode for AC operation and standard (350 kA/m^2) grades for DC operation were determined by Edneral, Eschenbach et al.(Edneral and Afanas' ev, 1979; Eschenbach et al., 1987) respectively. The graphite electrode having current density (700-800 kA/m^2) and 0.016 m (16 mm) diameter were adopted for the present work due to the smaller diameter of the crucible. Increasing more than 0.016 m (16 mm) diameter of electrode, erosion of side wall occurs adversely. A bore of 0.004 m (4 mm) diameter was drilled in the electrode of 0.61m (610 mm) long for the flow of plasma gas (Figure 5.1a).

5.2.3 Electrode holder

The half portion of the electrode holder was made of copper and another half was made of steel which was attached on the top of the roof having a hand wheel which gives ups and down electrode movement. One of the power supply (+ve) of 30 kVA transformer was connected to the electrode holder by flexible copper strip and another (-ve) power supply was connected to the bottom of the crucible by another flexible copper strip. The arrangement for water cooling of the electrode holder was provided as shown in Figures 5.1b.

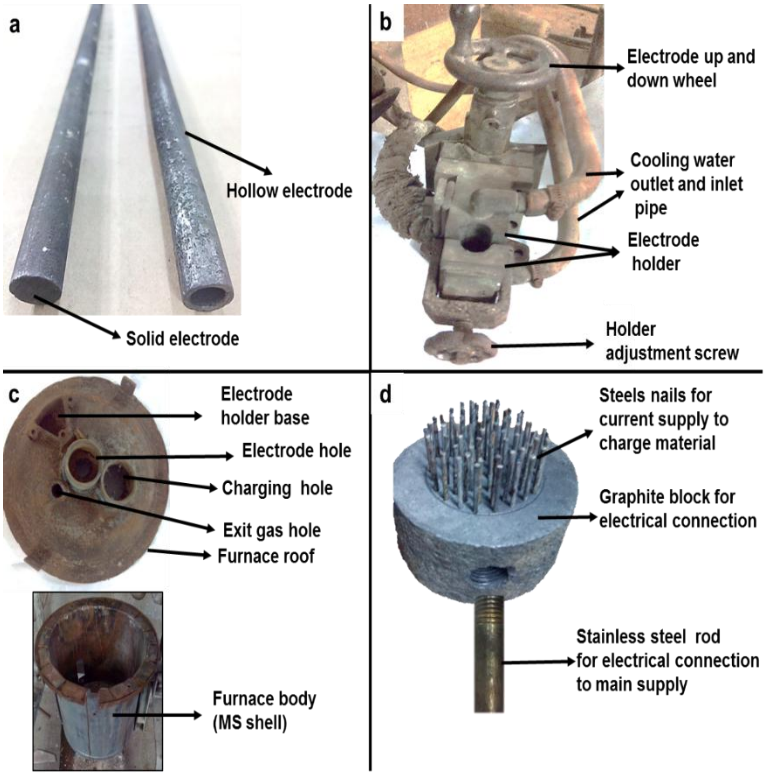

Figure 5. 1 Different parts of the fabricated Furnace : a) Solid and hollow graphite electrodes, b) electrode holder with cooling and moving arrangement, c) Furnace body and roof, d) Electrical connector block with nails and SS rod

5.2.4 Furnace body and roof

Mild steel sheet of thickness 0.003 m (3 mm) was used for fabricating furnace body having a cylindrical shape of diameter 0.300 m (300 mm) and height 0.280 m (280 mm). The top of the furnace was provided with a swinging lid, made of 0.005 m (5 mm) thick steel plate which could be easily lifted up and closed as required during melting operation. The inside of the mild steel roof was lined with magnesite to protect from direct heating. There are provisions made for charging, gas for exit and electrode holder assembly. These are shown in different views as in Figures 5.1c.

5.2.5 High-temperature electrical connector

A graphite block of 0.12 m (120 mm) diameter and 0.08 m (80 mm) height for providing electrical connection to the charge through the bottom of the crucible. It was connected by a stainless steel rod 0.025 m (25 mm) length screwed into it without any cooling system for providing (-ve) power. Around 20-25 steel nails, 0.003 m (3 mm) diameter and 0.035 m (35 mm) long were fixed on the top of the graphite block embedded in refractory lining for making electrical connection between melt and graphite block. These arrangements are shown in Figures 5.1d.

5.2.6 Lining

For 3 kg steel melt, a crucible diameter of about 0.08 m (80 mm) was adopted by experience which gave a melt depth of about 0.09 m (90 mm). For melting of one kg MS scrap, 3 kg melt capacity of the crucible was prepared for easy handling of lower density slag produced during smelting reduction study. The larger diameter was avoided for higher heat losses, and narrower diameter may cause difficulty of charging with bridge formation during melting operation. The different types of refractory materials used for making crucibles are discussed below.

5.2.6.1 Graphite crucible

To sustain high-temperature 2073-2273K (1800-2000°C), a readymade (available in the market) graphite crucible was used. Graphite crucible was placed at the center of the furnace on a graphite block and grog powder (crushed firebricks) was rammed between crucible and insulation bricks lining as shown in Figure 5.2a. A few numbers of melting trials were performed in this type of crucible.

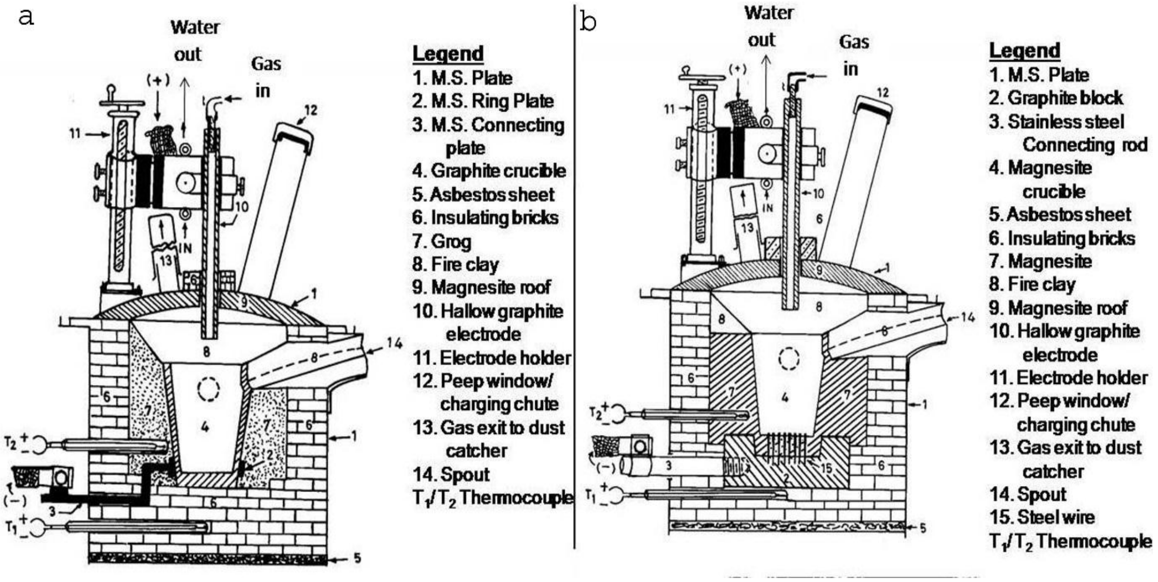

Figure 5. 2 Cross-section view of plasma arc furnace (a-graphite crucible; b- magnesite lining)

5.2.6.2 Magnesite crucible

In industry, magnesite is widely used for lining in electric arc furnace, for that reason major melting trials were performed by using magnesite lining to understand the reality of industrial scale practice, considering of such high temperature (Figure 5.2b). The combination of high-grade magnesite granules as well the as fines were used to make the crucible for avoiding surface crack generation during melting operation due to thermal shock. Excess quantity of coarser or finer is not suitable for lining life. The sieve analysis and composition of the material are shown in Figure 5.3 and Table 5.1 respectively.

