Journal of Advanced Research Design 147, Issue 1 (2026) 52-64

Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Enhancing Oxidation Resistance in Aluminium and Aluminium Alloy Through Lean Six Sigma Methodology

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ARTICLE INFO

Article history:
Received 27 March 2025
Received in revised form 26 July 2025
Accepted 14 August 2025
Available online 2 November 2025

Keywords:
Oxidation; Aluminum and Aluminum Alloys; Lean Six Sigma; Process Improvement; Quality Control

ABSTRACT

This research explores the enhancement of oxidation resistance in aluminum and its alloys through the utilization of Lean Six Sigma methodologies. The primary objective is to identify the root causes of oxidation in these materials and implement process improvements to bolster their resistance to oxidation. By employing Lean Six Sigma tools and techniques, the research aims to optimize manufacturing processes and elevate the quality of aluminum products. The study addresses the challenges associated with maintaining oxidation resistance in aluminum and its alloys, which can lead to material degradation and reduced product longevity. Through a thorough investigation of oxidation mechanisms, environmental influences, alloy compositions, and surface treatments, the research aims to mitigate these challenges and enhance the overall performance and durability of aluminum materials. Results and discussions from the study underscore the efficacy of Lean Six Sigma in enhancing oxidation resistance in aluminum and its alloys. The analysis provides valuable insights into the factors influencing oxidation and emphasizes the role of quality improvement methodologies in material science and manufacturing processes. The study's findings have implications for advancing material science, promoting sustainability, and improving quality assessment in the manufacturing sector. In conclusion, this research highlights the importance of continuous improvement and innovation in material engineering. By applying Lean Six Sigma methodologies to address oxidation challenges, the study contributes to the progression of material science, sustainability initiatives, and quality enhancement in aluminum product manufacturing. The outcomes offer practical implications for enhancing competitiveness, market positioning, and environmental stewardship in the production of aluminum-based materials.

1. Introduction

Aluminum and its alloys are among the most versatile, affordable, and aesthetically beautiful metallic materials. They can be used for anything from the most demanding technological

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https://doi.org/10.37934/ard.147.1.5264

applications to soft, incredibly ductile wrapping foil. Aluminum alloys are used in structural metal constructions more frequently than steels. Aluminum's density is only 2.7 g/cm3, or around one-third that of steel (7.83 g/cm3). Water-borne vehicles benefit greatly from the design and construction of sturdy, lightweight structures made possible by the combination of this lightweight and some aluminum alloys' exceptional strength, which surpasses that of structural steel [1].

Steel corrodes due to a kind of gradual oxidation that aluminum is resistant to. In order to stop further oxidation, the exposed aluminum surface reacts with oxygen to form an inert aluminum oxide coating that is only a few ten-millionths of an inch thick. In contrast to iron rust, the layer of aluminum oxide does not flake off and expose fresh surfaces to further oxidation. The aluminum protective layer is self-repairing if it gets scratched. Invisible to the unaided eye, the thin oxide layer is transparent, colourless, and firmly adheres to the metal. Unlike steel and iron, aluminum does not rust with flaking and discoloration. When alloyed and treated correctly, aluminum can resist corrosion from a variety of chemical and physical agents as well as variations in water, salt, and other environmental factors.

1.1 Oxidation in Aluminum and Aluminum Alloy

The oxidation of aluminum and its alloys is a critical aspect that significantly influences their properties and performance. Understanding the behaviour of oxide films, surface properties, corrosion resistance, and the impact of alloying elements is essential for optimizing the functionality and durability of aluminum and its alloys. The oxidation resistance of aluminum and its alloys is a critical aspect that significantly influences their performance and durability. Understanding the critical elements that contribute to oxidation in aluminum and aluminum alloys is crucial for a variety of applications, such as materials science, catalysis, and corrosion prevention. Researcher Medvedev and team investigated the influence of alloying elements on the mechanical properties of anodized aluminum and the adhesion of copper metallization, emphasizing the role of alloy composition in determining the mechanical properties and surface characteristics of aluminum alloys [2]. Peel tests and pull-off adhesions showed significant differences for both aluminum alloys, highlighting the importance of alloy composition in determining adhesion and mechanical properties.

