

REDUCING THE NUMBER OF REJECTS ON CERTIFIED REFERENCE MATERIALS VIA OPTICAL EMISSION SPECTROSCOPY

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TATA STEEL

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SCHOOL OF ENGINEERING (BENG MATERIAL SCIENCE)

Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Alex Greenslade

Date: 19/05/2025

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Abstract

This report details an investigation into the effects that surface preparation and milling depth have on the chemical analysis of steel samples. The process currently in place at Tata Steel is done so to improve time to test, although is in fact having a negative impact.

The project was designed with multiple objectives, the foremost being to investigate the frequent rejection of steel samples and to identify underlying causes in order to effectively reduce the rejection rate. Additional aims were to improve the time to test by reducing the amount of rework, which in turn will likely increase yields. Finally, investigating viable options for new equipment to support the installation of the Electric Arc Furnace.

The analysis identified significant issues related to sample preparation, a critical stage in ensuring the accuracy and reliability of steel sample analysis. Effective sample preparation is essential not only for producing correct and precise analytical results but also for ensuring that these results are delivered within the required turnaround times. These units play a vital role in the overall steel production process, as they are responsible for the addition of alloying elements and the removal of impurities, directly influencing the quality and properties of the final product.

The importance of this project extends beyond current operational needs, highlighting its long-term strategic value. Regular sample rejections present a range of significant challenges for the business. These include increased energy consumption due to repeated processing, reduced asset availability and operational efficiency, potential downgrading of product quality, and in some cases, complete loss of material. By addressing the root causes of sample preparation failures, the project supports improved process control, cost efficiency, and product quality, thereby contributing to more sustainable and resilient steelmaking operations.

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List of Abbreviations

<i>Abbreviations</i>	<i>Explanation</i>
UK	United Kingdom
EAF	Electric Arc Furnace
BOS	Basic Oxygen Steelmaking
C	Carbon
O	Oxygen
H	Hydrogen
N	Nitrogen
Si	Silicon
P	Phosphorous
Al	Aluminium
Al ₂ O ₃	Aluminium Oxide
Fe ₂ O ₃	Iron Oxide
FeMn HC	High-carbon ferromanganese
FeMn MC	Medium-carbon ferromanganese
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CSR	Coke Strength Reactivity
°C	Degrees Celsius
CAS-OB	Composition Adjustment Selected Oxygen Bubbling Unit
RH	Ruhrstahl Heraeus
RD	Ruhrstahl Deoxidation
ULC	Ultra Low Carbon
CRM	Certified Reference Material
SLA	Service Level Agreement
SWP	Safe Working Procedure
OES	Optical Emission Spectrometer/ Optical Emission Spectroscopy
PMTs	Photomultiplier tubes
DOE	Design of Experiments
LCL	Lower Control Limit
UCL	Upper Control Limit
MM	Millimeters
Min	Minute
CNC	Computer Numerical Control
5s	Sort, Set in Order, Shine, Standardise, and Sustain

Introduction

To ensure the successful completion of this project, the DMAIC (Define, Measure, Analyse, Improve, Control) methodology was employed as a structured, data-driven approach to process improvement. The use of DMAIC enabled a clear definition of the project's objectives, aligning them with organisational goals and customer expectations.

During the Define phase, the scope and purpose of the project were established, identifying key stakeholders and outlining the specific issues to be addressed. In the Measure phase, relevant data were collected to quantify current performance and establish baseline metrics, providing a clear foundation for comparison and improvement. The Analyse phase involved a thorough examination of the data to identify root causes of inefficiencies and process deviations. This analysis enabled informed decision-making and provided insight into the variables impacting quality and turnaround time. In the Improve phase, targeted solutions were implemented to address the identified root causes, leading to measurable enhancements in process efficiency and output consistency. These improvements were guided by lean principles, ensuring waste reduction and optimisation of laboratory workflows. Finally, in the Control phase, measures were put in place to sustain the improvements achieved. This included the development of standard operating procedures, performance monitoring tools, and regular audits to ensure continued adherence to quality standards.

The application of the DMAIC methodology not only enhanced the reliability and accuracy of results produced by the spectroscopy laboratory but also ensured that results were delivered within the agreed turnaround times as specified in the service level agreement (SLA). This led to a notable improvement in customer satisfaction, as stakeholders could rely on timely and precise analytical data to support decision-making across the plant. The systematic nature of DMAIC also facilitates continuous improvement, ensuring that quality standards are maintained and further refined over time.

Company Background

The Steelworks, originally established as 'The Abbey Works' in 1906, began as a modest facility focused on iron and steel production. In 1967, the site became part of the newly formed British Steel Corporation, marking a period of nationalisation. This arrangement continued until 1988, when the company was privatised as part of a broader governmental strategy aimed at improving the economic performance of the UK steel industry. At the time, British Steel was experiencing significant financial losses, which placed pressure on public finances (Kay & King, 1990). Privatisation was intended to enhance operational efficiency and competitiveness by introducing market forces and encouraging private investment (Vickers & Yarrow, 1988). This policy shift reflected the wider objectives of the Conservative government under Margaret Thatcher, which advocated for reduced state involvement in industry and promoted broader public share ownership (Thatcher, 1993). In 1999, British Steel merged with the Dutch firm Koninklijke Hoogovens to form Corus. The company's ownership changed again in 2007, when Tata Steel acquired Corus, integrating the business into its European operations (British Steel, 2024) (Yates, 2018) (Dawson, 2017).

Tata Steel is a global steelmaking company operating in 26 countries, with commercial links in over 35. Ranked as the world's sixth-largest steel producer, the company is also recognised as a leader in sustainable steel production. Its long-term vision includes the development of breakthrough technologies and innovations aimed at achieving carbon neutrality by 2050. Tata Steel maintains a significant presence across Europe and the UK, with operational facilities including rolling mills and raw material sites. In the UK, its primary locations include Port Talbot, Llanwern, Corby, Shotton, and Shapfell. The integrated steelworks at Port Talbot are particularly notable for producing high-quality steel, which is further processed at Llanwern, where it is rolled into strip steel and coated for corrosion resistance. These interconnected sites carry out processes such as hot rolling, cold rolling, and pickling, collectively enabling the production of up to five million tonnes of hot rolled coil annually. The strip steel produced is primarily used in the automotive, construction, domestic appliance, and packaging industries. Notable applications of Port Talbot steel include the Jaguar F-Pace, The Shard, Wembley Stadium, and the majority of UK 1p, 2p, 5p, and 10p coins (Tata Steel, 2024).

Despite Tata Steel's long-established presence in Port Talbot, operations at both of its blast furnaces ceased in September 2024. This decision forms part of a broader strategy to transition towards Electric Arc Furnace (EAF) technology, supporting efforts to produce lower-carbon steel. The move has been significantly influenced by the UK Government's commitment to achieving net-zero carbon emissions (Robins & Selvaraju, 2024). The existing blast furnace process relies heavily on carbon-intensive raw materials such as coke, derived from coal, and sinter, composed of iron ore and other inputs. Producing virgin steel using this method results in approximately 2.2 tonnes of carbon dioxide per tonne of steel. With Port Talbot's annual production capacity of up to five million tonnes, this equates to around 11 million tonnes of CO₂ emissions each year—roughly 3% of the UK's total emissions. In comparison, EAF technology emits only 0.3 tonnes of CO₂ per tonne of steel, representing an emissions reduction of over 85%. This transition not only offers substantial environmental benefits but also addresses the aging condition of the existing blast furnace infrastructure. From both a sustainability and operational standpoint, the adoption of EAF technology represents a necessary and forward-looking development for Tata Steel's Port Talbot operations (Attwood, 2024), which is outlined in Figure 1.

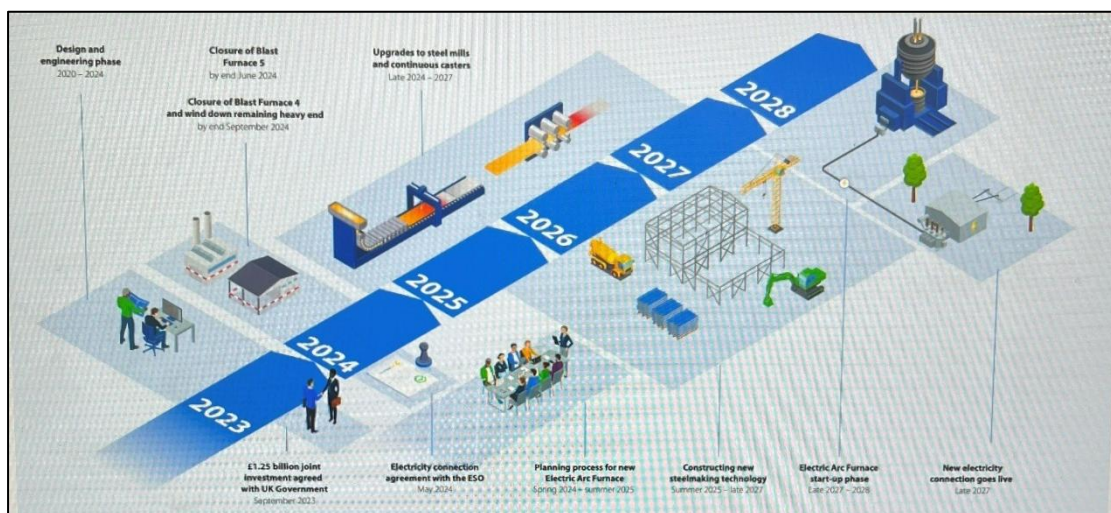


Figure 1 – Transition Plan (Tata Steel, 2024)

In 2023 Tata Steel's Port Talbot facility produced approximately 3.4 million tonnes of steel. This production level represents a slight decrease from its maximum capacity of 4.19 million tonnes in 2015 (Duffy, 2023). Thus, suffering significant financial losses, approximately £656 million worth (Suri, 2023). To help aid Tata Steel transition to greener steel making the UK Government are granting the Indian Company £500 million as part of a £1.25 billion invested by Tata (Gov.uk, 2024). Figure 2 below shows the planned position of the electric arc furnace at Tata Steel in Port Talbot.



Figure 2 - Planned Position for EAF (Mosalski, 2024)

1. Project Purpose

The research and analysis of this project will take place within the Spectroscopy Laboratory within Tata Steel, Port Talbot. The purpose of this study is to investigate the underlying reasons for the frequent rejection of steel samples at the Spectroscopy Laboratory. In this context, the term "rejection" does not solely indicate a pass or fail outcome. Rather, it encompasses any result that falls outside the specified tolerances for a given element, whether below or above the defined limits. The steel samples sent to the Spectroscopy Laboratory are initially milled to ensure a smooth and clean surface before being analysed using an Optical Emission Spectrometer. This spectrometer sparks the sample between two and four times, to obtain consistent results across all elements. Rejection occurs when the tie-up between sparks is not achieved. Conversely, when a tie-up is obtained, the sample is analysed and results are provided to the customer. Rejections are also occurring on the Certified Reference Materials (CRM), as it has been noticed that there have been large periods of instability of results which needs to be addressed.

A more thorough understanding of why these rejects keeps occurring needs to be achieved. This will allow the Basic Oxygen Steel plant or the Spectroscopy laboratory to make future improvements.

1.1. Aims and Objectives

The aim of this project is to gain a comprehensive understanding of the issues leading to the rejection of steel samples and to work towards resolving these problems. The anticipated outcomes of this project include a reduction in the frequency of rejections, thereby enhancing testing efficiency. Should this objective not be fully resolved, the project seeks to develop a thorough understanding that will facilitate recommendations for process improvements. These improvements may involve the acquisition of new equipment, contingent upon forthcoming investments.

