

Application of Plasma Arc Melting in Aluminium Recycling

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Abstract

RUSAL is investigating low temperature plasma arc melting of aluminium as part of its decarbonation strategy. Traditional gas- or oil-fired furnaces increasingly fall short of modern demands for energy efficiency, productivity, and low emissions (particularly carbon monoxide). Plasma arc melting technology delivers intense, rapid heating that dramatically accelerates aluminium melting. Developing such energy-efficient systems requires multidisciplinary collaboration across plasma science, heat engineering, and metallurgy – a convergence that generates substantial economic and technological benefits when executed effectively. Plasma technology is widely used in Russia in heavy industries such as Nuclear and the Ferrous industry. The system design for this project is based on experiences from the Ferromanganese industry. This paper outlines the R&D project scope and assumptions for utilizing low-temperature plasma arc melting, including furnace modelling, and strategies for maximizing efficiency and productivity.

Keywords: Plasma technology, Aluminium furnace, Remelting of aluminium scrap

1. Introduction

As one of the elements of its decarbonisation strategy, RUSAL is exploring plasma arc melting technology as a high-efficiency, renewable energy source for aluminium scrap remelting. This initiative is driven by RUSAL's continuous growth in remelting aluminium scrap to further reduce the carbon footprint of its aluminium.

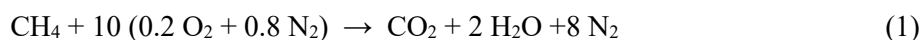
Unlike conventional oil or gas burner systems, plasma arc melting operates as an all-electric process. This enables direct integration with the same renewable energy sources powering RUSAL's primary smelting operations, eliminating reliance on fossil fuels. While plasma systems require higher upfront investment, they offer superior energy efficiency and enhanced metal yield compared to traditional fossil fuel-burning furnaces.

Beyond energy waste, combustion-based systems face compounding challenges: they demand cost-intensive fuel infrastructure and emission control systems (often exceeding the furnace cost itself). Critically, the release of untreated exhaust gases conflicts with both global decarbonization targets and tightening environmental regulations.

The current R&D project aims to quantify the operational advantages of plasma technology – specifically, determining when the gains in energy efficiency and material recovery offset the initial capital expenditure.

2. Natural Gas Combustion Systems

Natural gas combustion produces approximately 0.13 tonne of CO₂ per tonne of remelted aluminium. The chemical reaction is shown in Equation (1).



Natural gas generates approximately 11 kWh/Nm³ of thermal energy in the form of heat and radiation depending on the type of burner system. The process not only generates carbon dioxide, water vapour and nitrogen, but due to incomplete combustion, it is also create non-desirable products: CO (carbon monoxide), C (soot) and H₂ (hydrogen).

3. Energy Efficiency and Yield Comparison

A comparison between different combustion burner systems and plasma arc melting is shown in Table 1. Data source for the gas combustion burner systems is Mechaterm [1]. The oil burner data is based on actual oil consumption. The plasma arc melting is based on analysis, and initial tests. The values obtained with plasma arc melting will be confirmed as part of this R&D project.

Table 1. Benchmarking of combustion burner systems with plasma arc melting.

Process	Oil burner	Cold air burner	Regenerative burner	Oxy-fuel burner	Plasma Arc Melting
Energy to melt aluminium	1900 kWh/t	1050 kWh/t	700 kWh/t	660 kWh/t	< 500 kWh/t
Metal loss (dross)	10–17 %	8–15 %	8–12 %	5–10 %	< 5 %

Beyond high energy efficiency and a high yield, there are no direct CO₂ emissions and near-zero NO_x emissions in plasma arc melting (combustion-free process).

The higher temperatures enable faster melting and reduce energy waste. Technology is scalable for integration into existing cast house infrastructure. Furthermore, enhanced process control improves the alloy quality of the melt.

4. Low Temperature Plasma Arc Melting

Plasma arc melting is employed in the ferrous industry, utilizing extremely high temperatures (10 000–20 000 °C). However, these temperatures are inefficient for aluminium melting, which requires lower-temperature plasma systems. Some configurations operate under inert atmospheres (e.g., Ar/N₂) to prevent oxidation. Figure 1 illustrates common industrial plasma torch designs.