Macário et al., [3] investigation focused on the influence of environmental conditions on the corrosion resistance of aluminum alloys by investigating the corrosion behaviour of these alloys coated with DLC films in aviation fuel media. The present study emphasized the significance of corrosion prevention tactics for aluminum alloys utilized in aerospace settings. Plascencia and team investigated the oxidation resistance of copper-aluminum alloys at temperatures up to 1,000°C, highlighting the remarkable improvement in oxidation resistance achieved through alloying with 4 wt.% copper [4]. Researcher Urakawa and team characterized aluminum oxide thin films formed on surfaces of FeCo-V alloys by annealing under a low partial pressure of oxygen, demonstrating the influence of aluminum content, annealing temperature, and annealing time on the thickness of the aluminum oxide thin films [5]. Furthermore, Promakhov and team [6] studied the influence of vibration treatment and modification of A356 aluminum alloy on its structure and mechanical properties, demonstrating an increase in yield strength under tension with the introduction of TiB2 hardening particles. The oxidation of aluminum and its alloys is a multifaceted area of research that encompasses oxide film characterization, surface properties, alloy modification, corrosion behaviour, and advancements in surface treatment and coatings.

1.2 Oxidation Resistance in Aluminum

The oxidation resistance of aluminum and its alloys is a critical aspect that significantly influences their performance and durability. In addition, researcher Zhukov and team [7] examined the modification of pure aluminum structure and mechanical properties through the introduction of Al2O3 nanoparticles and ultrasonic treatment, demonstrating the potential for altering the oxidation behavior and mechanical properties of aluminum through innovative techniques. This study provides valuable insights into the potential for enhancing the oxidation resistance and mechanical properties of aluminum through advanced materials processing techniques.

Ueda and team [8] investigated the recovery of aluminum from oxide particles in aluminum dross using AlF3–NaF–BaCl2 molten salt, shedding light on efficient aluminum recovery processes and their implications for alloy quality and sustainability. This research contributes to the understanding of aluminum recovery and its potential impact on the oxidation resistance of aluminum alloys. In a related study, Xie et al. [9] explored the effect of different laser energy densities on the corrosion resistance of aluminum alloys, demonstrating improved corrosion resistance with increased energy density. This study provides valuable insights into the potential application of laser processing techniques for enhancing the corrosion and oxidation resistance of aluminum alloys. Furthermore, Zhu and team [10] investigated the surface properties of 5A12 aluminum alloy after YAG laser cleaning, revealing the generation of residual tensile stress and a slight decrease in corrosion resistance after cleaning. This study emphasizes the influence of surface treatments on the mechanical and corrosion properties of aluminum alloys, highlighting the need for comprehensive surface characterization and property assessment.

1.3 Factors Contributing to Oxidation in Aluminum

Understanding the critical elements that contribute to oxidation in aluminum and aluminum alloys is crucial for a variety of applications, such as materials science, catalysis, and corrosion prevention. Aluminum and its alloys' mechanical, chemical, and structural characteristics can be greatly impacted by oxidation. The importance of oxidation in affecting aluminum's mechanical strength was highlighted by the mechanical behavior of the material, underscoring the need of taking oxidation effects into account in crack formation simulations. Zhang & Dreizin [11] examined the heterogeneous oxidation of aluminum powders, highlighting the significance of aluminum ion outward diffusion in regulating the oxidation rate. To fully address the oxidation behavior of aluminum powders, it is imperative to comprehend the diffusion processes and the factors controlling them. Sundaram et al. [12] highlighted the importance of phase transitions in starting the oxidation process by focusing on the phase change of aluminum in the oxidation of aluminum nanoparticles. According to the study, the oxidation of oxide-coated nano-aluminum occurs when the aluminum core melts, causing the oxide coating to mechanically break and oxidize as a result. Li & Church [13] found that the two main variables influencing aluminum corrosion during the cathode production process were immersion time and the pH of aqueous-based cathode slurries. Creating successful corrosion prevention techniques requires an understanding of how environmental conditions affect aluminum corrosion. In summary, several elements such as phase shifts, diffusion processes, mechanical behavior, and toxicological consequences are among the essential factors that contribute to the oxidation of aluminum and aluminum alloys. For the purpose of environmental safety, materials engineering, and corrosion prevention to be successful, it is imperative to comprehend these variables.