This project sets to achieve several objectives, one of which is to conduct a comprehensive literature review and employ methods to gather primary data through representative and reliable sample testing.

Then the project will look to perform effective data analysis utilising an appropriate range of statistical techniques. Upon collecting data that indicates issues with the testing of steel samples, initiate research into new technologies that could potentially enhance the process. Finally, the project will look to draw conclusions based on the findings and engage in discussions with stakeholders to develop a more accurate and efficient process, which can be implemented once the Electric Arc has been assembled.

1.2. Timescales

A Gantt chart, shown in Figure 3 was employed to effectively plan and monitor the progress of the project's aims and objectives. This tool allowed for the allocation of specific tasks according to the deadlines, thereby optimising time management throughout the project. Moreover, the Gantt chart facilitated the measurement of both successes and any challenges encountered, thereby providing a framework for identifying and addressing issues that could impact the achievement of the project's objectives. The chart outlines several critical path tasks, which are denoted in red, are essential for project completion, with any delays directly impacting the end date.

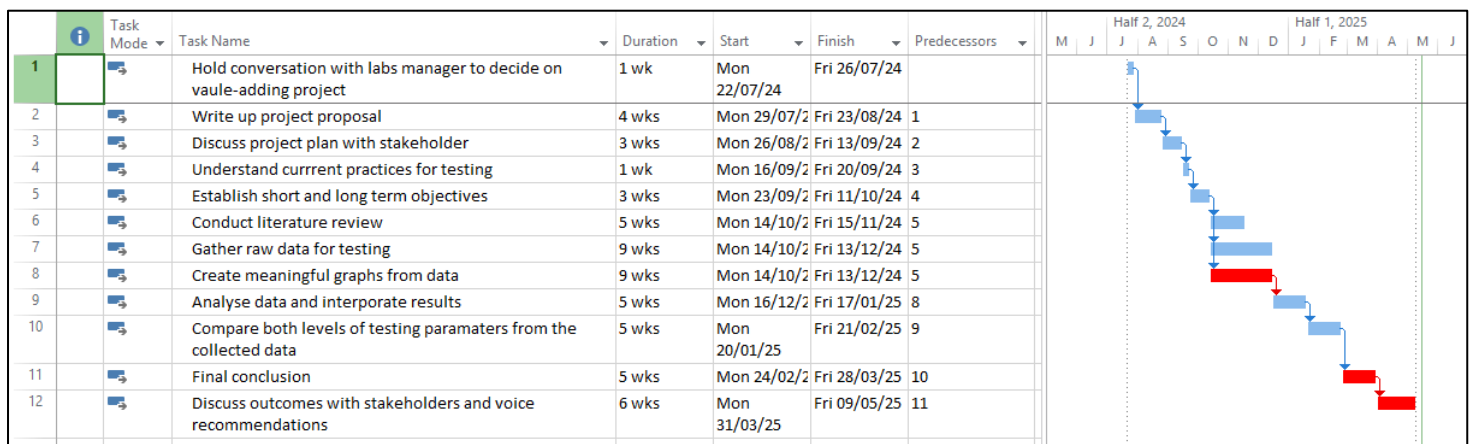


Figure 3 - Gantt Chart for the Project

2. Literature Review

The purpose of this literature review is to provide a comprehensive analysis of existing research and methodologies relevant to the steel making processes and Tata Steel and the importance of testing procedure of steel samples. Additionally, the section examines newer steel making methodologies to manufacture greener steel in line with the governments strategies. By synthesising the current body of knowledge, this review establishes a foundation for the research and identifies gaps that this study seeks to address.

2.1. Steelmaking Existing Practices

Steelmaking has been a longstanding industry in Port Talbot, significantly supported by the strategic location of the plant. Tata Steel's facility benefits from its advantageous position on the seafront, complete with its own harbour. This harbour provides a critical benefit for the steelworks by enabling the efficient delivery of essential raw materials, such as iron ore and coke. These materials are sourced globally from countries including Brazil, Australia, Canada, and Norway. The raw materials, which are the initial components of the steelmaking process, are extracted from mines in these countries and transported to the site via boat or rail (Tata, 2024). Figure 4 below shows an overview of Tata Steel at Port Talbot.



Figure 4 - Ariel View of Port Talbot Steelworks

2.1.1. Coke Making

Coke is a carbon-based fuel source for the Blast Furnace, which is used to reduce the iron oxide (Fe_2O_3). It is made by heating coal to around 1,100 degrees Celsius in the absence of Oxygen (O) in a coke oven. The lack of oxygen prevents the coal from burning. The coking process drives off various gases, liquids and volatile matter, leaving a solid mass of nearly pure carbon, coke. Coke serves as a reducing agent when introduced into the blast furnace. The Carbon (C) within the coke reacts with the hot gas from the tuyeres, forming carbon monoxide. This Carbon Monoxide (CO) subsequently reacts with iron oxide to produce metallic iron. Additionally, coke plays a crucial role in providing load support within the furnace. Pellets and sinter are charged in layers, and the coke, produced by Morfa Coke Ovens, must be sufficiently hard enough to support this material while being porous enough to permit gas flow. To ensure these properties, Tata Steel laboratories conduct tests on the coke material to assess its Coke Strength Reactivity (CSR) (Kumar, et al., 2022). Figure 5 outlines the coke making process used at Tata Steel.

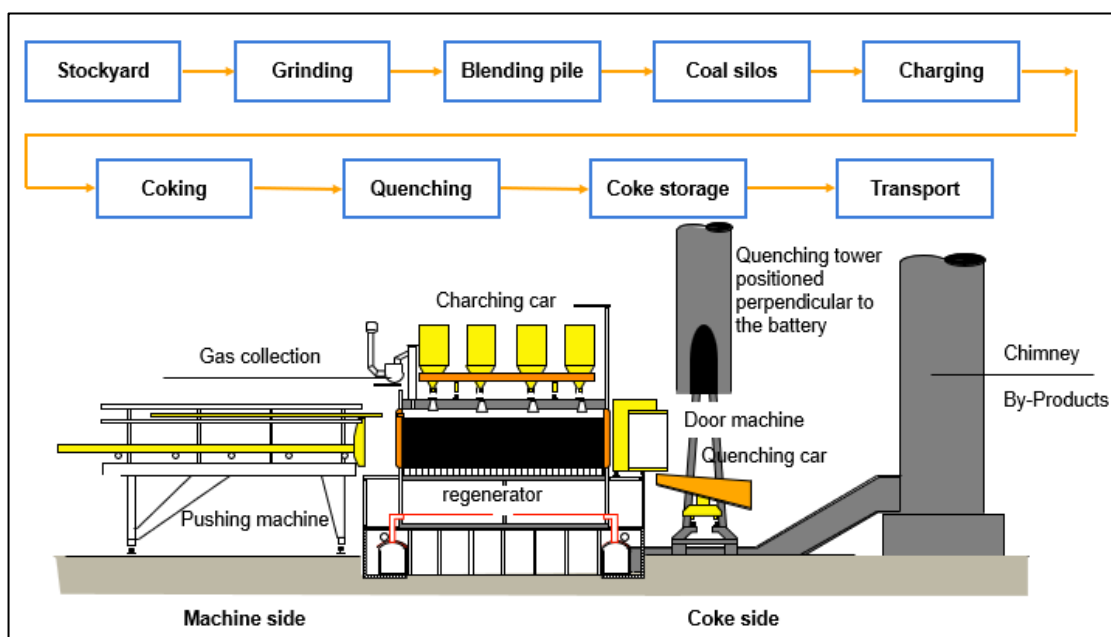


Figure 5 - Coke Making Process

2.1.2. Sintering

The sintering process involves converting a mixture of raw materials into a strong, porous material with a high iron content through precise control of chemistry and fuel additions. This method is the most widely used for preparing iron ore fines for a blast furnace. Prior to sintering, raw materials such as iron ore, flux, fuel, and sinter return waste are mixed together in a rotating drum with water to create the raw mix. The addition of water affects the particles, causing them to stick together and granulate into

sinter of sufficient size. The relationship between water addition and granulation is critical, as it increases the permeability of the bed on the sinter strand (Niu, et al., 2022).

Once the preparation of the raw mix is completed, it is ready for sintering. The sinter mix is transported toward natural gas burners, ignited by the coke fuel, forming the 'flame front.' This flame front, fuelled by the gas flow and breeze in the mix, progresses vertically through the bed from top to bottom, directed by fans. The heat generated by combustion causes partial melting and fusion of the iron ore fines and fluxes, forming a porous mass known as sinter. The temperature in the sintering zone typically ranges from 1200°C to 1400°C (Gonzalez, Bustinza, Mochon, Gonzalez-Gasca, & Verdeja, 2016).

The sinter material is then cooled using a series of fans, crushed to obtain the desired size distribution, and screened to separate the fines from the usable product, as demonstrated in Figure 6. The fines are recycled back into the mix, while the larger sinter material is transported to the blast furnace for iron making.

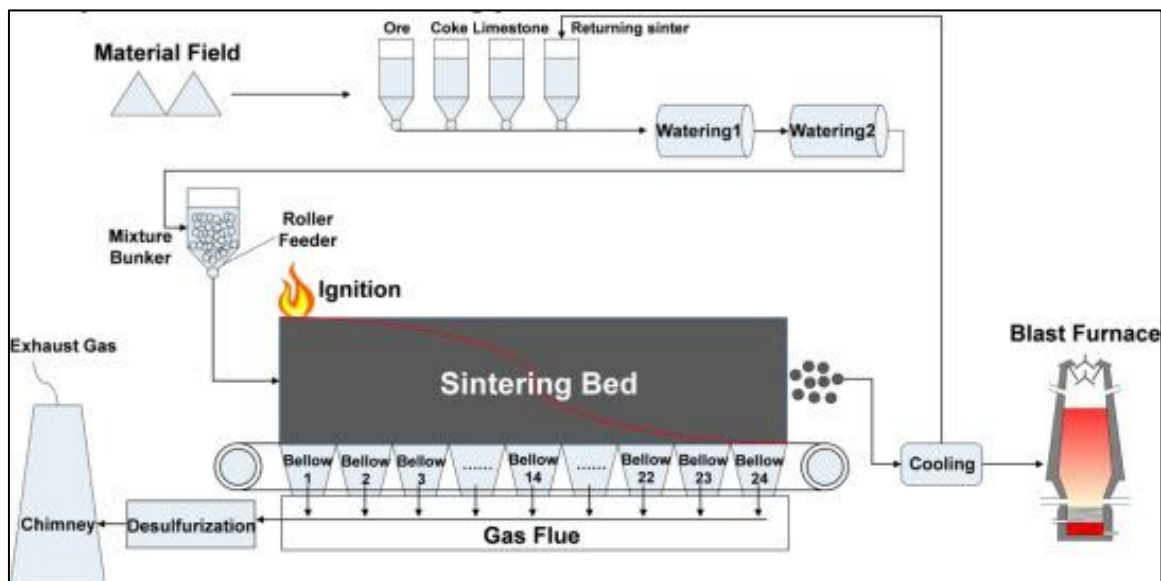


Figure 6 - Sintering Process

2.1.3. Iron Making

There are two primary process routes for the production of steel which involved the blast furnace process (shown in Figure 7) and the electric arc furnace process. These routes differ with respect to the type of products that can be produced. In the blast furnace process, iron ore and reducing agents such as coke and coal are transformed into hot metal. The iron ore and coke are charged in discrete layers at the top of the furnace. A hot blast of air, exceeding 1200°C, is blown into the furnace through tuyeres.