Different Plasma Torch Configurations

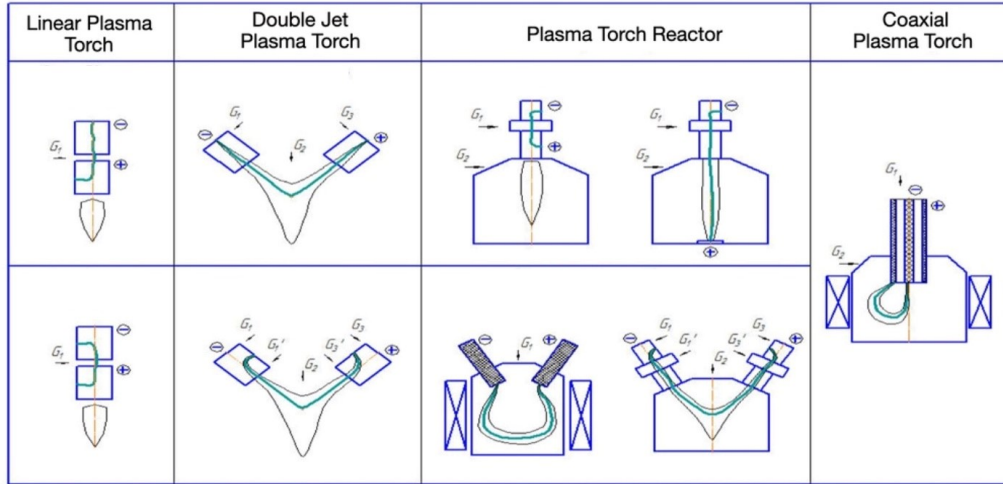


Figure 1. Plasma torch configurations (source: EPOS - Engineering).

A specialized low-temperature plasma arc melting system was selected for this project. Unlike conventional systems [2, 3], it operates without a plasma jet or inert cover gas, utilizing ambient air as the ionized medium – significantly reducing operational costs. Initial tests indicate an energy consumption lower than 500 kWh per tonne of melted aluminium. The torch achieves high efficiency through minimal heat loss and absence of off-gases.

Figure 2 (left) illustrates the operating principle: An arc forms between the internal electrode ($\text{\O}100\text{ mm}$) and external electrode ($\text{\O}500\text{ mm}$), ionizing air and heating the external electrode. Radiative transfer from this electrode heats furnace air to $\sim 2\,000\text{ }^\circ\text{C}$. Power is regulated by modulating the arc length.

During operation, the plasma unit's hood lowers onto the charged furnace, positioning the activated heater for melting. Heating occurs via uniform radiative flux from the plasma source.

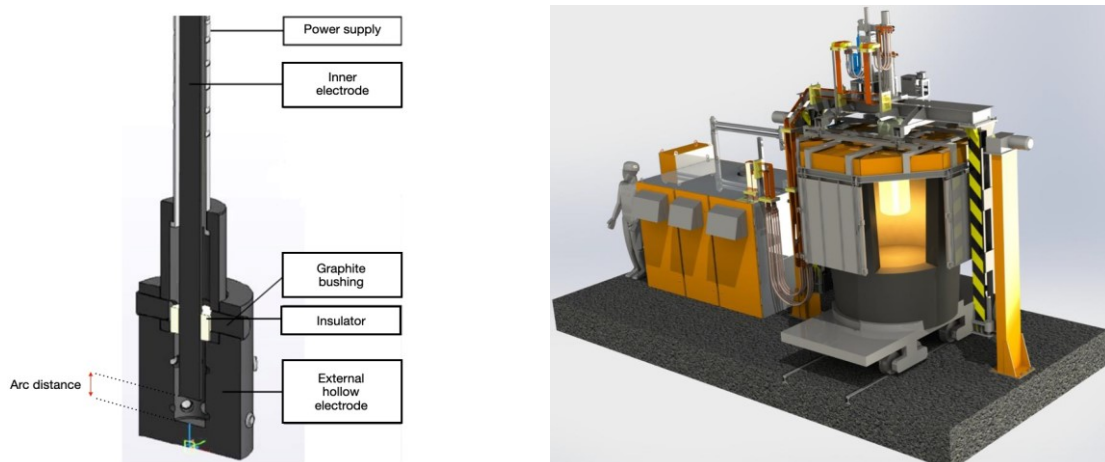


Figure 2. Left: Plasma arc heater, Right: Virtual model of the aluminium melting furnace with the plasma arc heater in the furnace arch.

The furnace temperature is controlled by a series of thermocouples installed in various locations in the furnace. Figure 3 shows an image of the plasma arc heater.



Figure 3. Plasma arc heater.