1.4 Lean Six Sigma Methodology in Oxidation of Aluminum and Aluminum Alloy

The application of Lean Six Sigma tools for analyzing oxidation resistance in materials and manufacturing processes is a critical area of research. This aims to synthesize and correlate various studies related to the application of Lean Six Sigma tools for analyzing oxidation resistance, encompassing topics such as process improvement, DMAIC methodology, and the integration of Lean and Six Sigma tools. Olanrewaju and team [14] reviewed and analysed literature on Lean Six Sigma (LSS) methodology tools and its applications in the manufacturing industries, emphasizing their potential for analyzing and improving oxidation resistance in manufacturing processes. Mustapha and team [15] conducted multiple case studies on Lean Six Sigma implementation, highlighting the interchangeability of tools between Lean and Six Sigma, which can be beneficial for addressing challenges related to oxidation resistance in manufacturing. Researcher Ray and John discussed using Lean Six Sigma tools in business process outsourcing to identify inefficiencies and non-value-adding activities, offering insights into addressing inefficiencies affecting oxidation resistance in manufacturing [16]. While Bhaskar [17] provided a comprehensive review of Lean Six Sigma in manufacturing, emphasizing the diverse tools and techniques for continuous improvement, such as the Kanban system, 5S, Cause and Effect analysis (C&E), and Value Stream Mapping (VSM). The application of Lean Six Sigma tools for analyzing oxidation resistance in materials and manufacturing processes is a critical area of research that encompasses diverse tools and methodologies.

By utilizing Lean Six Sigma techniques, this study attempts to close the knowledge gap over how to improve oxidation resistance in aluminum and its alloys. To minimize errors and enhance workflows, a methodical, data-driven strategy is required, whereas existing approaches concentrate on traditional treatments. Its potential to enhance material qualities, boost output, cut expenses, and advance sustainability in the manufacturing sector makes this research important. Using Lean Six Sigma methods, identifying important oxidation-influencing elements, and offering suggestions for enhancing the performance and longevity of aluminum-based goods are the key goals.

2. Methodology

The process of data collection involved retrieving information from mass production lots encompassing various part numbers. This comprehensive dataset was meticulously gathered to ascertain and define the foundational Sigma level for aluminum material within the manufacturing context. Through the systematic examination of multiple part numbers produced in large-scale manufacturing operations, the aim was to establish a robust baseline that accurately reflects the current performance and quality standards associated with aluminum material utilization in the production process. Table 1 shows the data collection and analysis based on defects caused by oxidation in aluminum and aluminum alloy.

Table 1
Data and analysis caused by oxidation

Part Number	Production Qty (PCS)	Defect Qty (PCS)	Yield	Defects	DPMO	Sigma Level
Design A	20	12	40%	60.0%	600,000	1.25
Design B	30	13	45%	55.0%	550,000	1.37
Design C	20	17	56.7%	43.3%	433,000	1.67

2.1 Root Cause Analysis on Oxidation of Aluminum and Aluminum Alloy

A useful tool in the Lean Six Sigma technique, the Ishikawa diagram, sometimes referred to as the fishbone diagram, is used to perform root cause analysis and pinpoint the underlying causes of a particular problem. The utilization of the Ishikawa diagram can be beneficial in methodically investigating the several factors that could impact the oxidation resistance of aluminum and aluminum alloys, with the goal of improving oxidation resistance [18]. The root cause of the oxidation was analysed as per Ishikawa diagram shown in Figure1.