This hot blast gasifies the reductant components in the furnace, and the Oxygen (O) in the hot blast converts to Carbon Monoxide (CO). The resulting gas, with a very high temperature ranging between 2100°C and 2300°C, ascends through the furnace and performs several essential functions. The first function is that it acts as a reducing agent, facilitating the chemical reduction of iron oxides (Fe_2O_3) into metallic iron. This occurs through a series of redox reactions in which carbon monoxide (CO) donates electrons to the iron oxides, producing carbon dioxide (CO_2) and elemental iron. The gas causes the iron ore to melt in the burden and removes the Oxygen (O) gas through chemical reactions (Ghosh & Chatterjee, 2008). Upon melting, the iron ore produces hot metal and slag, which drip down through the coke zone to the hearth, from where they are removed by casting through the taphole (Geerdes, 2009).

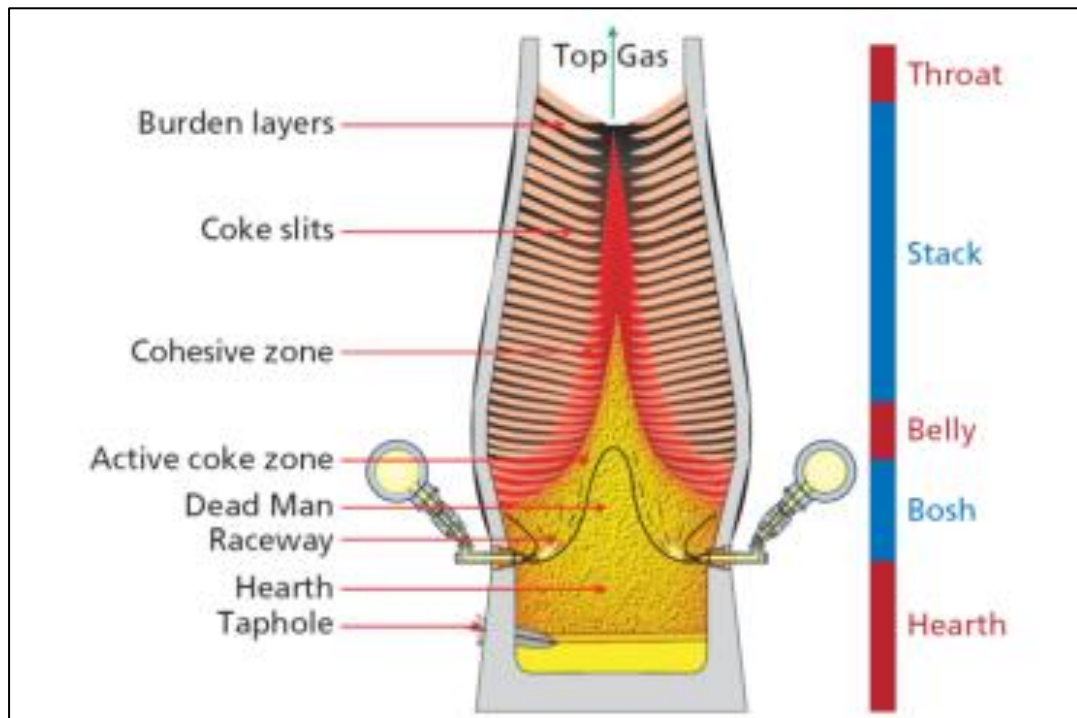


Figure 7 - Blast Furnace Overview

2.1.4. Basic Oxygen Steelmaking Plant (Bos)

The Basic Oxygen Steelmaking (BOS) process was invented in the early 1950s by an engineer named Robert Durrer and his collaborators. The development took place in Austrian company named 'Linz and Donawitz' (McGrath. J, 2022). The BOS Plant is where the hot metal from the blast furnace is turned into steel. Steel is defined as an alloy with a Carbon (C) content between 0.001% and 2.1%. The Hot Metal from the blast furnace typically contains 3.5% – 4.5% Carbon and other elements which have to be removed to form steel. During the BOS process the hot metal is purified from all

the unwanted elements to create steel. Alloying metals are also added to fine-tune the chemical composition. From the process map in Figure 8, there are four main steps to the steelmaking process, the first one being Hot metal desulphurisation, this to mainly reduce the Sulphur (S) content. Secondly, BOS is introduced to remove impurities such as Carbon (C), Silicon (Si) and Phosphorous (P). The secondary steelmaking process adds the final alloying elements and to ensure the chemical composition is correct prior to final step, continuous casting. This is where the liquid steel is cooled and cast into slabs (Deo, 1993).

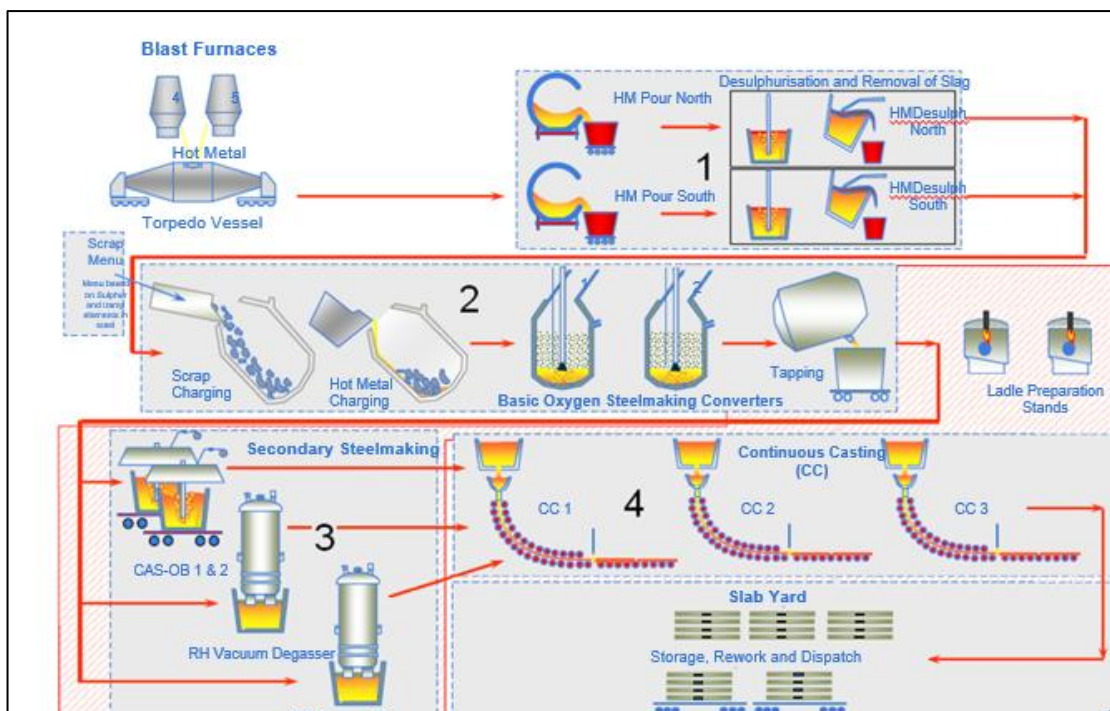


Figure 8 - BOS Plant Overview

2.2. Treatment Stations Within Secondary Steelmaking

The liquid steel arrives at the treatment stations from the converters in a teeming ladle. The primary goal of the treatment stations is to finalise the chemical composition and temperature of the steel. To achieve this, processes such as mixing, heating, the addition of alloying elements, and the extraction of certain elements are performed. Examples of alloying elements include manganese, chromium, nitrogen, vanadium, and silicon. Aluminium is also added to deoxidise the steel to prevent the formation of carbon monoxide bubbles during the casting process (Wente & Nutting, 2025).

The secondary steelmaking process comprises two units, each with distinct functions. The first unit is the Composition Adjustment Selected Oxygen Bubbling (CAS-OB) unit.

At Tata Steel in Port Talbot, there are two CAS-OB units, identified as number one and number two. These CAS-OB units perform functions such as alloying, mixing, and reheating by injecting argon and oxygen to mix the alloys into the steel.

The second units are the RH (Ruhstahl Heraeus) and RD degassers. The primary difference between these two units is the time required to perform their tasks, with the RH degasser being more efficient. The degassers facilitate the extraction of nitrogen, oxygen, carbon, and hydrogen using a vacuum. These degassing units are primarily used for producing Ultra Low Carbon (ULC) grades of steel (International, 2017).

2.2.1. CAS-OB Units

The initial step when molten steel enters the CAS-OB unit involves the bubbling of argon gas. This process creates an entry point on top of the melt where the slag is located, ensuring that when the bell is lowered, no slag is contained within it, as outlined in Figure 9. The bell is a machine that provides a protective environment for adding alloying materials while keeping the steel surface open and protected from the surrounding atmosphere. Proper use of the bell significantly reduces the amount of absorbed nitrogen. The environment under the bell is ideal for chemical reheating, which is achieved by adding solid particles of aluminium and blowing high-speed oxygen into the mix. The aluminium particles oxidise and end up in the slag atop the melt (Linnestad, Ollila, Wasbo, & Bogdanoff, 2021).

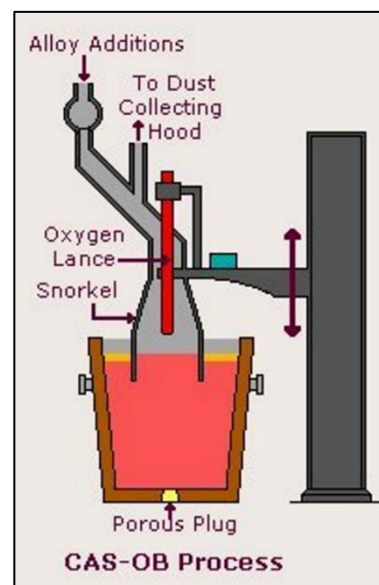


Figure 9 – CAS-OB Process

The reaction between aluminium and oxygen is extremely exothermic, heating the steel and increasing the temperature of the entire melt by approximately 10°C per minute (this reaction is represented as $2\text{Al} + 3\text{O} = \text{Al}_2\text{O}_3$). Most of the formed Aluminium Oxide (Al_2O_3) floats and becomes part of the slag layer. This process, known as "killing" the steel, is crucial as it prevents the formation of Carbon Monoxide (CO) bubbles during cooling ($\text{C} + \text{O} = \text{CO}$), which is essential for the casting process. The steel must be killed to avoid bubbles in the cast steel (uni, 2020).

The extent of deoxidisation is controlled by the amount of aluminium added. Aluminium additions can be as high as 20 tonnes, at a rate of 3 tonnes per minute, under an inert argon atmosphere. When molten steel contacts air, oxygen reacts with aluminium

deoxidisers, lowering their effectiveness and causing inclusions like aluminium oxides that weaken the steel and clog casting equipment (Ghosh & Chatterjee, 2008). Using an argon atmosphere blocks oxygen from re-entering, allowing better deoxidation and protecting valuable alloying elements from oxidation (Geerdes, 2009). Argon is also safe to use at high temperatures since it's non-toxic and non-flammable. Therefore, an inert atmosphere is essential to produce clean, high-quality steel and maintain process reliability (Biswas, 1981).

