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The Role of Washer Systems in Aluminum Can Manufacturing: Impact on Product Quality and Process Sustainability

ABSTRACT

The aluminum beverage can manufacturing process is a highly automated and tightly controlled industrial system where surface preparation plays a critical role in ensuring product quality and long-term performance. Within this production chain, the Washer system represents one of the most important stages, as it is responsible for removing process contaminants, preparing the aluminum surface, and enabling proper adhesion of subsequent coating and printing layers. This paper analyzes the role of Washer systems in aluminum can manufacturing, with a specific focus on their impact on product quality, process stability, and overall production sustainability. The study combines a literature review, analysis of industrial practice, and operational process data from production environments. Key process parameters such as pH, conductivity, fluoride concentration, and FA/TA ratio are discussed in relation to their influence on surface treatment efficiency and defect prevention. An experimental Etching Rate Test was conducted to quantitatively evaluate the intensity of aluminum surface etching as an indicator of accelerator activity within the Washer system. The results showed an average material loss of 8.6 mg per can (114 mg/m²), which falls within the established industrial reference range, confirming stable and controlled process conditions. The findings highlight the Washer system as a critical interface between mechanical forming and final surface finishing operations, directly influencing coating adhesion, defect formation, and downstream process efficiency. In addition, the study emphasizes the dual role of the Washer in ensuring both product quality and environmental sustainability through optimized chemical consumption, water recirculation, and process control strategies.

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KEY WORDS
Aluminum can manufacturing, washer system, aluminum surface preparation, chemical process control, etching rate, quality control, sustainability

1. Introduction

1.1. Industry context

The aluminum beverage can industry represents one of the most technologically advanced sectors of modern packaging production, with an annual global output exceeding 400 billion cans (Green, 2007). The widespread use of aluminum cans is primarily driven by their low weight, high recyclability, mechanical stability, and suitability for high-speed industrial filling and distribution systems. In addition to their functional advantages, aluminum cans are recognized as an important example of circular economy principles, since the average recycling cycle from a used can to a newly produced can, can be completed in approximately 60 days (European Aluminium Association, 2020a).

The manufacturing process of aluminum cans is highly automated and consists of multiple interconnected production stages, including material forming, surface preparation, coating, printing, curing, inspection, and palletizing. Modern production lines are capable of producing more than 2,000 cans per minute, requiring extremely stable process conditions and continuous quality monitoring throughout the entire manufacturing chain (Campbell, 2006). The quality demands of dry offset can printing require precise control of ink deposition, coating uniformity, and color variation, particularly in high-volume manufacturing environments (Oličkov et al., 2026). These requirements place significant importance on the Washer process, whose role is to create a clean and chemically stable substrate that enables consistent performance in subsequent coating and printing operations. Due to such production speeds and technical complexity, even minor deviations in one phase may negatively affect downstream operations and final product performance.

In parallel with quality requirements, sustainability has become a major priority in the packaging industry. Manufacturers are increasingly focused on reducing water consumption, chemical usage, energy demand, and environmental emissions while maintaining high production efficiency and consistent product quality (Ball Corporation, 2023).

Previous studies in graphic and printing processes have demonstrated that process variables such as pH and conductivity can significantly influence final product quality, highlighting the importance of systematic monitoring and control of chemical parameters in industrial production systems (Kiurski & Oros, 2012; Dharavath, 2021; Gurgal et al., 2013).

1.2. Washer systems and process challenges

Among all production stages, the Washer system represents one of the most critical processes in aluminum can manufacturing. Positioned between the forming and decorating operations, the Washer is responsible for removing lubricants, metal particles, aluminum oxides, and other contaminants generated during the drawing and ironing process. At the same time, it chemically prepares the aluminum surface for subsequent coating and printing operations by creating conditions necessary for proper adhesion and corrosion resistance.

Washer systems directly influence product quality, process stability, and operational efficiency. Inadequate Washer performance may lead to defects such as poor lacquer adhesion, surface staining, corrosion, mobility problems, or printing inconsistencies, ultimately increasing waste generation and production costs. Because Washer systems consume significant quantities of water, chemicals, and thermal energy, their optimization is also closely connected with sustainability objectives and resource efficiency (European Aluminium Association, 2020b).