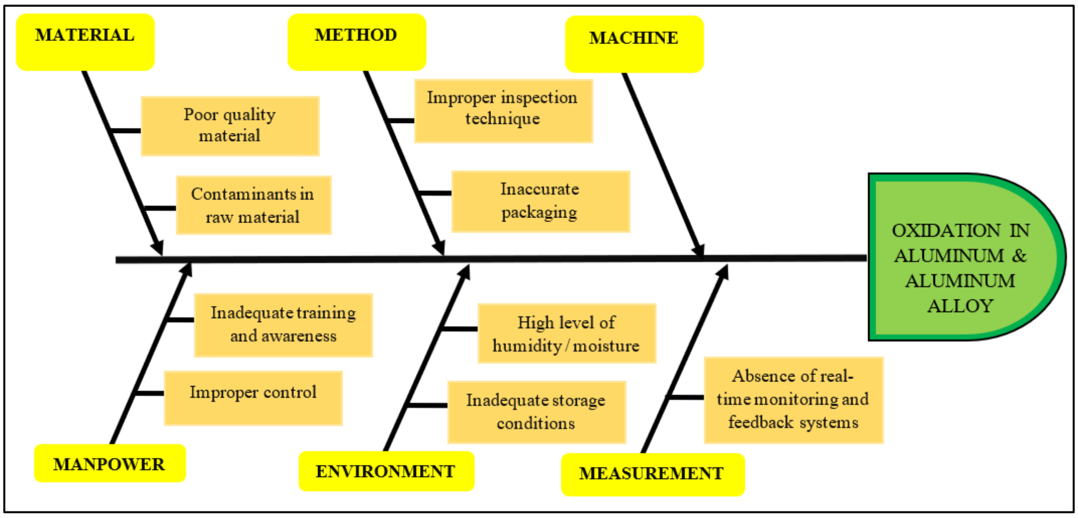


Fig. 1. Ishikawa diagram on the root cause of the oxidation in aluminum and aluminum alloy

The main root cause of the oxidations was identified using consensus group technique an organized communication approach that was first created as an interactive, methodical forecasting strategy that depends on a group of experts. This approach can be successfully utilized to get expert viewpoints, reach a consensus, and create common understanding on complicated issues in the context of improving the oxidation resistance of aluminum and aluminum alloys through Lean Six Sigma approaches. The step for consensus group technique can be shown as per Figure 2.

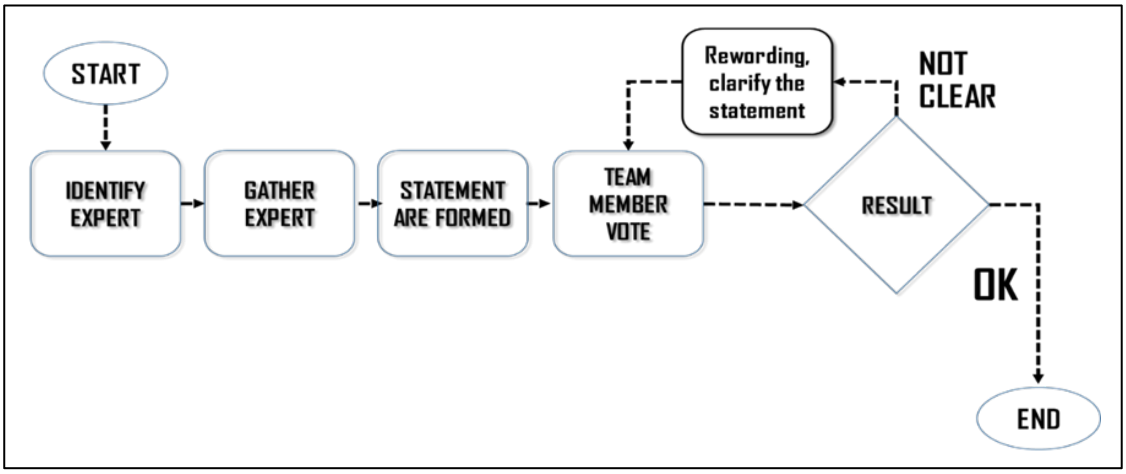


Fig. 2. Steps for consensus group technique

The data are gathered based on interviews from the expert regarding the cause of oxidation in aluminum and aluminum alloy. The key factors and category in Ishikawa diagram are used as a criterion in the interview with the expert regarding the oxidation in aluminum and aluminum alloy. Based on the interview, rating was provided by the expert on each category that caused the oxidation in aluminum and aluminum alloy. Table 2 shows the rating on each category of oxidation on the surface of the material.

Table 2
Rating for each category of oxidation in aluminum and aluminum alloy

	Ishikawa Criterion					
Interviewee	Material	Method	Machine	Manpower	Environment	Measurement
Expert A	2	2	1	4	6	1
Expert B	3	1	1	2	6	2
Expert C	1	1	1	4	4	1
Expert D	2	1	1	3	5	1
Expert E	1	3	1	3	5	1
TOTAL	9	8	5	16	26	6
						Ranking (1 = No Agreement, 6 = Perfect Agreement)

Table 2 offers a detailed view of the interviewees' perspectives on various factors affecting their work or project. The higher scores in Environment rating highlight areas that might need more focus or investment. These insights can guide decision-makers in prioritizing resources, identifying areas for improvement, and understanding the key drivers of success in their specific context. The data not only highlights the critical factors but also provides a framework for systematically addressing the aspects that could lead to enhanced performance and outcomes.