2.2.2. RH & RD Vacuum Degassers

As the teeming ladle arrives from the converter, it is placed in the installation, and two snorkels with a vacuum chamber on top are inserted into the melt. The molten steel is drawn up by the vacuum chamber, assisted by the flow of argon injection from one of the snorkels. This process reduces the weight of the steel in the snorkels, thereby encouraging circulation of the steel. During this procedure, the temperature is controlled by the addition of aluminium (Al) and oxygen (O) to provide more heat, as well as the addition of scrap to cool the melt (Guan, et al., 2024), where Figure 10 shows an example of the process.

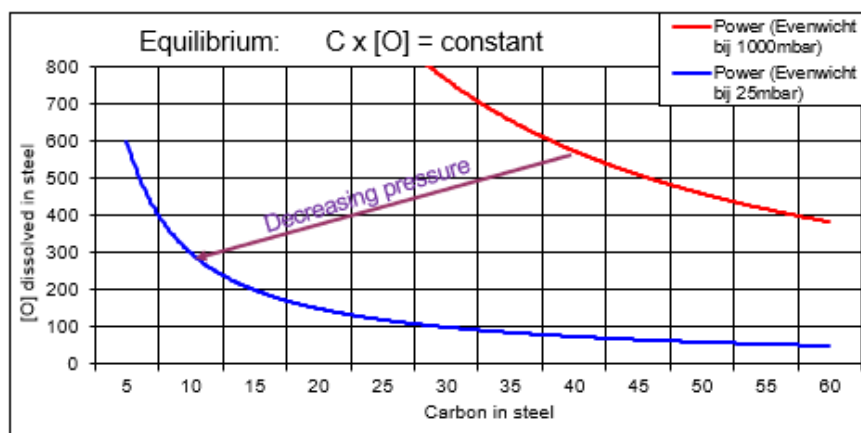


Figure 10 – Effects of pressure on Carbon & Oxygen

Initially, alloying materials are added and mixed, with the quantities varying depending on the grade of steel. The second step involves degassing. The carbon-oxygen (C+O), nitrogen (N), and hydrogen (H) in the steel are in equilibrium with the atmosphere. By decreasing the pressure, these elements dissipate from the steel, and the amounts are controlled by the pressure in the vacuum chamber. The concentration of carbon (c) can be further reduced by injecting oxygen (O). If the carbon (C) content is too low, it can be increased by adding carbon-containing alloys, such as high-carbon ferromanganese (FeMn HC), medium-carbon ferromanganese (FeMn MC), or anthracite (Li, Dai, Yang, Shao, & Zou, 2023).

After degassing, further deoxidation is achieved by adding aluminium, following the reaction $2\text{Al} + 3\text{O} \rightarrow \text{Al}_2\text{O}_3$. This "killing" of the steel is essential for the casting process. An additional advantage of deoxidised steel is that it prevents the burning of certain alloying elements. In the final step, other additives are introduced to fine-tune the chemical composition. Free carbon (C) and nitrogen (N) can be further reduced by adding titanium (Ti), which binds these atoms during solidification (Kacar, Kruger, & Pistorius, 2021). Figure 11 shows an example of a degasser commonly used in this process.

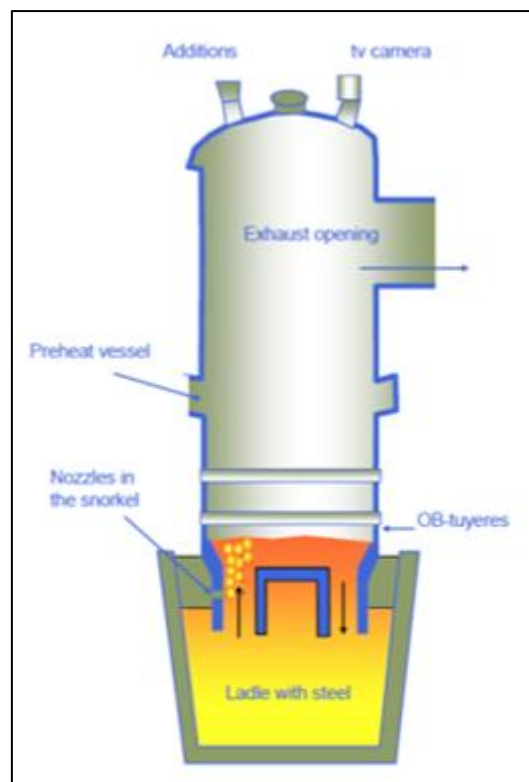


Figure 11 - Degasser

2.3. Steelmaking Via an Electric Arc Furnace

Tata Steel has traditionally utilised Blast Furnaces for steel production and plans to continue this method in its other plants located in India and the Netherlands. However, the Port Talbot Steelworks and Tata Steel are currently under pressure from the UK government to decarbonise the steel production processes. In response to this external pressure, Tata Steel and the UK government have agreed that the most effective way to achieve lower carbon emissions is to transition to an Electric Arc Furnace (EAF) that recycles scrap steel (McLachlan, 2024). This transition will mark

the end of coal-powered blast furnaces, replacing them with recycled scrap electric arc furnaces through an electrification process.

Despite the high emissions associated with the current practices at Tata Steel Port Talbot, steel production remains one of the six foundation industries, essential for producing green products such as wind turbines and electric vehicles. The shift from Blast Furnace ironmaking to an Electric Arc Furnace, however, is expected to have a devastating impact on the local community and current Tata Steel employees. Tata anticipates a loss of approximately 2,800 jobs, with an additional 300 jobs possibly affected in the near future. These job losses are primarily expected to occur in the heavy-end sectors, including the Sinter plant, Morfa Coke Ovens, Blast Furnaces, and the BOS Plant (Lawless, 2024).

During this major transition, the Morfa Coke Ovens ceased operations on Wednesday, 20th March 2024, due to significantly deteriorating operational stability. Although the Blast Furnaces require coke, they were able to continue operating by importing coke (Auskerry, 2024). Blast Furnace 5, which had been in operation since 1959, also ceased operations on Thursday, 4th July 2024. The Sinter Plant and Blast Furnace 4 followed suit in September 2024 (Thomas, 2024).

The Electric Arc Furnace (EAF) possesses several advantages, including lower carbon emissions compared to traditional blast furnaces. EAFs are more energy-efficient, as they can start and stop operations quickly, unlike blast furnaces that require continuous operation. The use of recycled steel in EAFs reduces waste, thereby enhancing sustainability. Additionally, the infrastructure of an EAF is less expensive to build and maintain than that of a blast furnace, and the use of scrap metal is more cost-effective than using raw materials such as iron ore. Furthermore, EAFs are considered safer, with a reduced likelihood of accidents related to high temperatures and hazardous materials (JinsunCarbon, 2024).

While the Electric Arc Furnace (EAF) presents numerous advantages, it also has several associated drawbacks. The quality of steel produced is highly dependent on the scrap steel used as feedstock, with variations in scrap quality affecting the consistency and quality of the final product. Another issue is the availability of scrap steel, which can be inconsistent. Additionally, the high electricity prices in the UK, compared to other European countries, can negatively impact Tata Steel by increasing energy costs due to the higher electricity consumption of EAFs. Furthermore, the

electrodes used to melt the steel are costly and require periodic repair or replacement (Carlsson, Samuelsson, & Jonsson, 2020).

2.3.1. Electric Arc Furnace Process

The process of steel production using an Electric Arc Furnace (EAF) involves melting the charge into steel, with each batch of molten steel referred to as a "heat". The EAF operating cycle comprises several operations during the tap-to-tap cycle, including furnace charging, melting, refining, deslagging, and tapping, as outlined in Figure 12. Prior to charging, proper sorting procedures must be implemented to ensure the recycled scrap's chemistry is adequate for producing the intended grade of steel. The quality of the scrap directly influences the quality of the final steel product (Nucor, 2024).

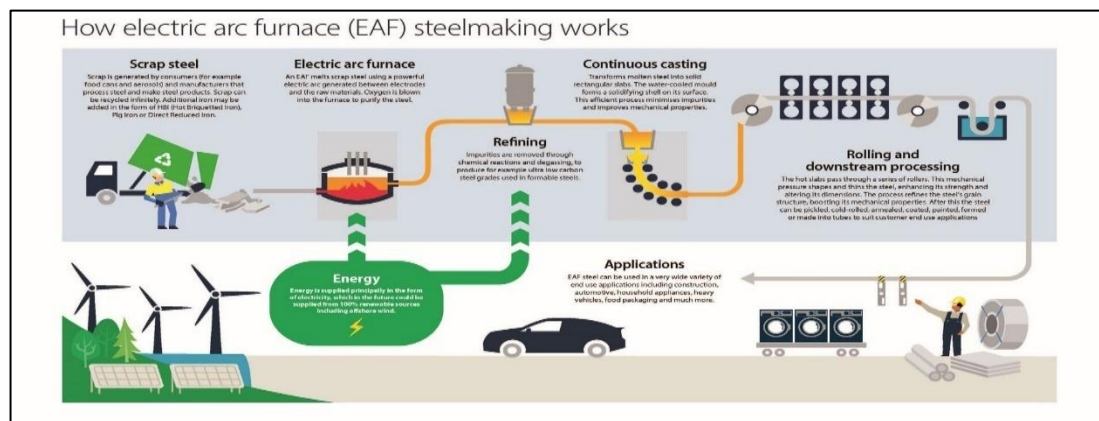


Figure 12 - EAF Steelmaking Process (Thomas G. , 2024)

During the charging phase, the furnace roof with the electrodes is opened to load the recycled scrap into the EAF. Once the material is loaded, the roof is closed, and the electrodes are lowered onto the scrap to initiate melting. An electrical voltage is applied to the electrodes, generating the heat required to melt the material into a liquid pool of metal in the furnace hearth. Additional chemical energy can be introduced by using oxygen lances to blow oxygen into the mix. The oxygen reacts with the hot scrap, burning iron to produce intense heat (Singh, 2016).

Once a molten pool of steel is achieved, oxygen is lanced directly into the mix to react with elements such as aluminium, silicon, manganese, carbon, and phosphorus. These reactions are exothermic, causing a further increase in temperature. The oxides formed during these reactions are incorporated into the slag. Refining the molten steel is necessary to remove impurities such as phosphorus, sulphur, manganese, and carbon, similar to the refining process in a blast furnace (Spooner, Seetharaman, Li, & Li, 2022).

Once the desired steel composition and temperature are achieved, the steel is ready to be tapped and further refined using CAS-OB units and degassers. This ensures the final steel product meets the required specifications and quality standards (Singh, 2016).

The Spectroscopy Laboratory at Tata Steel Port Talbot is anticipated to experience a significant reduction in workload following the closure of the remaining Blast Furnace. This closure will consequently halt operations at the BOS plant, the primary source of the laboratory's steel samples. Addressing current issues with steel samples is critical, necessitating the resolution and correction of these issues and the exploration of alternatives in light of substantial business changes in steelmaking. Despite these changes, the Electric Arc Furnace (EAF) will continue to process recycled scrap steel, requiring ongoing sample testing throughout the casting process, similar to current practices.

2.3.2. Testing Process

Upon arrival at the laboratory, prompt testing of samples is prioritised to ensure timely service delivery to the customer. Each sample is initially weighed and inspected to verify its suitability for analysis. Samples that are hollow, underweight, or improperly shaped can adversely affect the accuracy of Optical Emission Spectroscopy (OES) testing. Such deficiencies may lead to poor spark stability, resulting in noise interference on the spectrometer and inconsistent analytical results. It is therefore essential to assess the weight and condition of samples prior to commencing milling operations. Although this preliminary inspection requires only a few seconds, it ultimately saves time by reducing the likelihood of test failure and the subsequent need for retesting.