Modern Washer technologies therefore require continuous monitoring and precise control of chemical and mechanical process parameters, including pH, conductivity, fluoride concentration, acid balance, spray performance, filtration efficiency, and drying conditions. Maintaining stable operating conditions is essential for minimizing defects and ensuring consistent production quality in high-speed manufacturing environments.

1.3. Aim of the paper

This paper analyzes the role of Washer systems in aluminum can manufacturing, with particular emphasis on their influence on product quality, process stability, and sustainability. The study combines literature review, industrial process analysis, and experimental evaluation through a quantitative Etching Rate Test used to assess aluminum surface treatment efficiency. Special attention is given to the relationship between chemical process control, surface preparation quality, and defect prevention in downstream production stages. In addition, the paper discusses sustainability-related aspects of Washer operation, including water recirculation, chemical optimization, and reduction of environmental impact within modern aluminum can manufacturing systems.

2. Methodology

2.1. Approach

The methodology applied in this study combines literature review, industrial process analysis, and experimental evaluation in order to provide a comprehensive assessment of Washer systems in aluminum can manufacturing. The research approach was designed to examine Washer operation from both technical and sustainability perspectives, while simultaneously linking theoretical principles with practical industrial application.

Particular attention was given to the interaction between Washer performance, process stability, and final product quality. The study therefore integrates qualitative analysis of process design and operational practices with quantitative assessment of selected process indicators related to surface treatment performance.

2.2. Data sources

The research was based on multiple complementary sources of information. A review of available technical and scientific literature related to aluminum can manufacturing, metal surface treatment, and industrial qual-

ity control was performed to establish the theoretical background of the study (Ball Corporation, 2010). In addition to literature sources, industrial documentation and operational information from Washer systems and associated quality control procedures were analyzed. These sources provided insight into process design, chemical treatment principles, machine components, control systems, and sustainability-related practices used in contemporary can manufacturing environments (European Aluminium Association, 2020b).

Operational and laboratory data obtained through routine process monitoring and quality control procedures were also considered. Parameters such as pH, conductivity, fluoride concentration, and acid balance were reviewed as representative indicators of Washer process stability and chemical control.

2.3. Experimental method - Etching rate test

As part of the experimental methodology, a quantitative Etching Rate Test was conducted to evaluate the intensity of aluminum surface etching as an indicator of accelerator activity within the Washer process. The method is based on measuring the mass loss of individual aluminum cans before and after exposure to the etching stage, where the difference in mass represents the quantity of removed aluminum and provides a direct indication of chemical attack.

The experiment was performed using individually identified can samples measured on a calibrated analytical balance under controlled drying conditions. The obtained values were expressed both as average mass loss per can (mg/can) and normalized surface loss (mg/m²), allowing comparison with established industrial reference values. A detailed description of the experimental procedure, calculations, and results is presented in the dedicated experimental section of this paper.

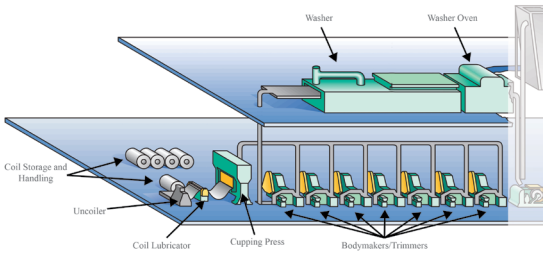
3. Overview of end-to-end can manufacturing process

The production of aluminum beverage cans is a highly standardized and technologically advanced manufacturing process characterized by high production speeds, automation, and strict quality requirements. Modern production lines are designed to ensure continuous material flow with minimal process interruptions and high operational efficiency, while simultaneously meeting sustainability and product quality standard The manufacturing process generally consists of two main technological segments: the front-end and the back-end production phase (Ball Corporation, 2010). Each phase includes several interconnected operations that must function in a synchronized manner to maintain process stability and product consistency.