Magnesite ramming mass was mixed with sodium silicate (Na_2O_2Si) solution having molecular weight 0.112 kg/mole (112 g/mole) to make the mixture moldable around a wooden pattern to give a crucible shape of desired dimensions. The mix of magnesite ramming mass and sodium silicate was rammed in between wooden pattern and insulation brick up to the top of the furnace.

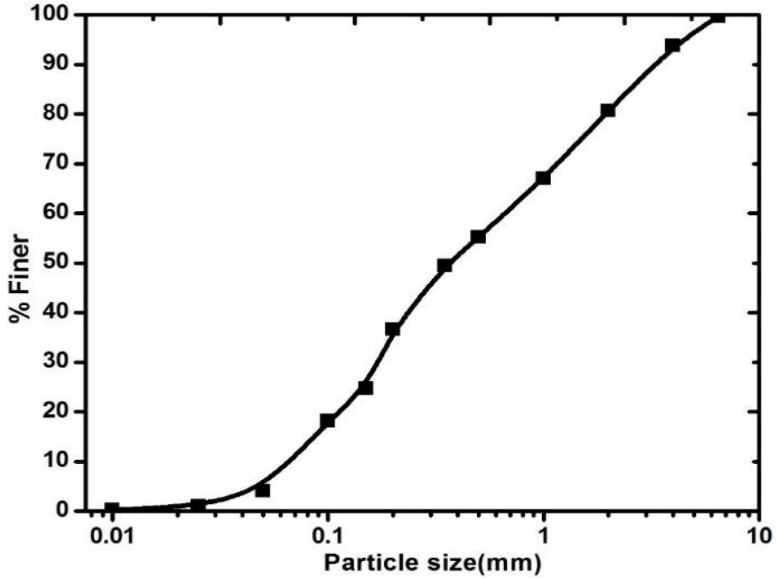

Figure 5. 3 Particle size analysis of the magnesite ramming mass

Table 5. 1 Chemical analysis of the magnesite ramming mass and sodium silicate paste

Constituents	Chemical composition (Wt. %)	
	Ramming mass	Sodium silicate paste
MgO	84	-
SiO_2	5	67.6
Fe_2O_3	7	-
Al_2O_3	1	-
CaO	3	-
Na_2O	-	31.4

On drying, the pattern was withdrawn slowly and crucible lip was made using refractory mixtures. The insulating bricks were used for supporting the magnesite crucible lining and also prevent the heat losses. Steps of crucible making are shown in Figure 5.4a-f.

Based on the experience, about 0.05 m (50 mm) thick magnesite lining followed by 0.06 m (60 mm) thick insulating bricks lining was found to be sufficient for the present work which is shown in Figure 5.4b-c.

Figure 5. 4 Steps of making magnesite crucible

5.2.7 Plasma gas flow control system

A gas purification train was designed and fabricated with mixing and flow control system to pass desired plasma gas (nitrogen/ hydrogen) or their mixture (Figure 5.5). In the present study, hydrogen and nitrogen gas were used separately. This system permitted the dry gas flow in a range of 8×10^{-6} to 33×10^{-6} m^3/s. The purification train was provided mainly to remove moisture in all gasses and moisture plus oxygen in nitrogen as well as to control backfiring of hydrogen gas.

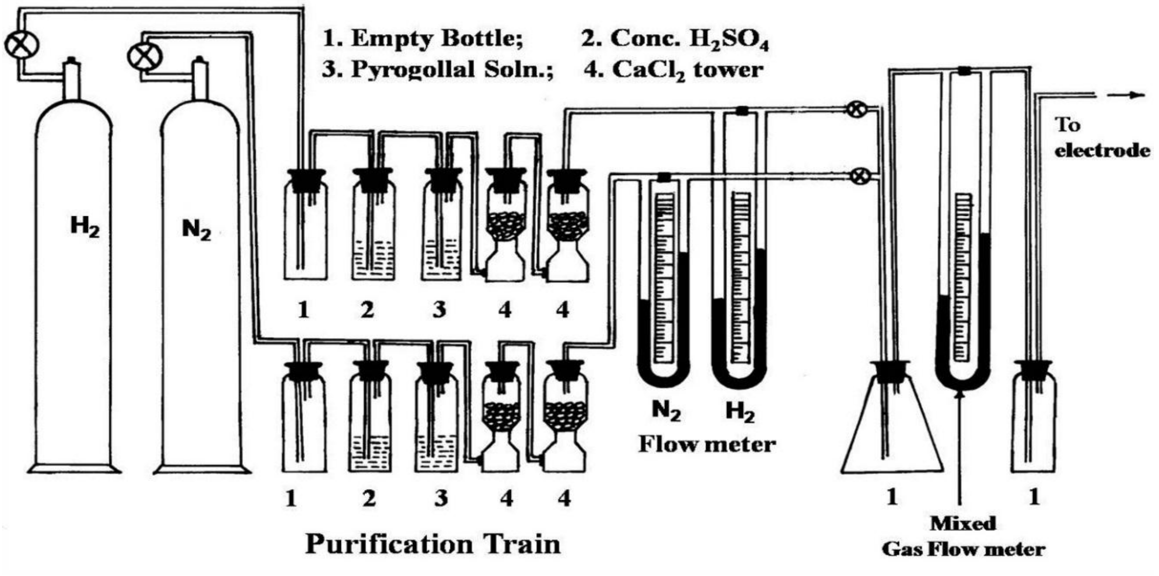

Figure 5. 5 Gas flow system with purification train

5.2.8 Sample collector

For the collection of molten samples during melting operation, a suction pipette was made of silica tube with rubber suction bulb as shown in Figure 5.6a. For the chemical analysis of the sample after completion of melting, a round shaped sample is required.