The milled surface must be clean and flat to ensure correct positioning of the sample on the OES stand. This prevents air ingress during sparking, which would significantly compromise the accuracy of the results. During analysis, a high-voltage spark vaporises a minute portion of the steel sample, creating a plasma. Atoms within this vaporised material become excited and, as they return to their ground state, emit light at characteristic wavelengths corresponding to the elements present in the sample.

The emitted light is collected and directed through a diffraction grating, which disperses it into its constituent wavelengths. A photomultiplier tube then converts the intensity of this light into electrical signals. These signal intensities are directly proportional to the concentration of each respective element. Calibration curves, generated using

Certified Reference Materials (CRMs), are applied to quantify the elemental concentrations. The internal software processes the spectral data and displays the results as percentage concentrations. Each element within the steel sample is associated with specific tolerance limits, with nitrogen typically requiring the most stringent control (Scientific, Thermo Fisher Scientific, 2024).

2.4. Summary of Research

Tata Steel Port Talbot benefits from its coastal location and harbour, enabling efficient import of essential raw materials such as iron ore and coke from countries like Brazil, Australia, Canada, and Norway. These materials, transported mainly by ship or rail, support steel production using traditional Blast Furnace (BF) methods. Coke, produced by heating coal in the absence of oxygen (O), serves as a carbon-rich fuel in blast furnaces, reducing iron oxide to molten iron through carbon monoxide (CO) generation. Tata Steel tests coke for strength and reactivity (CSR) to ensure performance in the Blast Furnace.

The sintering process prepares raw materials by mixing iron ore, flux, fuel, and return fines with water, forming granules that improve permeability. These granules are ignited using coke-fired burners, creating a flame front that fuses the mix into porous sinter, which is cooled, crushed, and sized before use in the blast furnace.

Steel production via the Blast Furnace route involves layering iron ore and reductants like coke and coal in the furnace. A hot air blast over 1200°C gasifies coke, producing carbon monoxide (CO) that reduces iron oxides to molten iron. This molten iron, along with slag, is tapped from the furnace hearth. The Basic Oxygen Steelmaking (BOS) process, developed in the 1950s, converts this hot metal into steel by removing impurities and adjusting carbon content from 3.5–4.5% down to desired levels of 0.001–2.1%.

Steelmaking generally follows four steps, hot metal desulphurisation, oxygen blowing to remove carbon and impurities, secondary steelmaking for alloy adjustments, and continuous casting into slabs. Alloying elements such as manganese (Mn), chromium (Cr), vanadium (V), and silicon (Si) are added for desired properties, while aluminium is used to deoxidise the steel, preventing carbon monoxide bubble formation during casting, a process known as "killing" the steel.

At Tata Steel Port Talbot, secondary steelmaking includes Composition Adjustment by Sealed Argon Bubbling with Oxygen Blowing (CAS-OB) units and vacuum degassers

(RH and RD). CAS-OB units inject argon and oxygen to mix alloys and control temperature, while degassers remove dissolved gases under vacuum, crucial for Ultra Low Carbon (ULC) steels. The aluminium-oxygen reaction in CAS-OB units generates heat and forms aluminium oxide slag, ensuring clean steel free from gas porosity.

Tata Steel traditionally relies on blast furnaces at Port Talbot, India, and the Netherlands. However, under increasing UK government pressure to reduce carbon emissions, Tata Steel and the government agreed to transition to Electric Arc Furnace (EAF) technology, which recycles scrap steel and eliminates coal-powered blast furnaces.

Despite high emissions from current operations, steel remains a vital foundation industry for green technologies such as wind turbines and electric vehicles. The shift to EAF will cause significant social and economic impacts, including an expected loss of about 2,800 jobs at Port Talbot, mainly in heavy-end sectors like the Sinter Plant, Morfa Coke Ovens, Blast Furnaces, and BOS Plant.

During the transition, Morfa Coke Ovens closed in March 2024 due to instability, with coke subsequently imported to support blast furnace operations. Blast Furnace 5, in operation since 1959, ceased in July 2024, followed by the Sinter Plant and Blast Furnace 4 closures in September 2024.

EAFs offer numerous benefits with lower carbon emissions, greater energy efficiency due to rapid start/stop capability, use of recycled steel reducing waste, and lower infrastructure costs. They are safer with fewer high-temperature hazards. However, EAF drawbacks include dependence on scrap steel quality and availability, higher UK electricity costs raising operational expenses, and expensive electrodes requiring regular maintenance.

The EAF steelmaking process involves melting scrap metal in a batch called a "heat." The cycle includes charging, melting, refining, deslagging, and tapping. Proper scrap sorting before charging ensures the desired steel chemistry. During charging, scrap is loaded with the furnace roof open; after closing, electrodes apply voltage to melt the scrap. Oxygen lances add heat by burning iron, raising the temperature. Oxygen injection during refining removes impurities like phosphorus (P), sulphur (S), manganese (Mn), and carbon (C), forming oxides incorporated into slag. Once the desired composition and temperature are reached, steel is tapped and further refined in CAS-OB units and degassers, ensuring quality standards.

Following the closure of the Blast Furnace and BOS plant, the Spectroscopy Laboratory at Port Talbot expects a significant reduction in workload, as these plants have been the main source of steel samples. Addressing current issues with steel samples and finding alternatives is critical amid these business changes. Nevertheless, the EAF process will continue requiring ongoing sample testing during casting, maintaining the laboratory's role in quality control.

3. Defining the Problem

This project has been initiated due to a significant number of steel sample rejections originating from the Secondary Steelmaking area in the BOS plant, where an example is shown in Figure 13. These rejections have persisted over an extended period, with no accurate record of the frequency or the underlying causes. The secondary steelmaking process is critical, and timely testing of samples at the laboratory is essential to ensure the appropriate additions are made and any impurities are removed from the cast. First-time failures of secondary steel samples increase the testing duration, preventing treatment stations, such as the CAS-OB units and degassers, from implementing the necessary modifications to the cast. Consequently, this delays the casting process and reduces the capacity at the BOS plant.



Figure 13 - Poorly prepared sample

The laboratories at Tata Steel provide services to the production areas on site, operating under service level agreements (SLAs) that outline key tasks necessary for customer satisfaction. A critical component of these SLAs is the requirement for timely testing, with a target turnaround time of seven minutes for all samples. However, the frequent rejections of steel samples on first-time analysis often prevent this turnaround time from being met, leading to customer complaints. These complaints are typically communicated to the shift teams conducting the testing. In instances where these issues result in the cast being downgraded or scrapped, reviews are convened between BOS plant personnel and laboratory staff to investigate whether tasks were performed in accordance with the safe working procedures (SWP).

3.1. Spectroscopy Testing Process

There are a number of casts which are produced each shift, prior to the closure of Blast Furnace 5 the number of casts was close to that of twenty, but since the closure of the Blast Furnace the number of casts are now much lower, closer to that of ten casts per shift. Each cast consists of roughly nine samples which are sent to the lab, this can increase if the treatment stations are unsure on the chemistry and require another

sample analysis prior to casting process. These nine samples are made up of one hot metal iron sample, a ladle sample, two treatment samples and three caster samples.

Each sample is delivered to the laboratory via Lamsen lines situated within the Spectroscopy lab. Shift technicians retrieve the samples, which are then weighed and inspected to ensure they exceed 100 grams and are of adequate quality for testing. This inspection ensures the sample is neither hollow nor misshaped, and free from any pinholes. Any samples that are underweight or otherwise inadequate are not entered into the system for testing, and the customer is informed to send an additional sample while the inadequate one is disposed of. Once a sample is deemed suitable for analysis by laboratory personnel, it is entered into the Samtracs system, which performs several tasks including milling the sample to achieve a clean, smooth surface.

The sample is then scanned by a camera equipped with software to assess if the preparation is adequate for analysis. If the sample is rejected by the camera, it indicates that the preparation was not correct, necessitating reprocessing starting with milling to achieve a better surface finish. Once the sample is approved by the camera, it is then sparked on the Optical Emission Spectrometer (OES). The OES sparks the sample up to four times, a tie-up must be achieved within these four sparks, or a rejection occurs. This issue is prevalent with secondary steel samples, this is due to the tighter chemistry tolerances for these samples. It could also be linked to higher temperature and poor mixing procedure out on plant which combined with the labs internal issues related to the milling procedure will result in higher number of rejections.

The Optical Emission Spectroscopy (OES) process involves subjecting a steel sample to a high-voltage pulse, which ionises the atmosphere between the electrode tip and the steel surface, rendering it conductive, as outlined in Figure 14. The ablated material is then excited within an argon plasma, where it is heated to several thousand degrees. This extreme heat causes the material to vaporise, atomise, and ionise.

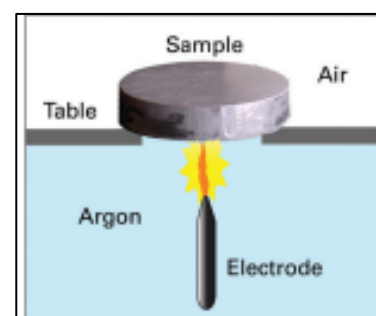


Figure 14 - How an OES works? (Scientific, Thermo Fisher Scientific, 2024)

The spark generated by the high-voltage pulse on the steel surface emits light, with the emitted light being characteristic of the elements present in the steel and their respective concentrations. The emitted light is directed towards the optical system, where it is dispersed into its constituent wavelengths by a diffraction grating over a

specified wavelength range, as shown in Figure 15. The photons corresponding to the wavelengths of the elements are detected and converted into electrical signals by photomultiplier tubes (PMTs). These signals are then transformed into elemental concentrations using calibration curves. The concentration data for each element are recorded for each spark, and an average of the results is calculated. The final averaged concentrations are then transmitted to the customer (Sanders, 2017) (Scientific, Spark-Optical Emission Spectrometry (OES), 2022).

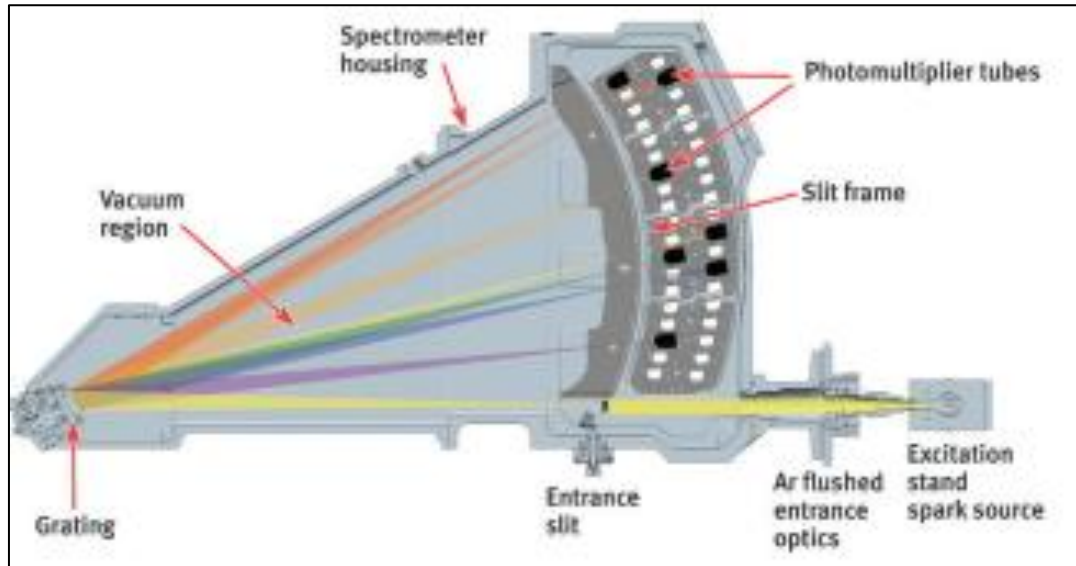


Figure 15 - How an OES works? (Scientific, Thermo Fisher Scientific, 2024)

To ensure accurate results, internal tolerances are applied to control the averaging process, mitigating the influence of any spurious results. Each cast of steel produced at Tata Steel is associated with specific concentration specifications, and the concentrations of the three caster samples analysed in the laboratory must fall within the specified ranges for that steel grade. Failure to meet these specifications could lead to the risk of downgrading or scrapping the material. This rigorous testing process is conducted continuously for each sample throughout the casting operation, maintaining a 24-hour testing cycle.