3. Result

3.1 Kendall's Coefficient of Concordance

The Kendall's coefficient of concordance is a statistical technique that evaluates the degree of agreement between several raters or judges when assigning a rating to a group of items or subjects. When measuring the consensus among experts or evaluators is necessary in a variety of sectors, including education, environmental science, medical, and economics, this test is especially helpful [19]. The rating on each category of the oxidation where compute in the Kendall's W test using SPSS software. Table 3, Table 4, and Table 5 shows the results of data compute using Kendall's W test.

Table 3
Descriptive statistical analysis on the oxidation in aluminum and aluminum alloy

	N	Mean	Std. Deviation	Minimum	Maximum
Material	5	1.8000	0.83666	1.00	3.00
Method	5	1.6000	0.89443	1.00	3.00
Machine	5	1.0000	0.00000	1.00	1.00
Manpower	5	3.2000	0.83666	2.00	4.00
Environment	5	5.2000	0.83666	4.00	6.00
Measurement	5	1.2000	0.44721	1.00	2.00

Table 4
Ranks of Oxidation Factors

	Mean Rank
Material	3.4
Method	2.8
Machine	1.9
Manpower	4.7
Environment	5.9
Measurement	2.3

Table 5
Test Statistics

N	5
Kendall's W[a]	0.775
Chi-Square	19.371
df	5
Asymp. Sig.	0.002

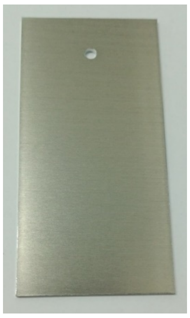
a. Kendall's Coefficient of Concordance

The high Kendall's W value suggests that raters strongly agreed on the significance of the oxidation factor. This agreement is not the result of chance, as further supported by the significant chi-square statistic and low p-value. Based on this test, it can be sum up that environmental factor highly contributes on the oxidation of aluminum and aluminum alloys.

3.2 Experimental Data and Analysis

An experiment has been conducted on the aluminum surface finish based on potential root cause that led to oxidation which is environmental factors with different conditions to identify the compatible humidity and temperature. Table 6 shows the experimental specification on the effect of the environmental conditions on aluminum surface finish.

Table 6
Experimental specification on the effect of the environmental conditions on aluminum surface finish

Specification	Experimental Setup		
Samples	Panel 1	Panel 2	Panel 3
Samples Visual			
Material Grade	ASTM B209, ALU 5052-H32, 1.50MM THICK		
Surface Finish	Original Material Surface Finish		
Temperature	16 °C	25 °C	35 °C
Humidity Level	67.60%	65.10%	41.50%

Based on this experimental specification, data on the related to oxidation are collected as per Table 7 and Table 8. The initial data measurements were collected which act as baseline on the sample's oxidation.

Table 7
Weight measurement at each inspection interval

Day	Panel 1	Panel 2	Panel 3
0	30.12	30.37	30.53
10	30.14	30.37	30.53
20	30.17	30.39	30.54
30	30.20	30.41	30.55

Table 8a
Surface Analysis Data

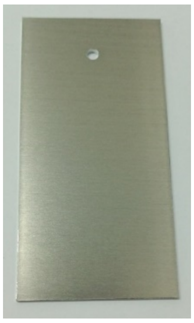
Day	Panel 1	Panel 2	Panel 3
0			
	No oxidation	No oxidation	No oxidation
10			
	Light oxide layer	Slight discoloration	Slight discoloration

Table 8b
Surface Analysis Data

Day	Panel 1	Panel 2	Panel 3
20			
	Light to moderate oxide layer	Visible oxide layer	Slight discoloration
30			
	Moderate oxide layer	Light oxide layer	Slight discoloration

Based on the result, due to high temperature and low humidity, the aluminum surface was better preserved in Panel 3, where the samples showed the least amount of oxidation, the thinnest oxide layer, and the least amount of visual deterioration. Overall, the findings imply that improving environmental factors, especially temperature and humidity levels, might greatly improve aluminum alloys' resistance to oxidation. For sectors that use aluminum as a primary material, these results are essential because they offer insightful information on how to manage the environment to increase the longevity and durability of aluminum goods.

