Defect reduction in steel manufacturing company using DMAIC approach

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Abstract:

In pursuit of operational excellence, a leading steel manufacturing company specializing in ingots, implemented the DMAIC (Define, Measure, Analyze, Improve, Control) methodology to systematically reduce defects and minimize waste. The company achieved a significant improvement, reducing the defect rate from 2.38% to 0.86837%, marking a 63.52% reduction. This enhancement elevated the process sigma level to 4.25. With a strong focus on continuous improvement, the organization now aims to achieve a 5 sigma level, reflecting world-class quality standards and further optimizing production efficiency while maintaining customer satisfaction and sustainability across operations.

Keywords: DMAIC Methodology, Waste Minimization, Ingot Production, Lean Six Sigma, Defect Rate, Sigma Level, Continuous Improvement.

1. Introduction

Steel ingot manufacturing is a vital stage in steelmaking, serving as an intermediate form for further processing into structural and mechanical components. Ingots are typically produced by pouring molten steel into moulds, forming a solid feedstock for forging, rolling, or extrusion. As Ghosh and Chatterjee (2008) highlight, ingot quality greatly affects the mechanical and structural properties of final products, making precise control of casting parameters essential. Traditional ingot casting involves teeming molten steel into metallic moulds for solidification under controlled cooling. Factors like mould geometry, thermal gradients, and cooling rates influence steel microstructure. According to Tupkary (2011), solidification may cause defects such as segregation, shrinkage cavities, and cracks, which require careful management. Ingot casting methods include top-poured and bottom-poured types, with bottom-pour casting reducing oxidation and turbulence (Abbaschian et al., 2009). Thermal contraction causes pipe formation, addressed using hot tops or exothermic materials (Llewellyn & Hudd, 1998). Advances in mould design and solidification techniques enhance uniformity and reduce segregation. The DMAIC (Define, Measure, Analyze, Improve, Control methodology in Six Sigma aids in process improvement. It helps define problems, measure baseline data, analyze inefficiencies, implement improvements, and maintain control, as emphasized by Pande et al. (2000) and George (2002). Ingot production involves casting units weighing around 100 kg, with heights ranging from 55 to 60 inches. Raw materials like MS scrap, sponge iron, and alloying elements Such as manganese and silicon enhance metal quality. Refractories line the furnace, providing insulation and heat resistance for efficient melting and casting operations.

2. Literature Review

Several studies have explored the application of Six Sigma and the DMAIC methodology in manufacturing and service industries. Abbaschian and Reed-Hill (2009) [1] provide foundational knowledge on physical metallurgy, crucial for process improvement. Trimarjoko et al. (2020) [10] review the consistency of DMAIC phases across industries, while Bhargava and Gaur (2021, 2021b) [2] apply Six Sigma in bearing manufacturing. Jirasukprasert et al. (2014) [6] demonstrate defect reduction in rubber gloves production. Yu et al. (2022) construct a DMAIC model for multi-characteristic products. Shamsuzzama (2023) [8] enhance productivity in can manufacturing using Lean Six Sigma. Condé et al. (2023) [3] focus on defect reduction in automotive parts. Pyzdek and Keller (2010) [11] present a comprehensive Six Sigma guide. E.V. Gijo et al. (2011) [5] optimize grinding processes, while Srinivasan et al. (2016) [10] improve furnace nozzle production through Six Sigma. These studies collectively highlight DMAIC's effectiveness in reducing defects and improving quality across various manufacturing sectors.

3. Steel Ingot Manufacturing process

Raw Material Selection, Using Magnetic crane, The scrap is brought to the Furnace Melting in Furnace, Refining and Alloying, Pouring into Moulds, Stripping and Cooling Inspection and Quality Control, Storage, Dispatch

Steel ingot manufacturing involves several key steps to ensure quality and efficiency. It starts with selecting suitable raw materials like MS scrap and sponge iron, followed by magnetic crane handling to feed the furnace. The melting process transforms scrap into molten metal, which is refined and alloyed for desired properties. The metal is poured into moulds, cooled, and stripped. Inspections ensure defect-free ingots, which are then stored safely. Finally, inspected ingots are dispatched with proper labelling and documentation.

4. Problem Statement

Over the four-month period from September to December, the company produced 4,149 metric tonnes of steel products, including ingots, while generating 98.964 metric tonnes of waste and experiencing a defect rate of 2.38%. This has impacted overall production efficiency and quality performance. To enhance competitiveness and operational excellence, there is a need to reduce waste, lower the defect rate, and improve the process sigma level.