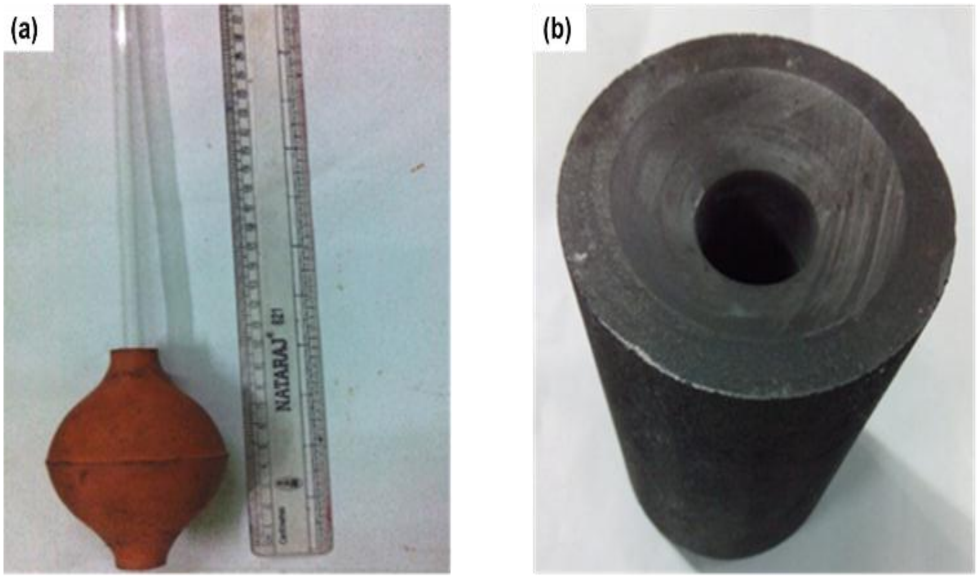

Figure 5. 6 Molten metal Sample collection tube (a) silica pipette) and (b) graphite mould

Therefore graphite mould was prepared by tapper boring in graphite block for easy removal of the samples after cooling (Figure 5.6b).

5.3 Fabrication

It may be pointed out that this unit was fabricated based on the available information from the literature and personal experiences. This design was accepted after three consecutive up-gradations in the design depending upon the problem faced during melting trails. Based on the design mention above the furnace was fabricated by assembling the components which are shown in Figure 5.7.

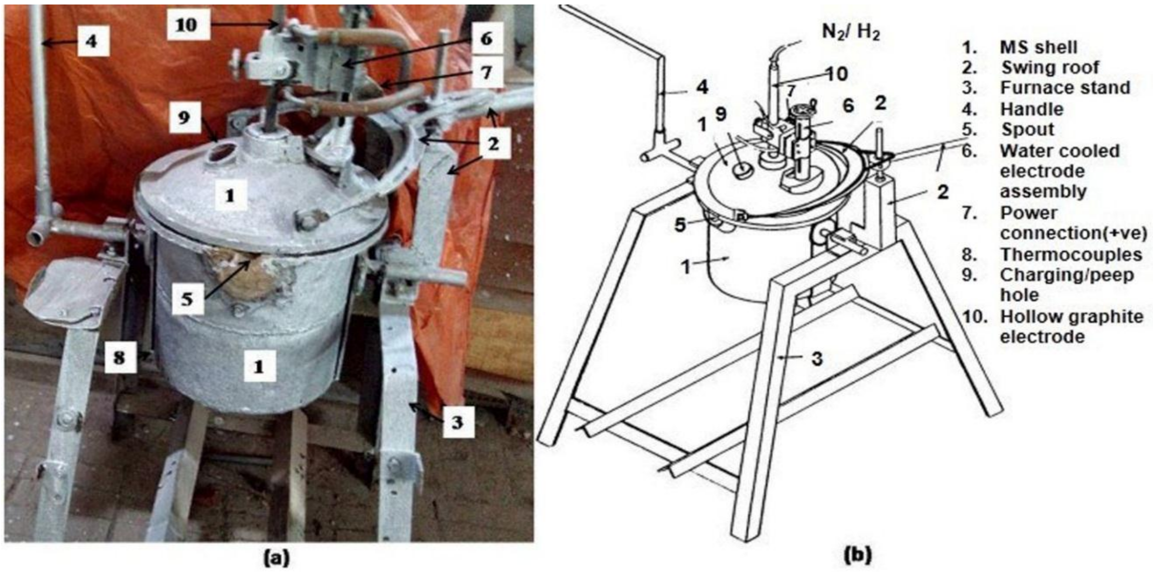

Figure 5. 7 Fabricated plasma arc furnace (a-Photographs of isometric view; b- Isometric view)

5.4 Characterization of TAP furnace

5.4.1 Operation of plasma arc furnace

The crucible of the furnace was prepared by using both graphite and magnesite lining material as described in section 5.2.6, was first tested for its proper functioning using normal as well as both plasma arc (H_2/N_2) for melting 2 kg mild steel (MS) scrap charge. Initially, 0.5 kg (500 g) MS scrap was charged in the crucible and put on the furnace power. The melting was initiated by striking the normal arc without plasma gas with the use of solid graphite electrode. The additional charge was made gradually through charging hole on the roof after melting the previous charge, and this was continued till all the steel scrap was molten. After ensuring the complete melting of the charge, nearly 2 kg of first heat was discarded as a wash heat to avoid excess carbon pick up by graphite crucible and to make crucible super-heated for a smooth running after further melting as shown in Figure 5.8.

A fresh heat was prepared after complete melting of scrap, and then solid electrode was replaced by hollow one. The arc was struck again by the hollow electrode, which was connected to the particular ionizing gas through gas purification train as shown in Figure 5.5. Before starting the plasma gas through hollow electrode, the temperature of the melt was measured and one sample was collected through the silica pipette made of silica tube and rubber bulb assembly (Figure 5.6a). The gas was started to pass at a constant flow rate through the electrode hole up to arc zone where it was ionized which increased the arc zone temperature.

Before going to study the smelting reduction characteristics of bottom ash, the furnace was operated for several melting to optimized the various processing parameters such as arc current, plasma gas flow rate and power rating on melt temperature, arc length, electrode wear, noise and energy consumption, etc.

5.4.2 Results and Discussions

The behavior of the fabricated furnace under normal arc and different plasma (N_2/H_2) conditions using various crucible materials were studied, and results are described in following sections:

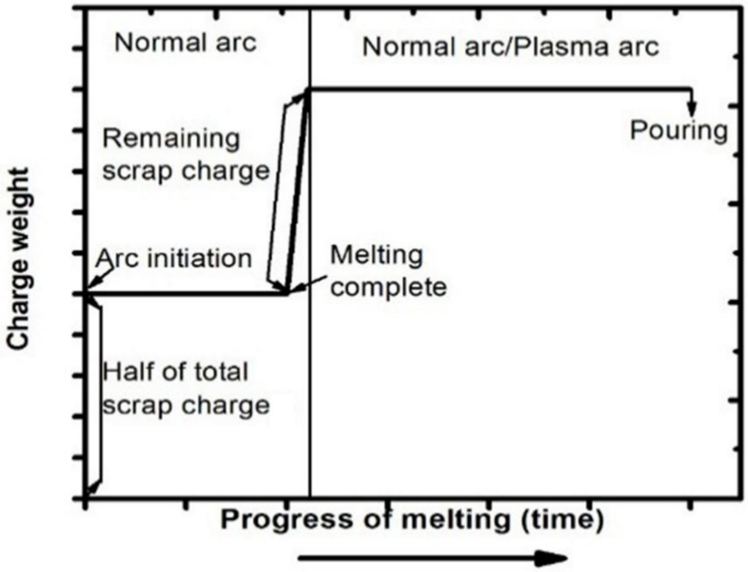

Figure 5. 8 Flow chart of scrap melting procedure

5.4.2.1 Melt Temperature and meltdown time

The temperature is an important parameter which controls the meltdown time and gas/metal reactions occur while exposing under plasma arc. The temperature depends on the arc types and current. Therefore, the furnace was first operated at the normal arc, and the effect of arc current on the melt temperature was noted. In the second phase, nitrogen and hydrogen gas were passed separately to get the plasma, and in the third phase, arc current was changed keeping fixed plasma gas flow rate such as nitrogen/ hydrogen. The effect of these on the melt temperature are illustrated in the following subsections:

(a) Effect of arc current on the melt temperature and meltdown time under normal arc

The arc current was increased from 188 to 278 A, which increased the melt temperature from 1898-1973K (1625° C to 1700° C) as shown in Figure 5.9. The increasing current gave higher energy input to the system which resulting increase in melt temperature and decreased in melt down time of the scrap from 65 to 25 minutes. These are well-known facts and confirmed the healthy functioning of the furnace system.