Plasma arc melting furnaces can be designed with power ranging from kilowatts up to megawatts and beyond. The furnaces can be equipped with the necessary amount of heating devices to meet the required melting capacity aluminium scrap.

5. System Specification

The technical specifications of the plasma arc melting furnace for a capacity of 11 tonnes are presented in Table 2.

Table 2. System specification.

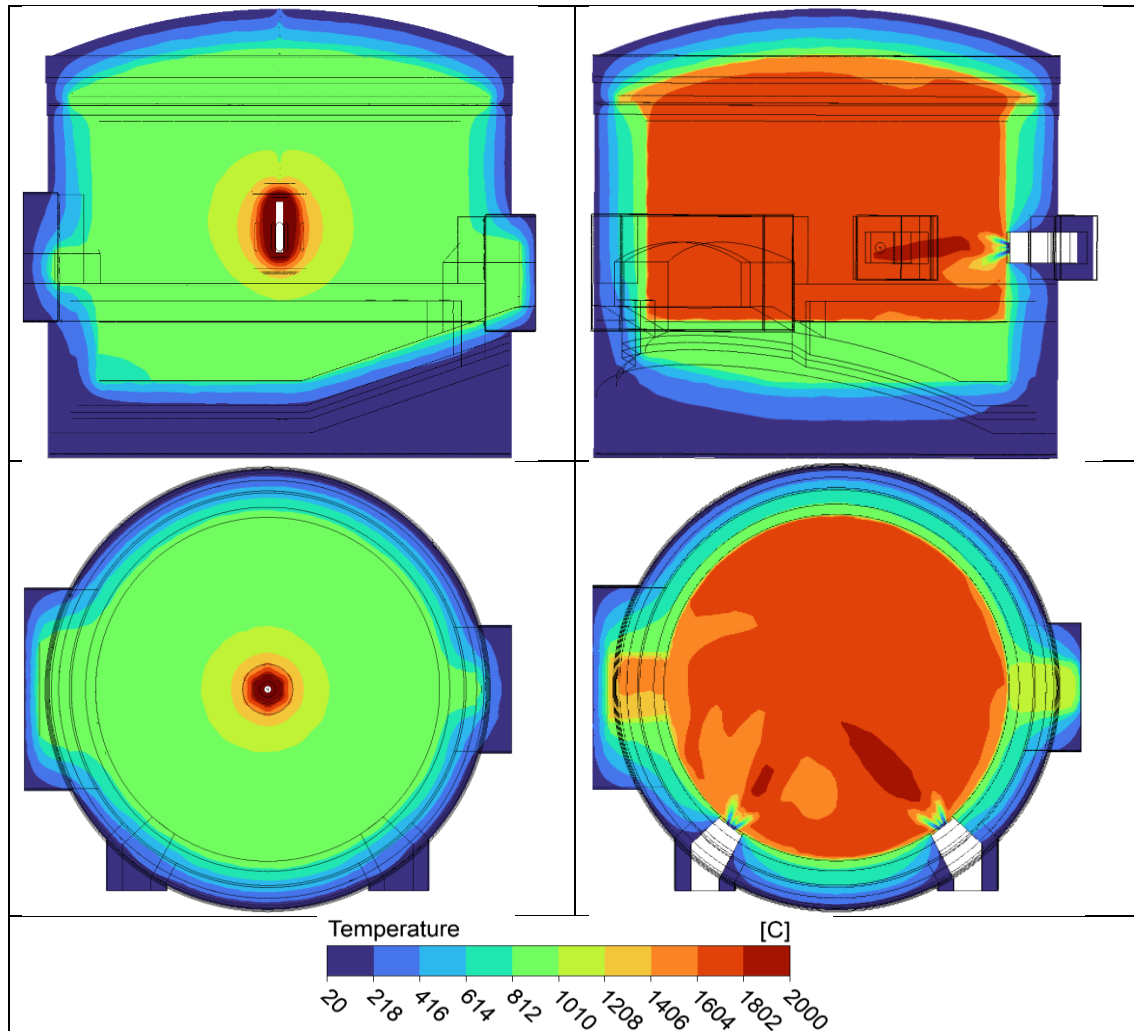
Parameter	Units
Plasma heater power max	600 kW
Power consumption control range	5–100 %
Heater material	Graphite
Thermal efficiency of the heater	90–97 %

The specification is based on an existing remelting furnace, currently operating with oil burners. RUSAL intends to conduct plasma melting trials employing aluminium ingots and multiple scrap types. The trials will evaluate melting efficiency, dross generation, and NO_x emissions, while also verifying the CAPEX/OPEX projections of the business case. Operational temperature measurements will be benchmarked against furnace modelling predictions.