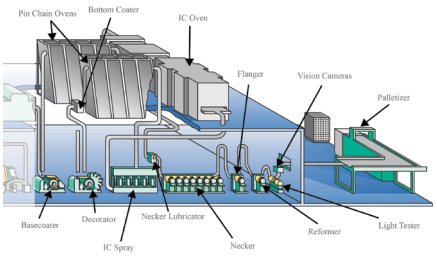
The front-end phase includes the primary forming operations of the aluminum can body. The process begins with coil handling, where rolled aluminum sheets are prepared and fed into the production line. In the cupper unit, circular aluminum blanks are formed into shallow cups, which are then transferred to the bodymaker machine. During the drawing and ironing process, the cup is elongated and thinned to achieve the final can body geometry. Afterward, the trimmer cuts the can body to the required height and dimensional specification. The formed cans then enter the Washer system and Washer Oven, where cleaning, chemical surface preparation, rinsing, and drying operations are performed prior to decoration and coating processes.

The back-end phase includes all subsequent coating, decoration, curing, forming, and inspection operations. A base coating layer is first applied to the can surface using a basecoater unit, after which the graphic design is transferred through dry offset printing in the decorator machine. The printed cans are then cured in the decorator oven (Pin Oven). Internal protective coatings are applied through internal coating spray systems, followed by thermal curing inside the Internal Bake Oven (IBO).

In the final production stages, the cans pass through necking, flanging, and dome reforming operations, where the final can geometry is achieved. Quality control systems such as light testers, vision inspection systems, and label verification units are used to identify defective products and ensure compliance with technical and visual quality requirements. Finished cans are then automatically palletized and prepared for transport and distribution. Among all production stages, the Washer system represents a critical interface between mechanical forming and final surface finishing processes. Its performance directly affects coating adhesion, print quality, corrosion resistance, and overall process stability, making it one of the most important quality-control stages in aluminum can manufacturing. Figure 1 presents the main operations of the front-end production phase, while Figure 2 illustrates the back-end manufacturing process.



» **Figure 1:** *Front-end phase of the technological process of making aluminum cans (Ball Corporation, 2022)*



» **Figure 2:** *Back-end phase of the technological process of making aluminum cans (Ball Corporation, 2022)*

4. Washer system – function and role in aluminum can manufacturing

The Washer system represents one of the most important process stages in aluminum can manufacturing, as it performs both cleaning and chemical surface preparation functions prior to coating and decoration operations. Positioned between the body forming and printing stages, the Washer is responsible for removing lubricants, metal particles, aluminum oxides, and other contaminants generated during the drawing and ironing process. At the same time, it prepares the aluminum surface for the application of protective coatings, base coats, inks, and overvarnish layers.

The importance of the Washer system can be observed from three closely connected perspectives: product quality, process efficiency, and production sustainability. From a quality standpoint, the Washer ensures a clean and chemically stable surface required for proper adhesion of coatings and printing layers. Inadequate cleaning or unstable chemical treatment may lead to defects such as poor lacquer adhesion, corrosion, staining, discoloration, or printing inconsistencies. From a process-efficiency perspective, Washer performance directly affects the stability of downstream manufacturing operations, including base coating, decoration, curing, and internal coating processes. Properly cleaned and dried cans reduce the probability of production interruptions, defect generation, and product rejection, thereby improving overall line efficiency and reducing operational costs.

In addition to quality and efficiency requirements, the Washer system also plays an important role in sustainable manufacturing. Since the process involves intensive use of water, chemicals, compressed air, and thermal energy, optimization of Washer parameters is essential for reducing environmental impact and resource consumption (European Aluminium Association, 2020b). Modern Washer systems therefore incorporate technologies such as water recirculation, filtration systems, automated chemical dosing, process monitoring sensors, and optimized drying systems in order to improve sustainability and operational stability.

The Washer process itself consists of multiple sequential cleaning, rinsing, chemical treatment, and drying stages designed to progressively prepare the aluminum surface for subsequent manufacturing operations. Typical process stages include pre-rinsing, pre-washing, surface preparation, rinsing phases, conversion coating treatment, deionized water rinsing, mobility enhancement treatment, and thermal drying. Each stage performs a specific function and requires precise control of process parameters such as temperature, pH, conductivity, spray pressure, chemical concentration, and flow conditions.