4. Problem Solving

Following discussions with colleagues and the customer, several key variables influencing the process were identified. However, the extent to which each variable contributed to process improvements remained uncertain. To address this, a Design of Experiment (DOE) approach was undertaken. The initial step involved systematically identifying all modifiable variables that could potentially enhance the process. Once these variables were established, appropriate parameter levels were defined to facilitate the testing phase. For instance, a Certified Reference Material (CRM) was milled using both new and worn milling tips to determine the optimal number of uses before rejection rates became unacceptable. This approach ensured that empirical data guided process optimisation and informed evidence-based decision making.

4.1. Testing Variables

Several variables within the milling procedure could be adjusted to enhance the preparation of steel samples. These variables included milling speed, milling depth, the condition of milling tips and clamps, miller bed alignment, the use of coolant, robotic placement accuracy, sample temperature, and potential deviations in the Optical Emission Spectroscopy (OES) system. Each of these factors had the potential to positively or negatively influence sample preparation quality. The Design of Experiments (DOE) methodology was employed to systematically evaluate these parameters and determine the optimal conditions for achieving the highest quality steel sample preparation.

A series of tests conducted on a Certified Reference Material (CRM) revealed that specific variables had a significant impact on rejection rates. While some findings aligned with expectations, such as the increased rejection rate associated with worn milling tips. Historically, several key factors had been overlooked within the Spectroscopy Laboratory at Tata Steel. The primary driver for minimising rejections is the need to reduce turnaround times, a priority dictated by customer requirements.

Previously, the Basic Oxygen Steelmaking (BOS) plant at Port Talbot was the primary customer when the site was fully operational. However, this project remains of critical importance in preparation for the transition to Electric Arc Steelmaking (EAF). High rejection rates are the leading cause of increased turnaround times, which impose substantial financial costs on the company.

The inability of the laboratory to achieve timely and accurate analysis results in various cost implications, including higher energy consumption due to extended casting times, increased chemical addition costs, and reduced production capacity, which can disrupt scheduling. Delays may also incur penalties from external customers due to late deliveries. In extreme cases, entire casts have been downgraded or, in the worst-case scenario, scrapped entirely. Such outcomes impose significant financial losses on the company and risk damaging Tata Steel's global reputation.

4.2. Route Cause Analysis

An Ishikawa diagram has been developed collaboratively between laboratory personnel and the customer to identify the key factors contributing to instability within the Spectroscopy laboratory, which is outlined Figure 16.

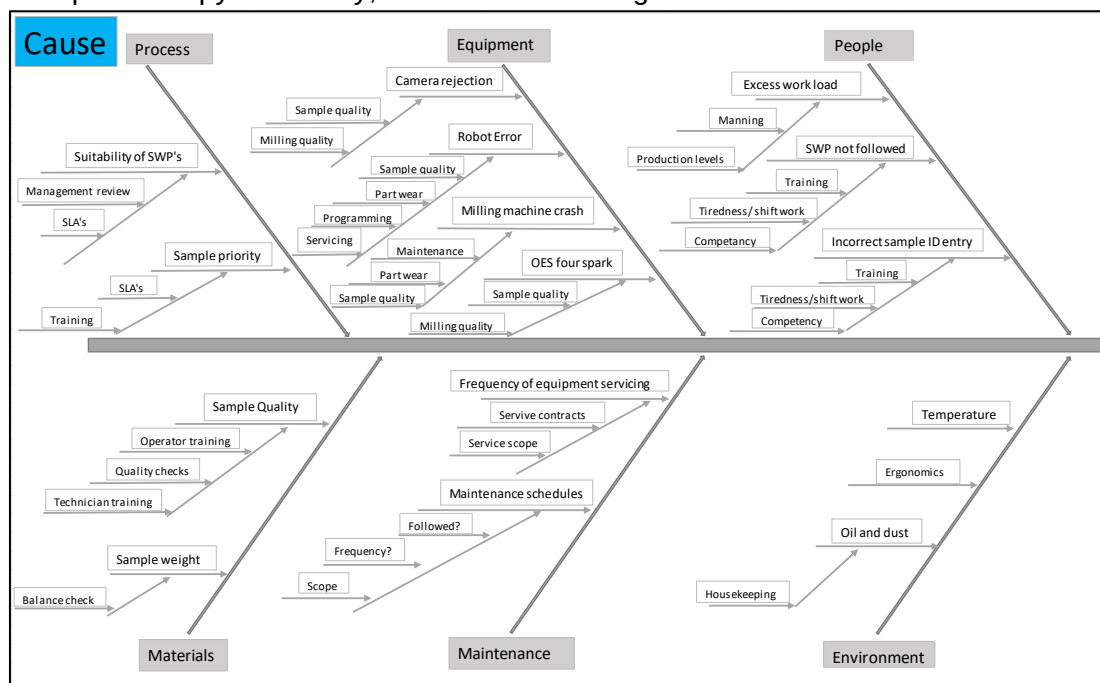


Figure 16 - Ishikawa Diagram

An Ishikawa diagram was developed collaboratively between laboratory personnel and the customer to identify the key factors contributing to instability within the Spectroscopy laboratory. The diagram encompasses a range of potential causes for the rejection of steel samples, with the primary factor identified as the milling procedure. Personnel and materials are also identified as potential contributing factors within the analysis framework, as both can influence the likelihood of sample rejection. For instance, procedural deviations by laboratory staff, such as failing to weigh a sample prior to testing may result in underweight specimens, thereby compromising the accuracy and reliability of the test results.

During the testing phase, the Safe Working Procedure (SWP) was adhered to, and all personnel involved in this improvement project were trained and competent in performing the relevant tasks. Considerable time and care were taken in data collection to ensure the accuracy and reliability of the results. Given the multiple variables that could be controlled during the milling process, efforts were made to capture each of these individually.

4.3. Standardising

Rejections of steel samples and Certified Reference Materials (CRMs) were not always linked to a specific chemical element. The optical emission spectrometer (OES) requires consistent alignment of results across all elements within the steel sample to achieve acceptance. Data collection indicated that nitrogen was the element most frequently subject to rejection. However, this did not imply that all other elements consistently achieved the required tie-up, as multiple elements were often rejected simultaneously. For the purpose of identifying the issue and facilitating improvements, nitrogen was selected as the primary element for tracking during the testing of CRMs. Nitrogen has a relatively tighter tolerance of results than a number of other elements due to the importance of its presence in steel.

On the certified reference material, named 057/2, this is a standard which contains a lower amount of Nitrogen. These are external standards, shown in Figure 17 which are bought in, with a certificate provided to deem the chemical content of each element. These standards were tested six times a day



Figure 17 - New 057/2 CRM

when the plant was operational and would need to be within specification throughout the entirety of the shift, this would allow continuation with testing of live material from the BOS plant. If the 057/2 standard resulted in rejection, which is what was frequently happening, then a full calibration of the OES would take place causing significant delays to the customer. The lower control limit (LCL) is set at 0.0019% and the upper control limit (UCL) is set at 0.0027 with the aim being 0.0023%.

4.4. Overhauling Testing Equipment

Prior to testing, initial steps were undertaken to ensure that all equipment was within specification and that the CRMs used were sourced from the same batch. The milling operation involves several components that require continuous monitoring, including the milling tips, milling clamps, milling bed level (shown in Figure 18), and overall cleanliness of the milling area.



Figure 18 - Miller Bed

To enhance the accuracy of the project, all these components were replaced with new parts at the outset of testing. Shown below in Figure 19 are comparison between worn and new miller clamps. As shown, it is clear to see that the older clamps have degradation to the teeth, therefore effecting the clamping efficiency.

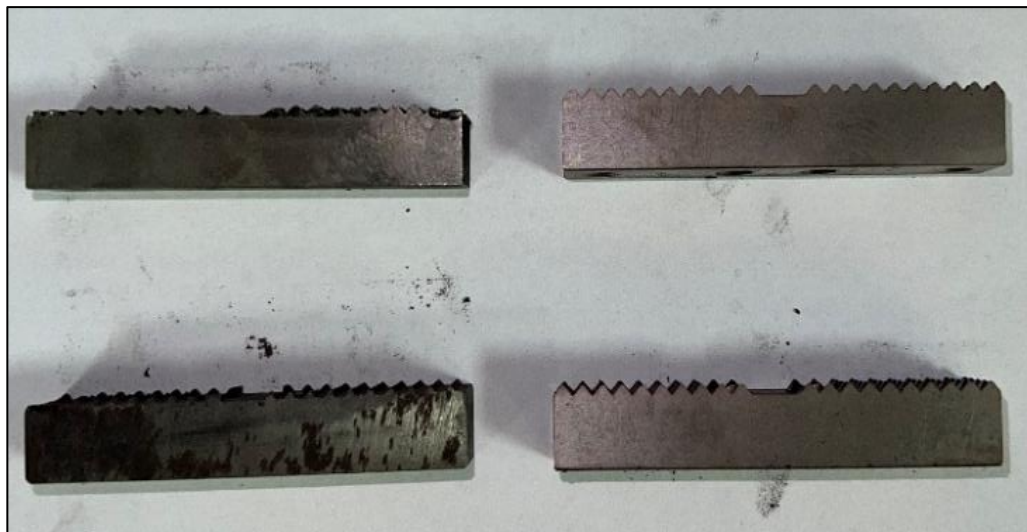


Figure 19 - Worn & New Miller clamps

Variations in results could also arise due to inconsistencies in the robotic system, where Figure 20 show the robotic arm at Tata Steel. These variations could be attributed to incorrect positioning, often caused by wear of the robot fingers or mechanical impact (crash). In instances where such issues occurred, the robot required recalibration to ensure correct sample positioning over the electrode. Before conducting any tests, the robot fingers were replaced with new ones, and the positioning was verified.



Figure 20 - Automated Robot

The electrode within the OES was also inspected and replaced. Over time, this electrode, which comes into contact with the milled surface of steel samples, can become worn and contaminated, as shown in Figure 21. The automatic cleaning head, equipped with spinning bristles, is designed to remove carbon buildup between each spark. However, before testing commenced, both the electrode and the cleaning head were replaced with new components to maintain accuracy.



Figure 21 - Poorly positioned CRM on electrode

Although these components should be inspected and replaced at regular intervals during the operation of the BOS plant, this maintenance had not been consistently carried out. Throughout the testing phase, these elements were frequently inspected to ensure their continued suitability for testing.