6. Furnace Modelling

The application of plasma-arc heaters in furnace modelling reveals higher efficiency and productivity relative to conventional heavy oil furnaces. Figure 4 presents the thermal fields and

temperature gradient distributions, comparing plasma arc (left) and oil combustion (right). The plasma heater induces a highly localized high-temperature region characterized by strong thermal gradients, whereas oil burners result in a more homogeneous temperature profile. This distinction between point heating (plasma) and room heating (oil) underscores the greater efficiency of plasma-arc technology for aluminium melting applications.



**Figure 4. Comparison of thermal fields at comparable power levels.
Left: Plasma arc furnace, Right: Oil furnace.**

The model of the heat balance in the application packages of the furnace is based on the following equations:

The equation of continuity (conservation of mass):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (2)$$

where:

- ρ gas density,
- \mathbf{u} velocity vector,
- t time.

Equation of momentum conservation:

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} \quad (3)$$

where:

- p pressure,
- $\boldsymbol{\tau}$ viscous stress tensor,
- \mathbf{g} free fall acceleration (natural convection is taken into account).

Energy equation:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{u} h) = \nabla \cdot (\lambda \nabla T) + Q_{arc} + Q_{rad} - \nabla \cdot \mathbf{q}_{rad} \quad (4)$$

where:

- h specific enthalpy,
- λ thermal conductivity,
- Q_{arc} arc power (heat source in the arc volume),
- Q_{rad} radiation heat transfer, \mathbf{q}_{rad} - radiation heat flux density vector.

Modelling of the arc through a volumetric heat source:

$$Q_{arc} = \eta \cdot \frac{P_{arc}}{V_{arc}} \quad (5)$$

where:

- η arc heat release efficiency,
- P_{arc} arc electric power,
- V_{arc} arc zone volume.

Equation of natural convection:

$$\rho = \rho_0 [1 - \beta(T - T_0)] \quad (6)$$

where:

- β coefficient of thermal expansion,
- T temperature.

Radiation transfer equation for spectral intensity $I_\lambda(r, s)$

$$\frac{dI_\lambda(r, s)}{ds} = -(k_\lambda + \sigma_s)I_\lambda(r, s) + k_\lambda I_{b, \lambda} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I_\lambda(\mathbf{s}') \Phi(\mathbf{s}, \mathbf{s}') d\Omega' \quad (7)$$

where:

- k_λ absorption coefficient,
- σ_s scattering coefficient,
- $I_{b, \lambda}$ blackbody intensity,
- Φ scattering indicatrix,
- $\int_0^{4\pi}$ means integration in all directions (full solid angle),
- $d\Omega'$ solid angle element in the direction \mathbf{s}' .

Equation of heat transfer on the furnace walls (convection + radiation)

$$q_{wall} = h_{ext}(T_{wall} - T_{\infty}) + \epsilon\sigma(T_{wall}^4 - T_{\infty}^4) \quad (8)$$

where:

h_{ext} heat transfer coefficient,
 ϵ degree of blackness.

Some of the modelling output is shown here in Table 3:

Table 3. Heat source comparison modelling results.

	Plasma Arc Heater	Oil Burner
Time to temperature 850 °C	7.5 hours	11 hours
Melting rate	1.5 t/h	1.0 t/h
Energy consumption	409 kWh/t	1900 kWh/t (150 kg of oil)
Thermal efficiency of the heater	80 %	21 %

All modelling parameters will be validated through measurements during the melting experiments.

The experimentation will show whether plasma arc heating is a promising route by itself, or whether a combination with standard electrical heating, e.g. induction heating should be pursued.

7. Conclusions

Plasma-arc melting model demonstrates significant potential as a sustainable, electrically powered solution for aluminium scrap recycling. Key advantages to be validated through ongoing R&D include:

- Energy Efficiency: Exceeds advanced oxi-fuel burners (< 500 kWh/t Al)
- Sustainability: Zero direct CO₂ emissions and near-zero NO_x
- High System Efficiency: Plasma torch COP (95–97 %) and furnace efficiency (> 90 %) outperform fossil-fuel systems
- Yield Optimization: Minimal dross formation
- Operational Simplicity: No water cooling required; robust, low-maintenance design
- Precision Control: Smooth power modulation and superior temperature uniformity
- Cost Effectiveness: Low OPEX with high operational readiness

8. References

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