Modern Washer systems are additionally integrated with automated control platforms and SCADA-based monitoring systems that enable real-time process supervision and optimization. These systems continuously monitor critical process parameters, allowing rapid correction of deviations and improved consistency in product quality and process performance (Astles Control Systems Ltd., 2022).

Due to its direct influence on surface preparation quality, downstream coating adhesion, defect prevention, and sustainability performance, the Washer system represents one of the key technological stages in modern aluminum can manufacturing.

5. Washer process description

The Washer process consists of multiple sequential cleaning, chemical treatment, rinsing, and drying stages designed to progressively prepare the aluminum surface for subsequent coating and decoration operations. Each phase performs a specific function within the overall surface treatment process and must operate under carefully controlled conditions in order to ensure consistent product quality and process stability.

Modern Washer systems are typically designed as multi-stage modular units through which cans are transported continuously at high production speeds. In addition to cleaning and surface preparation, Washer systems are optimized to minimize water and chemical consumption through recirculation and backflow principles (Ball Corporation, 2025b). A typical Washer configuration includes several rinsing and active chemical stages, combined with air blow-off and thermal drying systems.

The process generally begins with the pre-rinse stage, where loose oils, aluminum particles, and contaminants generated during body forming operations are removed from the can surface. This is followed by the pre-wash stage, where acidic solutions are used to eliminate the

majority of lubricants and prepare the surface for more intensive chemical treatment. The surface preparation stage represents the main chemical cleaning phase of the Washer system. During this process, a combination of sulfuric acid, surfactants, and fluoride-based accelerators is used to remove remaining contaminants, dissolve aluminum oxides, and create a clean and chemically active aluminum surface suitable for conversion coating treatment. Proper control of chemical concentration, temperature, and acidity is essential for achieving uniform surface quality and preventing excessive or insufficient aluminum etching. After chemical surface preparation, the cans pass through the first rinse stage, where process water is used to remove residual chemicals and stabilize the surface before conversion coating treatment. The conversion coating stage is particularly important because it forms a protective chemical layer on the aluminum surface that improves coating adhesion, corrosion resistance, and resistance to discoloration during pasteurization processes. In modern aluminum can manufacturing, zirconium-phosphate-based conversion systems are commonly used due to their improved environmental performance and process stability.

Following conversion coating, the cans enter additional rinsing stages designed to remove remaining treatment residues and minimize contamination transfer between process zones. Final rinsing is typically performed using reverse osmosis (RO) or deionized (DI) water with very low conductivity in order to prevent salt residues and ensure optimal surface cleanliness before coating operations. The final chemical stage of the Washer process commonly includes a mobility enhancer treatment, where specialized surfactants are applied to improve can mobility during downstream transportation and decoration processes. These additives also improve water drainage and reduce the probability of scratches and surface damage during high-speed production (Crown Holdings, 2020).

After completion of all chemical and rinsing stages, the cans enter the Washer Oven, where thermal drying removes residual moisture from the surface. Effective drying is essential because any remaining water may negatively affect coating adhesion, print quality, and curing performance in subsequent production stages. A typical example of Washer process stages is illustrated in Figure 3.

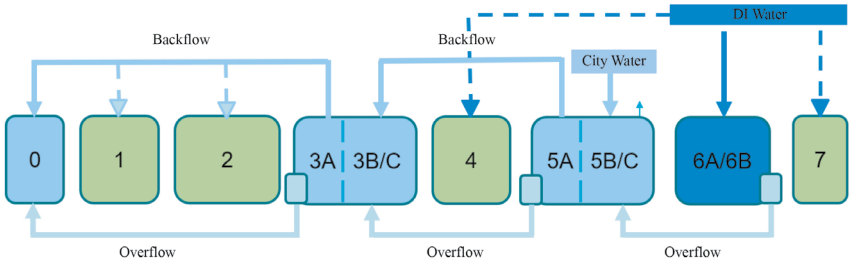
6. Washer equipment and process control systems

In addition to chemical treatment efficiency, the overall performance of a Washer system strongly depends on its mechanical components, transport systems, filtration units, spray technologies, and automated process control systems. Proper integration and maintenance of these elements are essential for ensuring stable operating conditions, minimizing contamination, reducing resource consumption, and maintaining consistent product quality throughout high-speed aluminum can production.