Prior to the closure of heavy end operations at Port Talbot steel works, the samples which were delivered to the lab via the lamsen lines were prepared at a milling speed of x100. Unsure of the revolution per minute, the rapid transverse override and incremental feed are both set at x100, with the run speed set at 50 mm/min.

The initial testing phase was run with the same parameters. The aim of the initial testing phase was to identify a maximum number of mills a brand-new set of tips could achieve before rejections started to occur. Three hundred mills were what had been recommended by the supplier. When plant was operational there was not enough capacity to run this improvement project as the equipment was needed to continue with the testing of live material being delivered from the BOS plant. During this period three hundred mills was over optimistic, based on the set parameters of the millers.

5. Analysis

This section investigates the impact of milling parameters on nitrogen stability in steel samples analysed via Optical Emission Spectroscopy (OES). Through a series of controlled experiments, the study examines three key variables: milling tip wear, milling speed, and the number of milling path cuts. Each subsection presents detailed findings on how these factors influence nitrogen measurements, highlighting the relationship between milling conditions, tip degradation, and surface integrity. The results underscore the importance of optimising milling parameters to minimise nitrogen variability, ensure accurate OES readings, and maintain sample quality.

5.1. Miller Tip Wear

The graph presented in Figure 22 illustrates the data collected during the initial period of testing. This graph represents the nitrogen results obtained while the CNC miller was operating at a milling speed of x100, with both the rapid transverse override and incremental feed set at x100, along with a run speed of 50 mm/min and brand-new milling tips. Two cuts of the surface were performed each time. Analysis of the graph indicates that at approximately 137 milling operations, the nitrogen results began to increase sharply, surpassing the upper control limit of 0.0027%.

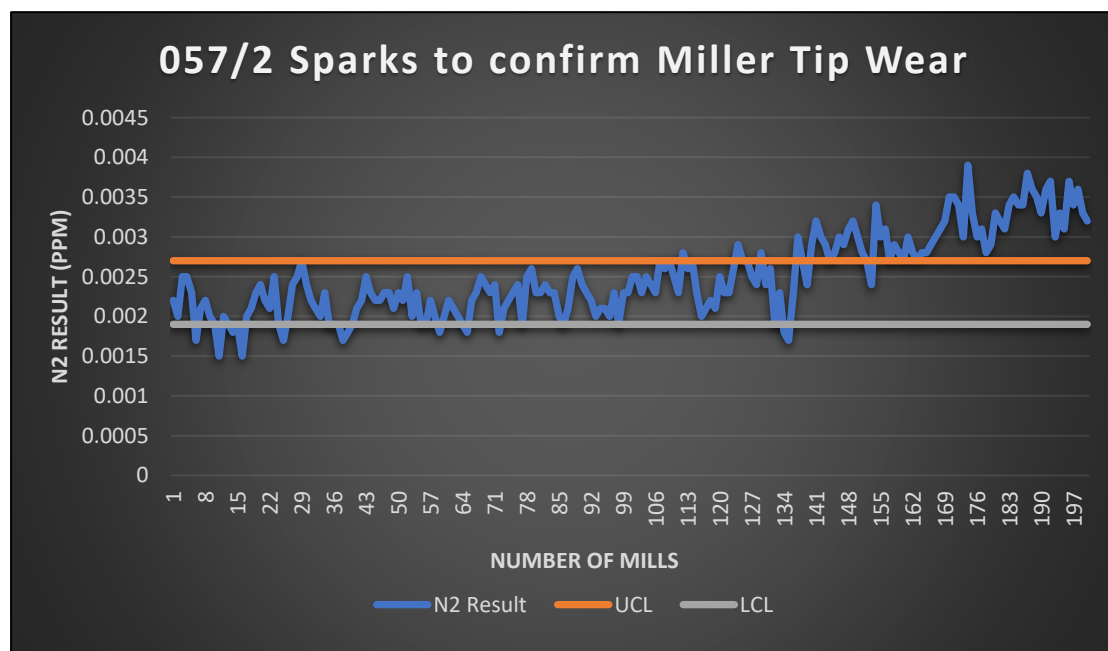


Figure 22 – Effects of Milling Tip Wear

A total of 200 tests were conducted using the 057/2 CRM. Upon completion of the tests, the milling tips were inspected, revealing that one of the five tips had cracked, while the remaining four tips exhibited significant wear. The nitrogen results displayed

considerable instability from the outset, with substantial variance observed throughout the testing phase. Once the tips had deteriorated, which is estimated to have occurred around 137 milling operations, nitrogen levels increased markedly.

This increase is believed to be directly associated with the condition of the worn milling tips. As the tips degrade, they generate greater friction during milling, potentially leading to oxidation of the steel sample's surface. Surface oxidation and contaminants can introduce additional nitrogen into the sample from the surrounding atmosphere. Furthermore, worn milling tips contribute to an inconsistent surface finish. If the sample does not sit flush on the OES stand due to an uneven surface, gaps may form, leading to nitrogen measurement variations.

Additionally, excessive wear on the milling tips can elevate the temperature of the steel surface. Increased temperatures can facilitate nitrogen absorption from the air, particularly in dry milling operations, as employed in this testing process. These findings highlight the critical importance of monitoring milling tip conditions to ensure accurate nitrogen measurements and overall sample integrity.

5.2. Milling Speed Variation

In the first phase of testing, the samples were milled at a speed of x100, with both the rapid transverse override and incremental feed set to x100. The run speed was maintained at 50 mm/min, and the number of cuts was kept consistent with the initial phase, with two cuts performed. The milling speed was identified as a controllable variable within this process. In the second phase of testing, the milling speed was reduced, and the results, plotted on the graph in Figure 23, were obtained using new milling tips. The clamps and electrode were thoroughly inspected to ensure they were in suitable condition. For this phase of testing, the milling speed was adjusted to x50.

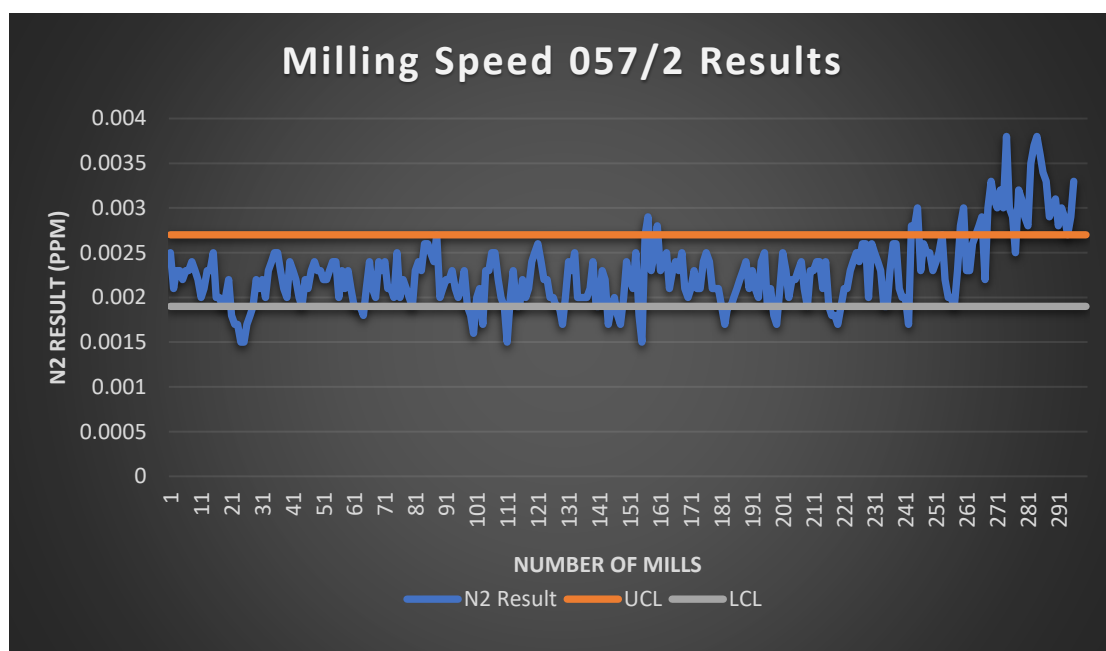


Figure 23 – Milling Speed Variation

The results depicted in the graph above demonstrate that by decreasing the milling speed, the nitrogen readings fell within tolerance for a greater number of tests. A total of 296 tests were completed, with the aim to complete 300 tests, however, the testing phase was truncated due to the audible sound of the milling operation, which indicated that the milling tips had either worn or broken. The nitrogen readings, as shown in the graph, remained within tolerance more frequently when the milling speed was slower compared to when it was faster. Notably, the nitrogen readings began to increase and exceed the upper control limit after approximately 266 mills.

The slower milling speed results in reduced friction and heat generation. Excessive heat generated by milling at higher speeds can cause softening or thermal degradation of the milling tips, leading to faster wear, as evidenced in the first chart. Milling at higher

speeds also increases the likelihood of fractures on the cutting edge of the tips, thereby reducing their lifespan. In contrast, a slower milling speed results in a smoother cutting action, which helps to extend the durability of the tips. As nitrogen is sensitive to temperature fluctuations, the slower milling speed proved more beneficial for maintaining nitrogen stability over a longer period. Although some nitrogen readings fell outside the control limits, the overall spread of nitrogen results was tighter compared to the first stage of testing.

5.3. Increased Number of Passes

The readings presented in the graph below were obtained from performing an increased number of cuts to assess whether this would positively impact nitrogen stability. Three cuts were carried out with the milling speed set at x50. All milling tips were replaced with new ones, and the miller clamps and electrode were thoroughly inspected to ensure they were in good condition. A total of 300 tests were completed. Throughout this testing phase, the nitrogen readings were generally higher compared to previous tests. For the majority of the tests, the readings remained within the control limits, although they were closer to the upper control limit compared to earlier results. This is thought to be due to the temperature increase associated with the additional cut of the surface. From the graph shown in Figure 24, at around 229 mills, the nitrogen results began to fall outside the upper control limit more frequently. The chart indicates that excessive wear or damage to the milling tips occurred at this point, leading to erratic results. Upon completion of the tests, the milling tips were inspected and found to be worn, with multiple tips exhibiting cracks.