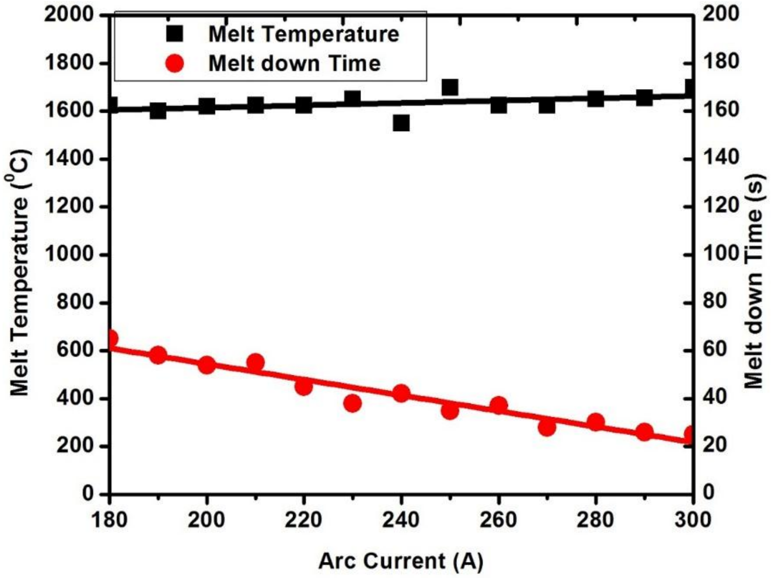

Figure 5. 9 Effect of arc current on the melt temperature and meltdown time under normal arc

(b) Effect of plasma gas on the melt temperature

To observe the influence of nitrogen and hydrogen gas on melt temperature, first steel scrap was melted under normal arc (~230 A) and the temperature was recorded for 300 s of normal arc exposure. Immediately solid electrode was replaced by hollow electrode and nitrogen/ hydrogen gas (flow rate ~16×10^{-6} m/s) was passed through electrode for 300 s. In the meantime, the temperature was recorded continuously by using radiation pyrometer at an interval of 10 seconds. The plasma forming gasses (i.e. nitrogen/ hydrogen) when reached in the arc zone of high temperature where it dissociated into first atoms followed by ions which liberated enormous heat around the arc. That's why, the temperature of arc zone increased tremendously in case of plasma as compared to normal arc, resulting more melt temperature. It was evidenced from the hydrogen plasma for increasing more melt temperature than nitrogen plasma due to combined effect of ionization and combustion of hydrogen gas. The plasma showed an increase of average melt temperature 300°C for hydrogen and 200°C for nitrogen as shown in Figure 5.10.

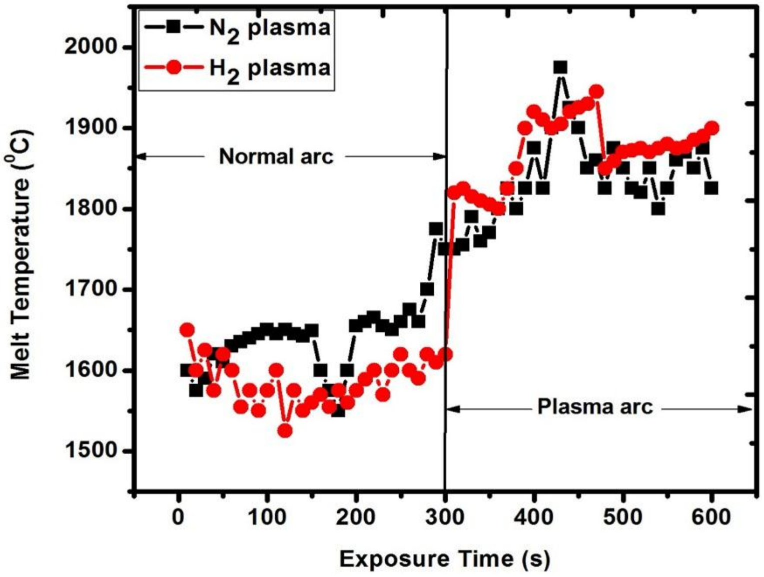

Figure 5. 10 Effect of plasma gas on the melt temperature when exposed to different plasma

(c) Effect of plasma arcs current on the melt temperature

As the gas-metal reactions are sensitive to the melt temperature, the effect of arc current in regulating the melt temperature was an important parameter for the present study. Several melts of 2 kg each were made with different arc current (200-280 A) while the flow rate of nitrogen/ hydrogen (8.33×10^{-6} m^3/s) was kept constant for 300 s exposure time. The melt temperature was found to be increased linearly with plasma arc current as shown in Figure 5.11. Hydrogen plasma generated more heat than nitrogen plasma, resulting in increased melt temperature. This trends served as a guideline for obtaining the required temperature inside the chamber of plasma furnace.

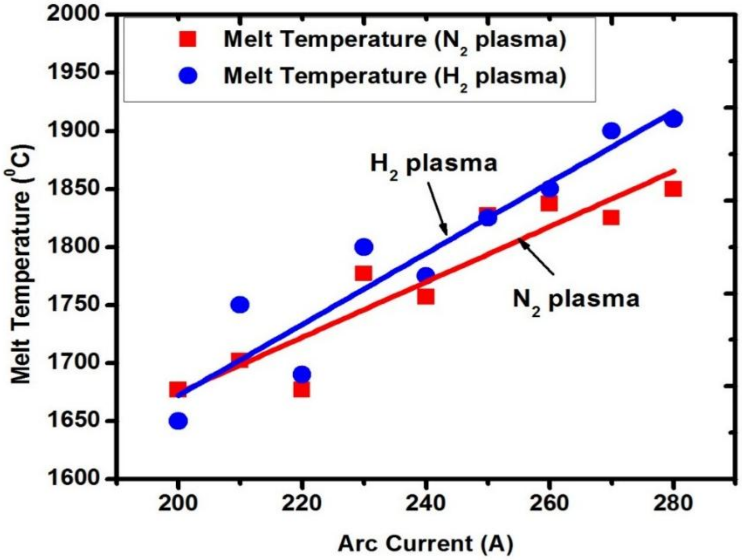

Figure 5. 11 Effect of arc current on the melt temperature when exposed to different plasma

(d) Effect of heat number on the melt temperature and meltdown time under normal arc

Heat was produced by normal, as well as plasma arc which play different roles in melting chamber. Generated heat was utilized for superheating the crucible refractories, melting the charging materials, superheating the melt as well as compensating the heat loss through radiation, conduction and off gas.