3.3 Improvement on Sigma Level of The Oxidation

The solution for the oxidation in aluminum and aluminum alloy have been implemented on the production side to address and mitigate the key factors contributing to defects. These measures include controlling environmental conditions such as temperature and humidity, optimizing storage practices, and enhancing surface treatments to improve oxidation resistance. As a result of these implementations, the defect rate has significantly decreased, leading to an improved sigma level. Table 9 shows the result on the sigma level after implementation of the solution for oxidation in aluminum and aluminum alloy, and the comparison on the sigma level before and after improvement have been charted as shown in Figure 3.

Table 9
Improved sigma level after improvement implementation

Part Number	PO Qty (PCS)	Defect Qty (PCS)	Yield	Defects	DPMO	Sigma Level
Design A	30	2	93.33%	6.67%	66,666.67	3.00
Design B	25	1	96.00%	4.00%	40,000.00	3.00
Design C	20	1	95.00%	5.00%	50,000.00	3.14

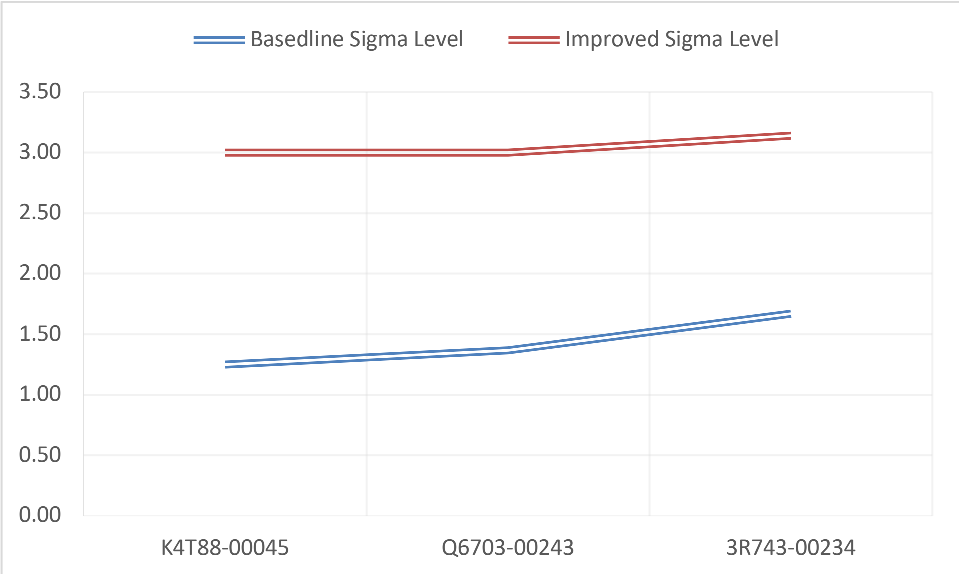


Fig. 3. Comparison on sigma level before and after improvement implementation on the oxidation of aluminum surface

In summary, there has been a significant reduction in defect rates and an improvement in yields in line with the increased sigma levels when compared to the prior sigma levels. These enhancements show how the adopted solutions are successful in lowering variability, raising productivity, and guaranteeing better product quality, which eventually results in significant cost savings and enhanced customer satisfaction.

3.4 Improvement Control

The DMAIC cycle's Control phase is essential for preserving ongoing process advances, particularly when it comes to boosting aluminum and its alloys' oxidation resistance. Implementing strategies to maintain the gains made during the Improve phase and avoid a return to earlier conditions is the main goal of this phase [20]. Organizations can ensure that implemented improvements continue to yield desired outcomes over time by implementing control mechanisms to monitor key process indicators [20]. Figure 4 shows the goal of control phase in DMAIC.