Objective

This study aims to systematically reduce defects and minimize waste in ingot production through the structured implementation of the DMAIC methodology—Define, Measure, Analyze, Improve, and Control. This data-driven approach is designed to identify the root causes of inefficiencies and implement sustainable improvements throughout the production process. The primary goal is to reduce the defect percentage by 70%, thereby enhancing overall production efficiency, improving product quality, and increasing customer satisfaction. Additionally, the project seeks to elevate process performance from a sigma level of 4.25 to 5.0, signifying a substantial improvement in process capability. Achieving this milestone will lead to greater consistency, reduced variability, and lower rework costs.

5. Six Sigma and DMAIC Approach

5.1 Define

Starting with the project Defect Reduction in Steel Manufacturing Company, the project charter is as follows in Table 1,

Background and reasons for selecting the project	Vast number of ingots has been rejected by the customers due to defectives. This problem causes several losses to the company, i.e. time, materials, capital as well as customers dissatisfaction, which negatively affects the organization image.
Project Goal	To reduce the defects after applying six sigma into the quality steel ingots.
Voice of the Customer (VOC)	Products quality
Team Members	Production manager, Operators
Expected Financial Benefits	A considerable cost saving due to the defect reduction.
Expected Customer Benefits	Receiving the product with expected quality.

Table 1 Project Charter

Complementing the charter**,** A SIPOC Diagram is done based on the industry details as shown in figure 2.

Figure 2. SIPOC Diagram

5.2 Measure

The furnace performs 10 melting's daily, each yielding about 5 metric tonnes, totalling nearly 50 metric tonnes per day. Wasted ingots are divided into rejections and reworks, with 579 rejected and 410 reworked. Monthly data was systematically recorded and analysed. In the measure phase the date is shown in below table**,**

Month	Total Ingots Wasted	Rejected Ingots	Reworked Ingots	Total Ingots Wasted in M.T	Total Ingots Produced in M.T
Sep	250	105	145	25 M.T	958.438 M.T
Oct	226	95	131	22.625 M.T	1090.766 M.T
Nov	272	115	157	27.125 M.T	1158.806 M.T
Dec	241	95	146	24.125 M.T	941.397 M.T
Total	**989**	**410**	**579**	**98.964 M.T**	**4149.40 M.T**

Table 2. Monthly Defects

The defects are categorized into two types: N/A defects and shop floor defects, as illustrated in Table

N/A Defects	Sep	Oct	Nov	Dec	Total
Vendor	33	21	21	25	100
Production	36	27	24	28	115
Customer Rejections	19	18	20	16	73
Lab Testing	16	19	23	19	77
Planning	11	15	17	12	55

Shop Floor Defects	Sep	Oct	Nov	Dec	Total
Cracks	26	28	25	26	105
Porosity	25	24	24	25	98
Shrinkage	24	23	24	25	96
Segregation	16	13	17	18	64
Misrun and Cold shut	10	12	12	14	48
Surface Defects	8	12	11	9	40
Centre Line Cracks	9	7	6	8	30
Hot Tears	5	8	9	8	30
Ghost Lines	5	4	7	6	22
Non Metallic Inclusions	7	11	9	9	36

Table 3. N/A and Shop Floor Defects

5.2.1 Pareto chart

The Pareto chart, incorporating both N/A and shop floor defects, highlights that most issues arise from the shop floor.

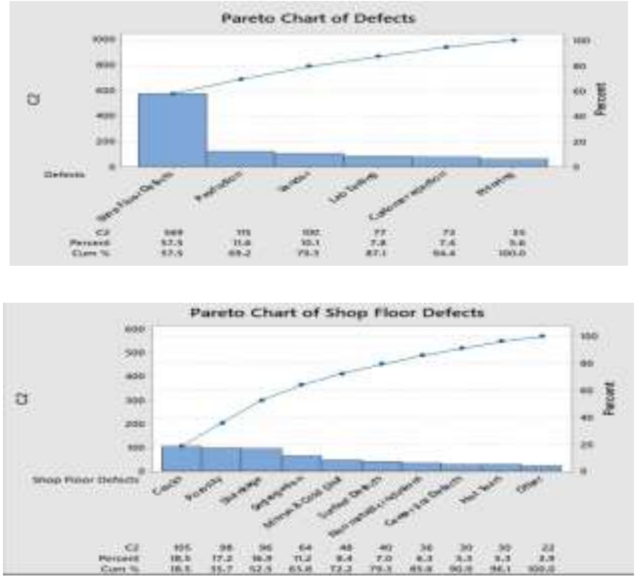

Figure 3. Pareto chart

Among these, cracks, porosity, shrinkage, and segregation are found to occur more frequently.