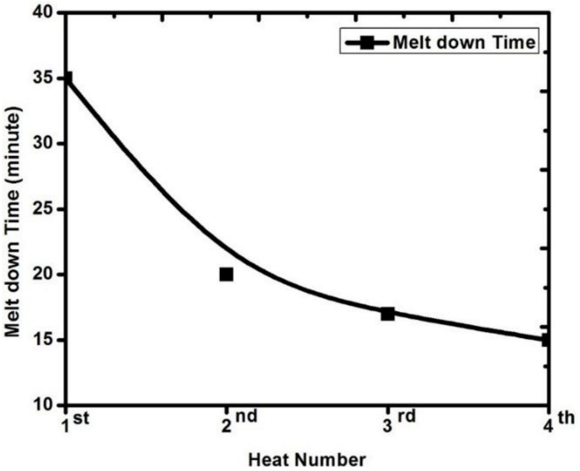

Figure 5. 12 Effect of number of heat per campaign on melt temperature and meltdown time under normal arc

For that reasons, the heat requirement is more in the initial stage of melting operation. Gradually after superheating of the furnace refractory, the need of thermal energy was reduced for further continuous melting. That’s why the melt down time was increased to get the same metal temperature for initial heat and decreased for further continuous melting. Meltdown time for achieving ~1823K (1550°C) temperature for different heats are shown in Figure 5.12. It was observed that in the normal arc melting, meltdown time was reduced for the same quantity of scrap melting from 35 minutes (for initial casting) to 15 minutes (at the schedule 4th heat).

5.4.2.2 Arc length

The length of the arc in free arcing condition decides the area of arc impingement on the melt surface. The longer arc length will give wider plasma impingement area above the melt. This area is significant for the gas-metal reaction occurring during melting/smelting reduction studies. The longer arc length will also be desired for smelting studies to have a higher retention time for the particles in the plasma flame. Further, the shorter arc length offers concentrated heat in narrow zone whereas longer arc length offers even heat distribution over a wider area. Thus, depending upon need, flame length is adjusted.

The present study was done to know the effect of current and gas flow rate on arc length. These observations are described in the following subsections.

(a) Effect of power rating and arc voltage on arc length

To study the above parameter, 2 kg steel scrap was first melted in the crucible using normal arc without plasma gas. Subsequently at a given arc voltage setting, the arcing was allowed freely at certain power rating without using plasma gas (i.e. normal arc) and the length of the arc was measured using the scale fitted on electrode holder to indicate the distance between melt and electrode tip. This arc length was measured at different power ratings and voltages. The experiment was repeated with gas flow rate (8.33×10^{-6} m^3/s) through electrode for generating plasma arc. These observations are shown in Figure 5.13. It could be noted that arc length was longer in case of plasma gas compared to normal arc at all levels of power rating. Further, longer arc length was also obtained in the case of lower arc voltage (77 V) and power rating (~17 KVA).

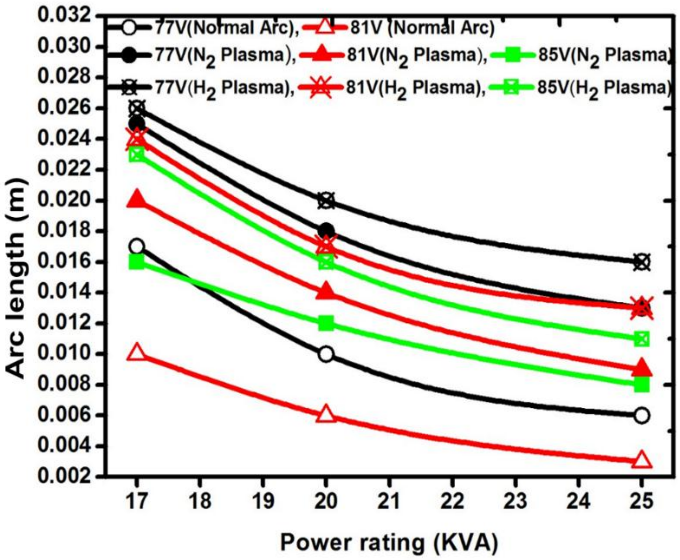

Figure 5. 13 Variation in arc length with power rating under normal and plasma arcs

The falling trend is the characteristics of increasing arc conductance with increasing current caused either by an increase of the electrical conductivity (i.e. high temperature) or the arc diameter or both (Pfender, 1999) (as shown in Figure A.2 of Appendix-A). The diameter of a graphite electrode is constant therefore conductance is varied with increasing temperature. The conductance of N_2 plasma arc is more than normal arc due to increased temperature. In the case of hydrogen plasma, this value is again increased as shown in Figure 5.14. Details of calculation for conductance values are given in Table B.6 of Appendix-B.

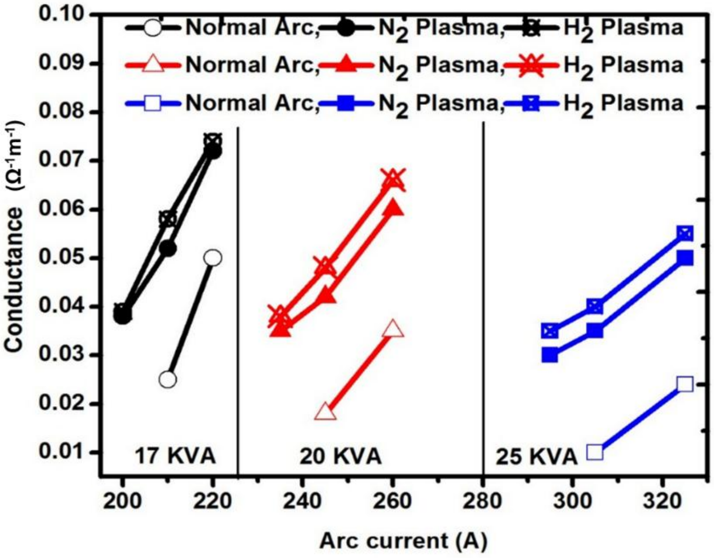

Figure 5. 14 Variation in arc conductivity with current under normal and plasma arc

(b) Effect of gas flow rate on plasma arc length and conductance

In the previous section 5.4.2.2(a), it was shown that longer arc length with better conductance could be obtained by flowing nitrogen as a plasma gas. This study was made in the same manner as mentioned in section 5.4.2.1 by keeping arc voltage at 85 V and power rating at ~17 kVA.