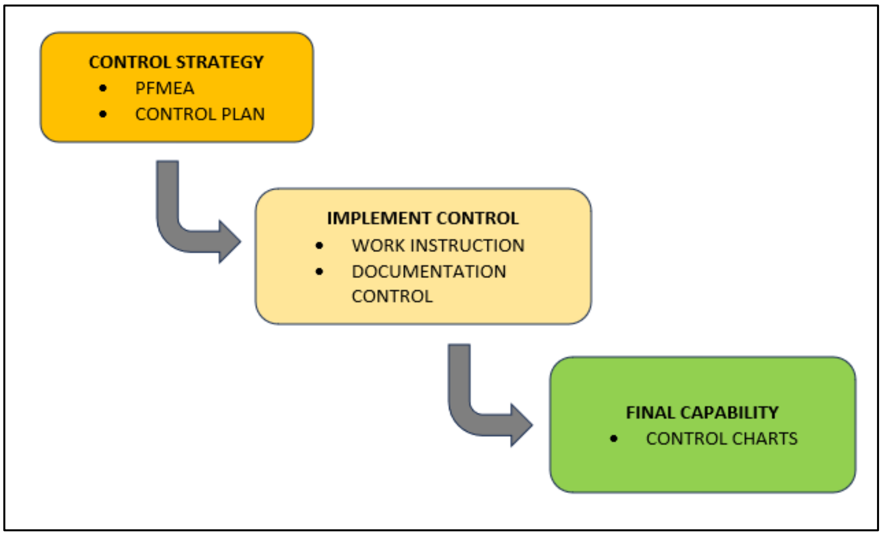


Fig. 4. Control phase goals

The control strategy consists of two main parts: the Control Plan and PFMEA. The PFMEA identifies possible failure modes in the storage process caused by changes in humidity and temperature. By assessing the severity, occurrence, and detection of these failure modes, actions can be taken to reduce risks and prevent oxidation in materials. The Control Plan outlines protocols for continuously monitoring environmental parameters, including temperature and humidity, and defines roles and responsibilities to ensure these conditions are met. This comprehensive approach addresses all potential hazards and implements safeguards to maintain the quality of aluminum.

Detailed work instructions are developed to help personnel manage storage conditions effectively. These instructions include how to monitor and adjust temperature and humidity levels, handle deviations, and respond to emergencies. Documentation control is essential for maintaining records of environmental conditions, inspecting, maintaining, and taking corrective actions. Ensuring all procedure changes are updated and communicated to relevant staff maintains consistency and compliance. Strict documentation guidelines and detailed instructions make the process of controlling environmental conditions reliable and efficient.

Control charts are used in the control phase to achieve its ultimate capability. These charts monitor temperature and humidity data over time, allowing patterns to be identified, out-of-control situations to be spotted, and ensuring the control plan is followed. Control limits must be regularly reviewed and updated based on process performance and improvements. Control charts provide a statistical and visual method to monitor process stability and ensure long-term maintenance of gains.

4. Conclusion

In conclusion, this study has provided important insights with wide-ranging implications. It has offered valuable information on optimizing production processes, advancing material science, and promoting sustainability by identifying the causes of oxidation and implementing targeted process improvements.

Lean Six Sigma techniques have effectively addressed the oxidation issues in aluminum and its alloys. The study demonstrated that controlling environmental factors like humidity and temperature significantly reduces oxidation rates, enhancing the performance and durability of aluminum products. These improvements lead to fewer errors, increased production, and cost savings in manufacturing. Better quality aluminum products not only make producers more competitive but also help them meet changing consumer demands.

Additionally, the study's impact goes beyond local production. It supports resource efficiency and sustainability through waste reduction, energy conservation, and minimizing environmental impact. Integrating quality improvement methods into material science shows the potential for continuous innovation in engineering and production processes. The study highlights the need for long-term research and real-world applications to confirm the results. Comprehensive economic evaluations and implementation across various industries will provide further insights into the practical benefits and cost savings of improved oxidation-resistant alloys.

In summary, the research highlights the importance of Lean Six Sigma approaches in enhancing the oxidation resistance of aluminum and its alloys. It opens up opportunities for future studies on new alloys, advanced surface treatments, and the integration of smart manufacturing technologies. Continued progress in this area can lead to better material performance, sustainability, and economic benefits across multiple industries, achieved through collaboration between government, industry, and academics.

Acknowledgement
This research was funded by MTD Industries Sdn Bhd, Malaysia to improve the oxidation in aluminum and aluminum alloy.

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