5.3 Analyse

5.3.1 Fishbone Diagram

The fishbone diagram presented in Figure 10 highlights the causes of shop floor defects and provides insights into why they occur.

Figure 4 Fish bone Diagram

Casting defects in steel manufacturing arise from multiple factors, including machines, personnel, methods, measurements, environment, and materials. Improper ladle handling, pouring temperature, and melting parameters lead to defects like porosity or shrinkage. Unskilled labour, poor SOP adherence, and incorrect handling contribute to quality issues. Machine misalignment, excessive heat, and poor flame control cause dimensional inaccuracies and surface flaws. Inaccurate chemical analysis and inadequate temperature monitoring result in structural inconsistencies. Environmental issues like poor ventilation and high humidity impact surface quality. Additionally, low-grade scrap, improper slag removal, and high impurity content in materials lead to weak mechanical properties and internal defects.

5.3.2 5 WHY'S

The 5 WHYs analysis was conducted to identify root causes for the most frequently occurring defects in production—cracks, porosity, shrinkage, and segregation.

Cracks

5 WHY'S	Question	Reason
WHY 1	Why do cracks appear on the ingot?	Due to internal or external stress during or after solidification.
WHY 2	Why is there stress during/after solidification?	Because of uneven cooling or thermal gradients.
WHY 3	Why is there uneven cooling?	Cooling rate is not controlled or mold design is poor.
WHY 4	Why is the mold design poor or cooling not uniform?	Improper cooling system or incorrect mold material/geometry.
WHY 5	Why is the cooling system or mold design not modified?	Lack of proper process design or insufficient monitoring of mold temperature.

Table 4. Root Cause of Crack

Suggestions

- Standardize mould preheating process.
- Install thermocouples for real-time monitoring.
- Use controlled cooling techniques to minimize stress.

Porosity

5 WHY'S	Question	Reason
WHY 1	Why is there porosity in the ingot?	Gas gets trapped during solidification.
WHY 2	Why does gas get trapped?	Due to improper degassing or turbulent metal flow.
WHY 3	Why is degassing not effective or metal flow turbulent?	Inadequate degassing process and poor pouring techniques.
WHY 4	Why are degassing and pouring not effective?	Lack of process standardization and operator training.
WHY 5	Why is operator training or process control lacking?	No proper SOP or quality checks in place.

Table 5. Root Cause of Porosity

Suggestions

- Improve melt degassing technique.
- Use inert gas purging (e.g., nitrogen, argon).
- Train operators on flux ratios and melt stirring methods.

Shrinkage

5 WHY'S	Question	Reason
WHY 1	Why is shrinkage occurring in ingots?	Metal contracts during solidification.
WHY 2	Why does contraction lead to defects?	There is not enough feed metal to compensate for shrinkage
WHY 3	Why is there not enough feed metal?	Risers are not properly designed.
WHY 4	Why is the riser design inadequate?	Lack of experience-based design only
WHY 5	Why simulation not used or designs is not modified?	Cost-cutting or lack of technical knowledge/tools.

Table 6. Root causes of Shrinkage

Suggestions

- Optimize riser size and placement.
- Use solidification simulation software.
- Use insulating sleeves or exothermic risers.

Segregation

5 WHY'S	Question	Reason
WHY 1	Why does segregation occur in ingots?	Impurities or alloying elements separate during solidification.
WHY 2	Why do elements separate?	Because of variation in freezing points of different elements.
WHY 3	Why does this cause uneven distribution?	Improper solidification rate or slow cooling.
WHY 4	Why is cooling rate not controlled?	Poor mold design or inconsistent process parameters.
WHY 5	Why are process parameters not controlled?	Lack of monitoring systems or automation.

Table 7. Root causes of segregation

Suggestions

- Use molds with better thermal conductivity.
- Control cooling rates with mould coatings or insulation.
- Improve melt stirring before pouring.

DPO, DPU, DPMO AND Sigma Level values

Defects-989, Total units-41,494,

Opportunities per unit-8, **DPU- 0.002947382,**

DPO-0.023579058, DPMO- 2947.382224

SIGMA LEVEL- 4.25

5.4 Improve

5.4.1 FMEA (Failure Mode and Effect Analysis)

In steel ingot manufacturing, FMEA highlights key failure risks. Melting Furnace issues (RPN 288) require automated temperature control. Mould Filling (RPN 175) needs tilt automation. Solidification defects (RPN 192) call for consistent cooling systems. Ingot Removal risks (RPN 120) can be reduced through training and SOPs to enhance process quality.