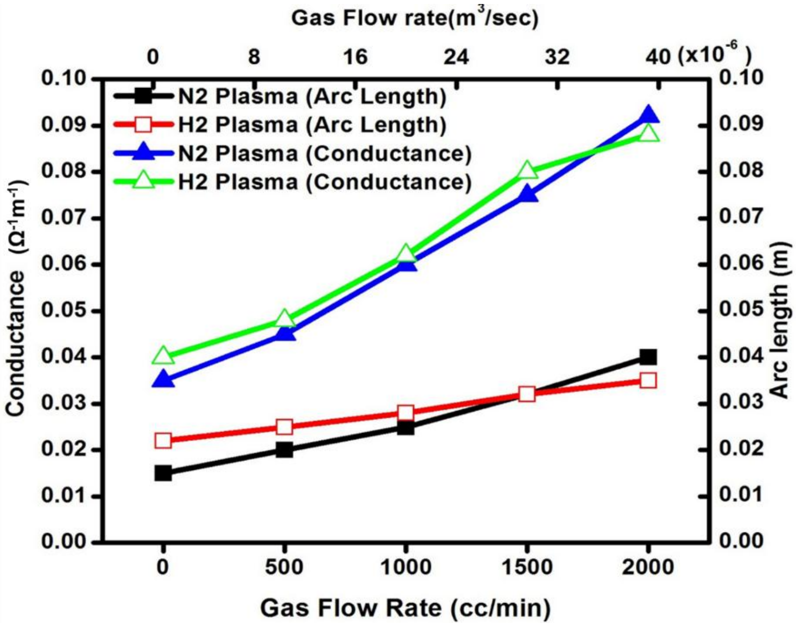

Figure 5. 15 Effect of gas flow rate on arc length and its conductance

The change in arc length was noted when the gas flow rate was increased as shown in Figure 5.15. The values of arc conductance was calculated and plotted to indicate that higher gas flow rate (8.33×10^{-6} -$33\times10^{-6}m^3/s$), resulted in longer flame (0.020 to 0.040 m) with better conductance (0.047 to 0.094 $\Omega^{-1}m^{-1}$) (Figure 5.15).

5.4.2.3 Energy consumption

The total energy consumption in arc melting process depends on the efficiency of heat transfer to the melt. Any savings on electric power will obviously be a major factor in promoting the use of plasma arc. The energy consumption in the present study was noted directly from the energy meter.

(a) Energy consumption for melting

Three separate melts (2kg scrap) were prepared under normal arc as well as nitrogen and hydrogen plasma arc respectively. The meltdown time, energy consumption, electrode consumption, and power fluctuations were noted (Table 5.2). It can be seen that normal arc melting takes more time (35 minutes) with more energy consumption (28.8 MJ) compared to the nitrogen plasma. In the case of hydrogen plasma, it takes the least time for melting (20 minutes), also consuming less energy (19.5 MJ).

Table 5. 2 Comparison of melting under normal and different plasma arc

Parameters	**Normal Arc**	**Nitrogen plasma**	**Hydrogen plasma**
Charge weight (kg)	2	2	2
Scrap meltdown time (s)	35	25	20
Energy consumption for total melting (MJ)	28.8	21.6	19.5
Electrode consumption (kg)	0.018	0.012	0.010
Power fluctuation	High	Low	Low

This is due to high flame temperature and better heat transfer from longer and wider plasma flame. It may be pointed out that nearly 2412 MJ/ton energy consumption was observed during industrial practice using 3-ton plasma arc furnace (Knopper, 1985; Neuschutz et al., 1985).

(b) Energy consumption during melt heating

Once the charge was completely melted down, then the arc energy was consumed for super heating the melt. It can be noted from the Figure 5.10 that higher melt temperature was obtained in the case of plasma arc compared to a normal arc. The melt temperature was further increased with continuing arc current.

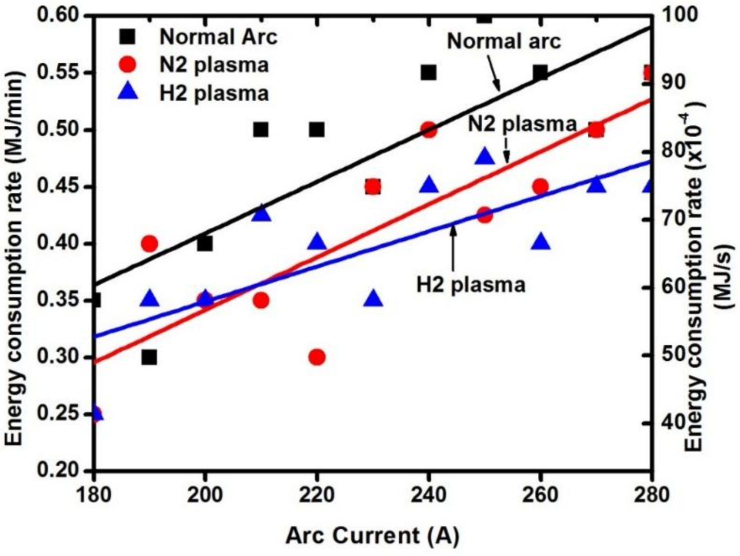

Figure 5. 16 Effect of arc current on energy consumption rate under normal and plasma

The energy consumption for 5 minutes arc exposure in different melts at different arc current for normal and nitrogen plasma arc is shown in Figure 5.16. The lower energy consumption for plasma arc in comparison to normal arc at all current level was distinctly observed. It means that plasma technology was found to be an attractive tool which could be utilized in the study of smelting reduction of oxides

5.4.2.4 Sound level

The noise has long been a well-known cause of nuisance and annoyance. Recently it has been recognized that higher level of noise encountered in many working environments can result in loss of hearing ability among those who exposed for a prolonged period. The effect of noise among human being has been reported by *Wills* (Wills, 1978).

In the present investigation, some efforts were made to note the relative sound level of the laboratory plasma arc unit during melting under normal arc and while switching over to different plasma arc. The effect of arc current on sound level was also noted with normal and plasma arc. These are described briefly in the following two subsections. Sound meter (software version 1.0 pro) was used for recording of noise level from the distance of a one-meter radius of the furnace.

(a) Effect of arc type on sound level during melting

To observe the above-said effect, 2 kg scrap charge was first melted under the normal arc. The values of arc current, power rating, and average sound levels were noted during melting as shown in Figure 5.17.

From the figure, it may be noted that at the beginning stage of the melting, the sound level is nearly 90 dB, which gradually downs to 70 dB after the complete melting of the charge.

During starting melting of scrap, the flickering of arc gradually decreased resulting in a reduction in sound level. After complete melting of scrap, the arc becomes stable, resulting in less noise level and stable power rating with decreasing current. When plasma gas was introduced through the hollow electrode, a substantial reduction in sound level was observed followed by power rating as well as arc current. It was due to very smooth and intense flame produced in plasma which experienced a better path for current flow through ionized gasses.

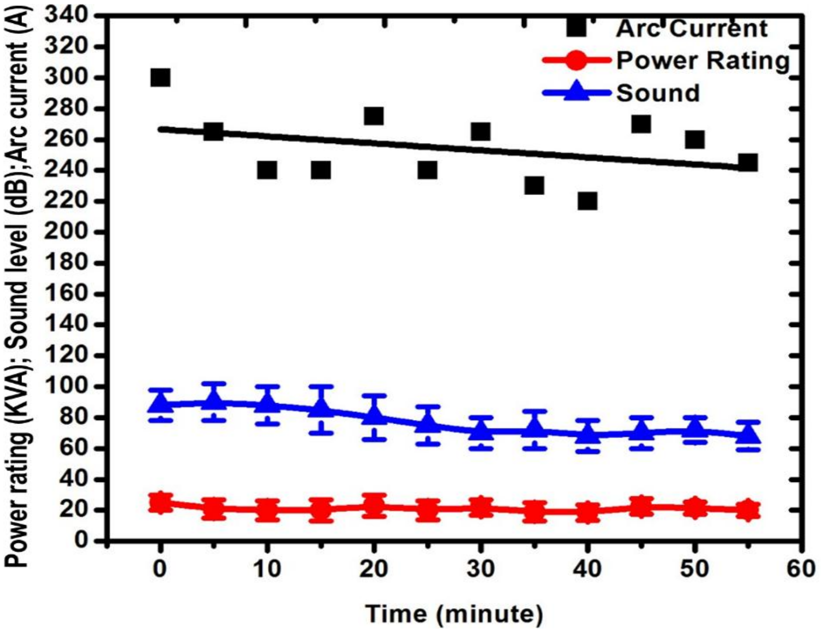

Figure 5. 17 Variations of sound level, arc current and power rating during melting under the normal arc

In the case of hydrogen plasma, sound level was slightly more than nitrogen plasma although it experienced a smoother arcing. It may be due to the generation of 'hissing' sound produced during combustion of flammable hydrogen gas (Table 5.3).