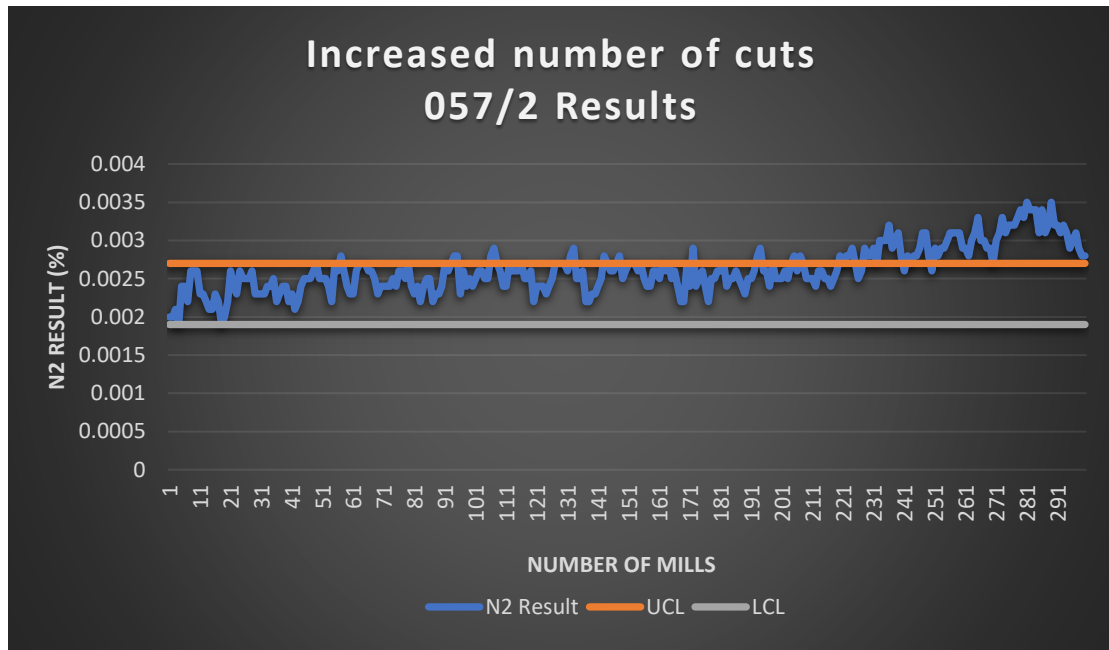


Figure 24 - Final Testing Phase

The increased number of cuts resulted in more contact time between the milling tips and the sample surface. As a result, the number of tests performed before the nitrogen readings became erratic was lower than in the previous testing phase. This was due to the additional wear on the milling tips caused by the increased number of cuts. The thermal degradation also increased, as a higher number of cuts generates greater heat. The average nitrogen readings were higher, which is believed to be due to the elevated temperature, however, it could also be attributed to excessive work hardening. Work hardening can alter the nitrogen stability on the surface, thereby directly impacting the OES results.

6. Improvements

As part of the project's implementation phase, visual management tools were introduced across key pieces of laboratory equipment to reinforce expected standards of operation and support consistent technician performance, as shown in Figure 25 and Figure 26. These visual cues served as constant reminders of best practice and have contributed to an improved process discipline.

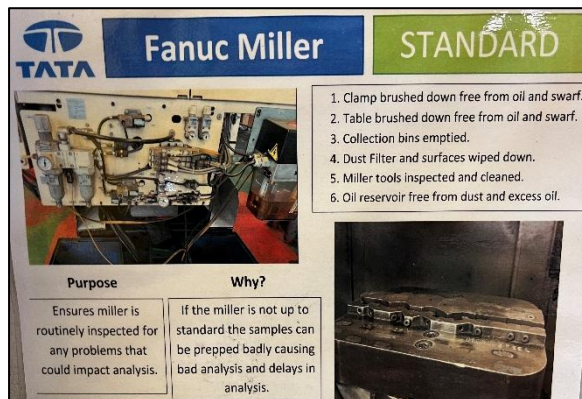


Figure 25 - Expected Miller Standard

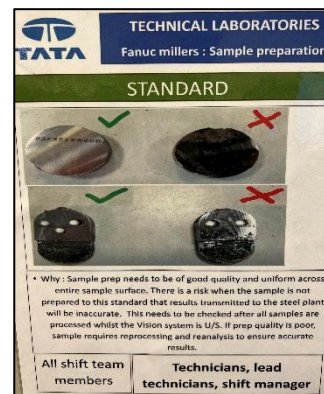


Figure 26 - Expected Surface Preparation Standard

During collaborative problem-solving sessions, technicians were encouraged to contribute ideas. One particularly effective suggestion involved the procurement of spare milling heads (as shown in Figure 27), enabling rapid replacement during tip changes. This measure significantly reduced downtime by eliminating the need to take the CNC miller out of service for extended periods during routine maintenance. The proposal was adopted as part of the project and was recognised as a key factor in improving operational efficiency and reducing overall test cycle time.



Figure 27 - Spare Miller head with new tips

The maximum number of tests achieved prior to an increase in nitrogen-related rejections was determined to be 296. In response to this finding, automated warning limits were introduced into the control systems. A soft warning was configured at 250 tests, alerting technicians that tip replacement would soon be required. A hard limit was then set at 270 tests, at which point the milling machine would cease operation until new tips were installed. This represented a significant improvement over previous practices, where no such warning mechanisms were in place and tip inspections were conducted irregularly, often only after instability had occurred. The absence of proactive checks had previously contributed to a higher frequency of out-of-tolerance results. The newly implemented automated prompts were integrated into the laboratory's internal system interface and are now displayed directly on the technician's workstation PC, ensuring clear visibility and timely action.

Conclusion

An investigation carried out at the Port Talbot Tata Steel Spectroscopy Laboratory yielded modest but meaningful improvements. What initially appeared to be a straightforward issue required extensive time, iterative testing, and detailed interpretation. Through collaborative effort involving all relevant stakeholders, the proportion of tests exceeding nitrogen specification limits was successfully reduced. This outcome was achieved through the application of well-designed and carefully planned Design of Experiments (DoE) methodologies, coupled with structured problem-solving sessions. These efforts enabled the identification of all critical variables influencing the nitrogen testing procedure. Once these variables had been established, they were examined and replaced with new components to ensure a reliable and consistent baseline for the testing phases.

Several key mechanical variables were identified as having the potential to affect OES test outcomes. These included the milling bed, milling clamps, robot fingers, and electrode. While these elements were found to influence results, the frequency at which they required inspection or replacement was determined to be lower than that required for milling tips and robot positioning mechanisms.

At the start of the project, the milling bed was replaced with a new unit and remained level throughout the investigation. To maintain this condition, a weekly inspection protocol was introduced by the laboratory team leader. Similarly, the milling clamps which had shown considerable wear prior to the project, were replaced and remained in acceptable condition throughout. Weekly checks of their condition were also implemented. The robot fingers, responsible for accurately positioning samples on the electrode, were replaced at the outset of the testing phase and retained their condition over the project duration. Their status was added to the weekly inspection checklist, although sample positioning was also verified through daily automated pre-flight checks. The electrode, another critical component, was discovered to be in extremely poor condition prior to the investigation, with no record of its last replacement. A new electrode was installed and monitored throughout the project. It remained within acceptable limits and was included in the weekly inspection protocol. These weekly checks were introduced to ensure that all critical variables remained in a controlled and functional state. In the event of any out-of-control conditions or loss of test result stability, these components were subjected to immediate inspection as part of a rapid problem-solving protocol. Finally, milling tips, which have a direct and frequent impact

on surface preparation quality, were subjected to daily pre-flight inspections to ensure their condition was consistently within specification.

The primary objective of this project was to reduce the number of sample rejections during the analysis of steel specimens via Optical Emission Spectrometry (OES). Based on the outcomes and supporting data presented in this report, it is considered that this objective was successfully achieved by the department.

Data from the experimental phases, as visualised in the accompanying charts, demonstrate that through a structured Design of Experiments (DoE) approach, where milling speeds, the number of surface cuts, and milling tip conditions were systematically varied and controlled, optimum milling parameters were identified.

Prior to the commencement of this project, the CNC milling machine was operating at a milling speed setting of x100, with both the rapid transverse override and incremental feed also set at x100. The run speed was maintained at 50 mm/min, and samples were subjected to two surface cuts using new milling tips. Under these conditions, the system maintained acceptable stability for up to 137 tests before instability or elevated nitrogen results occurred.

In the subsequent test phase, the milling speed was reduced to x50, while the rapid transverse override and incremental feed settings were retained at x100. Again, performing two surface cuts, this adjustment significantly extended the number of consecutive stable tests to 296 before issues were observed.

To ensure thoroughness, an additional test phase was conducted where the number of cuts was increased from two to three, while maintaining the milling speed at x100. This yielded a partial improvement, increasing the number of successful tests to 229, though this remained less effective than the previous configuration.

From these results, the optimum milling parameters for sample preparation were determined to be a milling speed of x50, rapid transverse override and incremental feed of x100, and two surface cuts. While the optimisation of these parameters did not directly resolve all causes of sample rejection, their identification allowed the department to implement new procedural standards and regular equipment checks. These measures have since contributed to a significant reduction in the incidence of nitrogen-related rejections, fulfilling the broader aims of the investigation.

Further Work Required

While the existing process has been significantly improved and optimised, there remains scope for further enhancement. In the short term, additional gains can be achieved through improvements to the laboratory's 5S routine. Specifically, the effectiveness of the 5S system could be enhanced by reviewing the current storage arrangements for spare components and implementing a robust Kanban inventory management system. Introducing a structured Kanban system would streamline the availability of critical spare parts, thereby reducing the time required for technicians to locate key inventory items. This would not only improve overall testing efficiency, but also further reduce the likelihood of test rejections by ensuring that worn or defective components are replaced promptly. The proposed Kanban system would function by clearly indicating minimum stock levels and reorder points for essential items. This information would be visually accessible and regularly communicated to laboratory management during daily morning meetings. By establishing this feedback loop, delays associated with unavailable inventory could be minimised, thus supporting sustained improvements in both the consistency and reliability of the testing process.

The camera shown in Figure 28, which is integral to the automated process, could also benefit from improvement. Its role is to scan the surface of samples and determine whether they should be accepted or rejected based on the quality of the surface. Currently, the camera is not able to clearly identify inclusions or defects on the surface, leading to the testing of samples that are ultimately unsuitable. This results in an increased likelihood of rejection and inaccurate test results. Ongoing discussions with both the department and the supplier are focused on investigating potential enhancements to the internal software, with the aim of improving its performance.

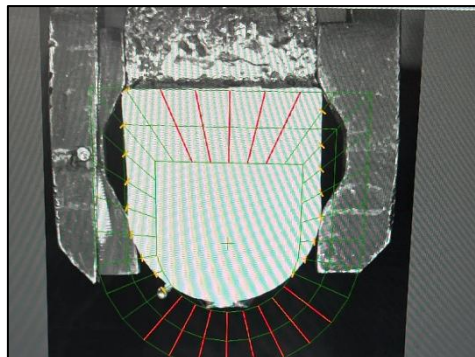


Figure 28 - Current Camera Software

Although the culture within the department is generally strong, there is still room for further improvement. When a sample falls out of tolerance, it is crucial that the laboratory follows a series of key steps to ensure that the service provided to customers remains acceptable. These steps include running an internal CRM to verify that the OES is within specification, checking the condition of the milling tips, re-examining the sample that has been sparked to confirm it meets the correct weight, and ensuring there are no inclusions or hollow holes present. These fundamental procedures are essential in enhancing the service to customers and will support effective problem-solving when the Electric Arc Furnace is operational. Additionally, ongoing efforts are focused on upskilling staff through training courses, with positive outcomes being observed. This initiative aims to improve the laboratory's expertise and experience, ensuring the department is as well-prepared as possible for the implementation of new electric arc steelmaking processes.

The Spectroscopy Laboratory is optimistic about future investment, which is part of the broader transition towards greener steelmaking. It is anticipated that current practices and equipment may be retired or potentially repurposed as backup should the lab acquire new technology. Discussions with stakeholders involved in this project have been held to explore available technologies on the market that could enhance the lab's capabilities, focusing on improving the stability of testing, reducing test times, and increasing automation. One technology of particular interest to the department is nitrogen-free cryogenic milling. This advanced sample preparation technique involves cooling steel samples to cryogenic temperatures using an inert, nitrogen-free gas, such as argon or liquid CO₂, before and during the milling process. Cryogenic milling produces a clean, contamination-free, low-temperature milled surface, which is ideal for accurate OES nitrogen analysis, particularly in ultra-low nitrogen steels (Ravi & Kumar, 2011). While this technology could offer significant improvements for the Spectroscopy Laboratory, there is uncertainty regarding the associated costs and the funding that will be allocated to the department as part of the transition to electric arc steelmaking.

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