Process Step	Potential Failure Mode	Potential Effects of Failure	Severity (S)	Potential Causes	Occurrence (O)	Current Controls	Detection (D)	RPN (S × O × D)	Recommended Actions
Melting Furnace Operation	Temperature not maintained	Poor ingot quality, defects	8	Sensor malfunction, human error	6	Manual temperature monitoring	6	288	Install automatic temp controllers & alarms
Mould Filling	Uneven pouring	Voids, surface defects	7	Improper tilt or spillage	7	Operator skill-based	5	175	Use automated tilting system
Solidification	Uneven cooling rate	Cracks, shrinkage defects	8	Cooling water flow inconsistency	6	Manual flow check	4	192	Standardize cooling rate, use flow sensors
Ingot Removal	Improper handling	Physical damage to ingots	8	Mishandling by crane operator	5	Operator training	4	120	Provide material handling SOPs

Table 8. FMEA

6.5 Control

This is a theoretical implementation to improve production efficiency, reduce the defect rate, increase the sigma level to 5.0, and create SOPs for the company.

Daily Production Planning and Coordination

A structured daily production planning system ensures productivity through morning meetings, target setting, manpower allocation, and equipment readiness checks. Shift-wise goals and real-time production board updates enable effective monitoring and coordination.

Raw Material Inspection and Preparation

Before melting, raw materials must be inspected for chemical composition, moisture, and size. Using checklists, pre-weighing, and proper staging near the furnace improves batch consistency and material flow efficiency.

Standardized Charging and Melting Process

A defined SOP ensures proper charging of materials into the furnace. Operators follow sequences and weight limits, monitor real-time temperatures, preheat the furnace, and remove slag regularly to maintain metal purity.

Efficient Mold Preparation and Handling

Mold preparation is a critical step in ensuring casting quality. Molds should be thoroughly cleaned, preheated, and coated with a standard mold release agent to prevent metal adhesion and thermal cracks. The mold inspection checklist must be followed to detect cracks, wear, or damages before casting. Preheating also helps maintain flowability of molten metal, ensuring proper filling and uniform solidification

Controlled Pouring and Casting Techniques

Molten metal should be poured steadily to avoid turbulence and defects. Ensure ladle cleanliness, correct temperature, and proper pouring height. Monitor flow rate and mold filling to prevent cold shuts and cavities.

Standardized Cooling and Solidification Process

Ingots should cool under controlled conditions using water, air, or forced cooling systems. Avoid rapid temperature drops to prevent cracks. Maintain time logs to ensure consistent cooling for each production batch.

Post-Casting Ingot Handling and Storage SOP

Once solidification is complete, ingots must be removed carefully using tongs or lifters to avoid surface damage. Ingots should be placed on standardized pallets and stored in designated areas with proper labeling. Random stacking must be avoided to ensure ease of traceability and prevent re-handling losses. Material handlers must follow a defined material movement route to optimize space utilization and reduce transport time.

Preventive and Autonomous Maintenance SOP

Operators must perform routine checks and follow preventive maintenance schedules to avoid breakdowns. Autonomous maintenance helps detect issues early, reducing downtime and maintenance dependency.

Standard Operating Procedures (SOPs) are implemented to decrease the Defect Rate.

To improve ingot manufacturing quality and sigma level, implementing well-defined SOPs is crucial. Molds should be cleaned, inspected, and uniformly preheated to avoid cracks and surface defects. The melting process must ensure clean raw materials, accurate temperature control, proper degassing, and effective skimming. Pouring should be steady, with optimal temperature and minimal turbulence to prevent cold shuts and misruns. Scientifically designed gating and riser systems support directional solidification and reduce shrinkage. Controlled cooling using chill blocks and gradual mold ejection prevents stress and hot tears. Regular inspections, NDT checks, and equipment maintenance enhance process reliability. Operator training ensures SOP adherence and defect detection. To raise the sigma level beyond 4.25, SOPs must standardize key parameters, adopt defect prevention techniques, enable root cause analysis (Pareto, 5 Whys, Fishbone), and promote data-driven control through SPC and Six Sigma tools. These actions reduce variation, enhance consistency, and drive world-class manufacturing excellence.

Kaizen Sheet

KAIZEN SHEET – Continuous Improvement Report

Date: 17-03-2025

Department/Section: Melting and Furnace Operation

Kaizen Title: Improving Production Efficiency in Ingot Manufacturing

Identified By: Production Improvement Team

Team Members (if any):

Current Situation (Before Kaizen):

Current Situation (Before Kaizen):

Manual production tracking and inconsistent production planning led to delays, lack of transparency, and frequent communication gaps on the shop floor.