Table 5. 3 Comparison of arc current, power rating and noise level in different arc exposure

Parameters	**Normal arc (after complete melting)**	**Nitrogen plasma exposure**	**Hydrogen plasma exposure**
Arc current (A)	245	200	195
Power rating (KVA)	20	16.5	16
Sound level (dB)	68±8	58±5	62±4

(b) Effect of arc current on sound level for different arc environment

It was noted in previous sections that arc current is an important parameter for arc furnace operation. Few more experiments were conducted with 2 kg steel charge in the molten stage using different arc currents for both normal and plasma arc to observe this effect on sound level. The observations are shown in Figure 5.18.

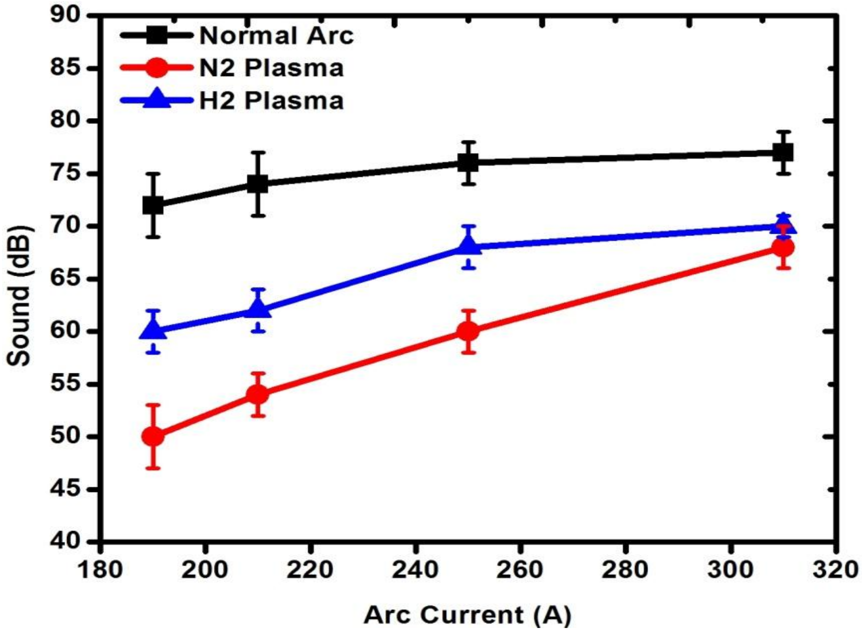

Figure 5. 18 Effect of arc current on sound level while exposing arc to liquid melt

From the figure, it could be noted that with increasing arc current, the sound level increases for all type of arc condition. The increased current level, however caused in increase noise level due to the discharge of ions and their movement. As mention above that due to hissing sound of hydrogen burning, the average value of noise level in case of hydrogen plasma is always more.

5.4.2.5 Electrode consumption

The consumption of graphite electrode not only reflects the total cost of the melting but also adds the carbon in the metal. Lower electrode consumption is always preferred due to its higher cost. In the present study, the electrode consumption during melting was observed for both the normal and plasma arc conditions. Eschenbach et al was reported that the consumption of the graphite electrode increased with increasing electrode current (Eschenbach et al., 1987).

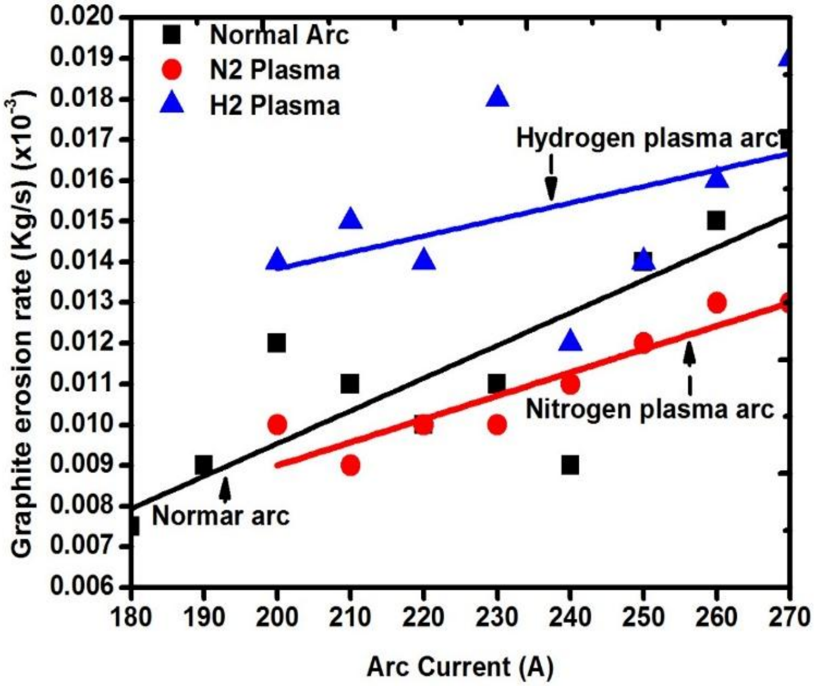

Figure 5. 19 Graphite electrode erosion as a function of arc current

In the present work, drilled graphite electrode was used for generating plasma arc. The electrode consumption was observed by measuring the change in weight of the certain known exposure time, during melting of 2 kg steel using normal and plasma arc respectively. The trends of graphite erosion rates (kg/s) with the different arcing condition is shown in Figure 5.19.

From the Figure 5.19, it was also observed that the erosion rate of graphite electrode used in nitrogen plasma arc is slightly lesser than the normal arc. It was happened due to smoother arcing in plasma as well as creates an inert atmosphere inside the melting chamber which prevents oxidation loss of graphite electrode. But an interesting feature was observed in the case of hydrogen plasma where the rate of electrode consumption was more than that of nitrogen plasma and normal arc as shown in Figure 5.19. It may be due to the formation of the methane (CH_4) gas by reacting hydrogen plasma with the carbon of graphite. Due to this reaction, graphite electrode inside the furnace chamber was eroded as like a needle shape whereas, in the case of nitrogen plasma, erosion at the tip of graphite electrode was observed due to the generation of heat only as shown in Figure 5.20.