Identify the actual cause using tools like 5 Why or Fishbone Diagram.

Root Cause Analysis:

Lack of real-time production monitoring system, poor raw material staging, and improper maintenance scheduling resulted in low production efficiency.

Target / Objective:

Improvement Idea / Kaizen Action:

Implement digital production boards, introduce barcode tagging for raw materials, define charging sequences, and implement preventive and autonomous maintenance practices.

Action Step	Person Responsible	Timeline	Status
Daily production planning meeting and shift-wise target allocation	Production Supervisor	Daily	In progress
Visual production boards for real-time tracking	Planning Team	2 Days	In progress
Barcode tagging and raw material checklist implementation	Quality Control	1 Week	In Progress
Raw material staging and pre-weighing area setup	Stores & Logistics	4 Days	Completed
Charging SOP implementation with weight tolerances	Furnace Operators	3 Days	In Progress
Slag removal schedule and standardization	Production Team	2 Days	Ongoing
Routine equipment cleaning and lubrication	Operators	Every Shift	Ongoing
Preventive maintenance schedule revision	Maintenance Team	1 Week	In Progress
Operator training on autonomous maintenance tasks	HR & Maintenance	2 Weeks	In progress

Result After Kaizen (After Implementation):

Target / Objective:

Increase production efficiency, reduce defect rate to 70%.

Parameter	Before Kaizen	After Kaizen	Improvement (%)
Production Efficiency	Manual, inconsistent tracking and planning	Structured planning and real-time tracking	Improved visibility and workflow
Defect Rate	Unmonitored material quality and charging variations	Standardized charging SOP and raw material checks	Enhanced consistency and defect prevention
Equipment Downtime	Unscheduled breakdowns and reactive maintenance	Preventive and autonomous maintenance practices	Reduced unplanned stoppages

Benefit Realized:

Result After Kaizen (After Implementation):

Real-time tracking enabled quick response to delays, raw material quality improved, charging consistency enhanced, and downtime reduced through autonomous maintenance.

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Verified By: (Supervisor/Manager)

Benefit Realized:

Benefit Realized:

✅ Sigma Level Improvement ✅ Productivity Increase ✅ Safety Improvement

Verified By: Mr. Ajmal Khan (Production Manager)

Approved By: Mr. Radha Krishna (Lean Coordinator).

Before and After Improvement

Improving production rate, reducing defect rate, and increasing sigma level for January, February, and March.

Following the implementation of improvement initiatives such as SOP standardization, equipment calibration, and operator training, production increased significantly—reaching 1,178.3 tonnes in January, 1,242.7 tonnes in February, and 1,309.9 tonnes in March. The combined output of 3,730.9 MT reflects steady and sustainable growth, validating the effectiveness of enhanced operational efficiency measures.

Month	Total Defects	Total Units	DPMO	Defect Rate	Sigma Level
Sep to Dec (Before)	989	41,494	2979.36	2.38%	4.25
Jan to Mar (After)	324	37,311	1085.471	0.86837%	4.56

Table 9. Before and After Improvement

The initial sigma level was 4.25, and the targeted sigma level was 5.0 and After improvement, sigma level is 4.56

7. Conclusion

This theoretical implementation focuses on enhancing production efficiency, reducing defect rates, and achieving a sigma level of 5.0 through structured Standard Operating Procedures (SOPs) in ingot manufacturing. Daily production planning with morning meetings, manpower allocation, and shift-wise monitoring ensures effective coordination. Raw material inspection for chemical composition, moisture, and size improves batch consistency. Standardized charging and melting processes, including furnace preheating and slag removal, maintain metal purity. Proper mold preparation with cleaning, preheating, and release agents helps prevent surface defects. Controlled pouring techniques reduce turbulence, spillage, and cold shuts. Standardized cooling using water or air systems avoids thermal stress and micro-cracks, while time logs ensure process consistency. After implementing SOP standardization, equipment calibration, and operator training, production increased steadily—1178.3 tonnes in January, 1242.7 in February, and 1309.9 in March—demonstrating improved efficiency. Out of a total defect reduction of 989 from September to December, the number of defects further decreased to 324 during January, February, and March. This represents a 63.52% reduction in the defect rate, achieving a Sigma level of 4.56. With sustained efforts and continuous improvement, reaching a 5 Sigma level is well within reach.

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