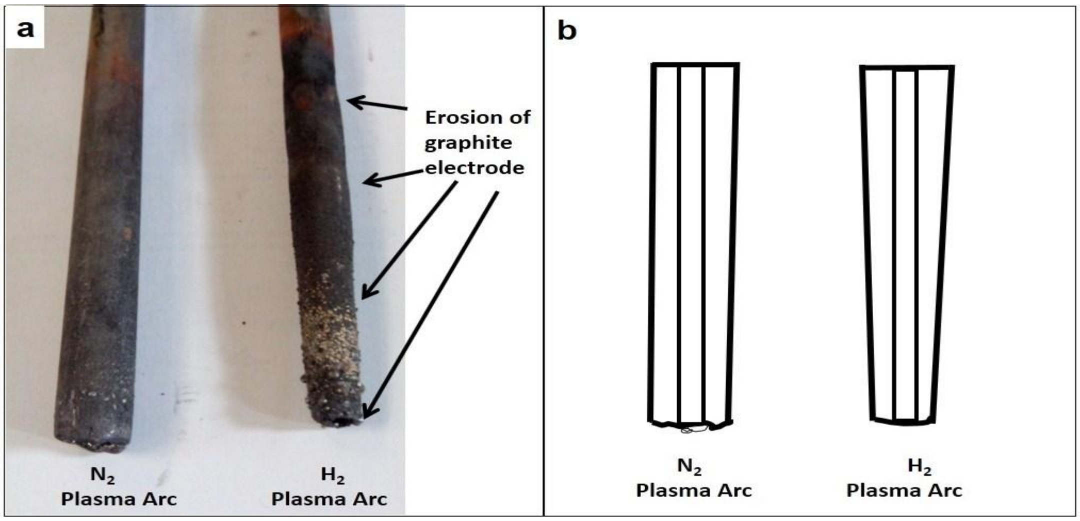

Figure 5. 20 Erosion trends of graphite electrode in different arc plasma condition, a) Photograph of electrodes, b) Sketch of electrodes

5.4.2.6 Lining life

The wearing of lining assumes to be the important due to its cost addition and also influences the quality of the melt. In the present unit, maximum numbers of heat were sustained by magnesite crucible in the case of nitrogen plasma melting was seven. But in the case of hydrogen plasma, only six numbers of heats were sustained.

Table 5. 4 Rate of lining erosion as well as the number of heat sustainability in different arc exposure.

Parameters		Normal arc	Nitrogen plasma arc	Hydrogen plasma arc
Maximum Number of heat done		-	7	6
Number of heat under consideration		4	7	6
Time of total heat (min)		220	300	280
Total erosion	Volume (m^3) x10^{-5}	765	873	957
	Weight (Kg)	0.186	0.522	0.783
Rate of Erosion	kg/heat	0.047	0.075	0.131
	kg/hr	0.051	0.104	0.168

In the case of normal arc melting this type of calculation was not done but the erosion rate (i.e.kg/heat) was determined for crucible having three types of arc exposure as listed in Table 5.4.

The erosion of lining was happened due to the generation of intense heat inside the furnace as well as chemical reactions at the interface between the metal-lining material and gas-lining material. From the Table 5.4, it was cleared that the erosion rate was least in the case of normal arc compared to plasma arc. Hydrogen plasma was produced more heat and also created reducing atmosphere, resulting in more erosion rate of the refractory lining. Normal arc and nitrogen plasma eroded lining uniformly throughout the area as shown in Figure 5.21 b, c. In the case of hydrogen plasma, the arc zone area above liquid metal eroded very fast may be due to the reduction of magnesite lining in the presence of hydrogen gas at a very high temperature of arc zone as shown in Figure 5.21 d.

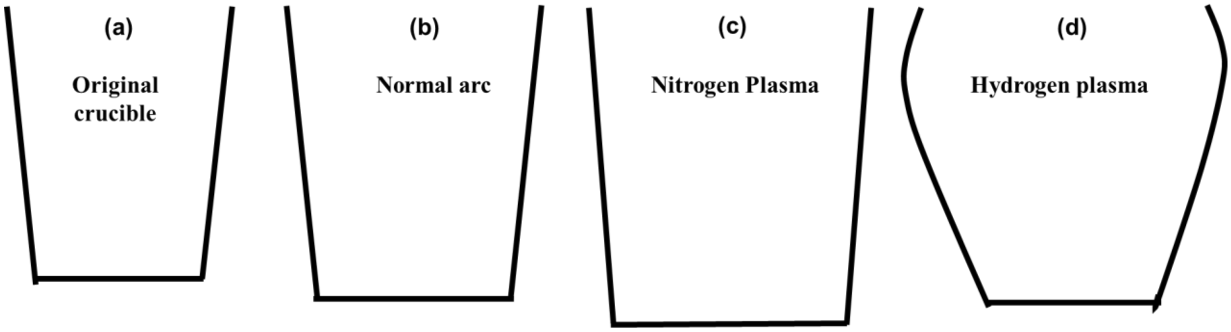

Figure 5. 21 Erosion patterns of magnesite crucible in different arcing condition

Figure 5.22 shows the photograph of sintered magnesite crucible after using 7 numbers of heat in nitrogen plasma which was attached to a graphite block for electrical connectivity.

Figure 5. 22 Photograph shows the condition of sintered crucible after using 7 heats in nitrogen plasma

5.5 Conclusions

The major observations could be noted based on the experimental studies are summarized as follows:

1. The plasma arc furnace designed and fabricated from local resources was found suitable to melt 2 kg steel and its attachment for various functions offered trouble free operation.
2. Nearly 200K increased melt temperature, and ~10dB lower sound levels were observed with nitrogen plasma arc compared to a normal arc.
3. Hydrogen plasma offered 100K higher melt temperature with higher ~5 dB sound level than nitrogen plasma.
4. Lower energy and electrode consumption were noted with nitrogen plasma arc melting than normal arc melting. Whereas lower energy consumption and higher electrode

consumption was observed in the case of hydrogen plasma in comparison to nitrogen plasma.

5. The higher plasma arc temperature resulted in shorter meltdown time than normal arc with smoother arcing.
6. Hydrogen plasma permitted more heats, reduced meltdown time, lower energy consumption but with increased graphite consumption and crucible wear.

Several melting experiments were performed on indigenously fabricated transferred arc plasma furnace and qualified for its operational worthiness due to the following results:

1. Temperature could be varied by varying arc length, arc current, power rating as well as varying plasma gas, etc.
2. Required melt temperature could be achieved by changing arc current and plasma gas.
3. Arc length could be adjusted by varying power rating and regulating voltage for required heat distribution above the melt.
4. The feeding system was working satisfactorily for charging of raw materials.
5. Exit gas system was working smoothly without spreading the gasses in the working area.
6. Functioning of pouring system was also worked smoothly.
7. Sample collection system during the running of the furnace as well as after melting was worked normally.
8. Sound level could be controlled by controlling arc current as well as the plasma gas.
9. Lining thickness was sufficient to hold liquid metal in the case of graphite as well as magnesite lining. No overheating was observed in the furnace shell during melting operation.

10. Gas purification and its flow system were worked smoothly. No backfiring or explosion happened during plasma run by using flammable H_2 gas.

The smooth functioning of the melt unit was considered suitable for studying the smelting behavior of industrial wastes for recovery of metals, which is the subject matter for the next chapter.