One of the key mechanical elements of the Washer system is the transport section, including infeed and outfeed conveyor systems. These systems ensure continuous and synchronized movement of cans through all Washer stages while minimizing the risk of jamming, instability, or mechanical damage (Yam, 2010). In industrial applications, air table systems are commonly used to improve can mobility and reduce surface contact between cans and transport components. Sensors installed within the transport system continuously monitor can flow conditions and help prevent accumulation or transport interruptions (Henry, 2012).

Spray systems and nozzle design also play a critical role in Washer performance. Each process stage contains dedicated spray bars equipped with specially designed nozzles that distribute water or chemical solutions across the entire can surface. V-jet nozzles are commonly used for wide and uniform surface coverage, while full-cone nozzles provide more intensive rinsing and improved contaminant removal efficiency (Spraying Systems Co., 2020). Proper nozzle alignment, spray pressure, and flow conditions are necessary to achieve consistent cleaning and minimize chemical consumption.

To reduce liquid carryover and contamination between Washer stages, blow-off systems are positioned between process zones. These systems use high-velocity air



» **Figure 3:** *Washer phases (Ball Corporation, 2025)*

streams to remove residual liquids from can surfaces and conveyor sections before the cans enter the next stage. Additional brush systems located beneath the conveyor help remove accumulated liquids and improve drainage conditions. Proper adjustment of blow-off units is particularly important in high-speed production environments because insufficient liquid removal may negatively affect downstream chemical stability and rinsing efficiency.

Filtration and separation systems further contribute to process stability and sustainability. Screen filters installed inside Washer tanks prevent large particles and debris from entering pumps and spray nozzles, while inline filters provide additional removal of smaller particles and contaminants. In addition, coalescer systems are commonly used in pre-wash and surface preparation stages to separate oils and emulsified lubricants from process liquids. By reducing oil concentration inside the tanks, coalescers help maintain chemical efficiency, reduce contamination levels, and extend bath lifetime At the exit of the Washer system, vacuum transfer units are used to transport cans from the Washer conveyor to the drying oven conveyor. These systems also help remove overturned or damaged cans that could otherwise cause contamination, transport instability, or mechanical interruptions in downstream operations.

Modern Washer systems are highly automated and integrated with chemical dosing and process monitoring platforms such as Astles and VisCan systems (Astles Control Systems Ltd., 2025). These systems continuously monitor critical process parameters including pH, conductivity, fluoride concentration, free acid (FA), total acid (TA), and chemical dosing conditions. Data collected from sensors installed throughout the Washer are transferred to centralized software platforms that enable real-time monitoring, automatic dosing correction, alarm management, and process optimization.

The implementation of automated monitoring and control systems provides several important advantages, including improved process consistency, reduced chemical consumption, increased operational safety, faster detection of process deviations, and enhanced sustainability performance. As a result, modern Washer systems represent a combination of chemical engineering, mechanical design, automation, and digital process control technologies integrated into a single high-performance production system.

7. Quality control in washer process

Quality control in the washer process is a critical factor in ensuring consistent surface preparation of aluminum cans, minimizing process variability, reducing waste, and supporting overall production sustainability. Within the washer system, quality assurance is achieved through a combination of chemical monitoring, laboratory verification, and functional testing of treated cans. The objective of these procedures is to ensure that all chemical stages (pre-washing, surface preparation, treatment, and rinsing) are correctly executed, that the can surface is properly cleaned and prepared for coating and printing, and that no defects are present which could compromise final product quality or downstream performance. Quality control in the washer process includes:

- chemical analysis of process baths,
- laboratory testing in dedicated CPO facilities,
- functional quality tests on cans,
- defect detection and corrective actions.

This multi-level approach ensures continuous process monitoring and timely correction of deviations, reducing quality risks and production losses.

7.1. Chemical analysis

Chemical analysis represents the primary control layer of the washer process, providing real-time information on bath composition and process stability. Key monitored parameters include pH, conductivity, fluorides, FA/TA ratio, and metal content (ME).

- pH indicates bath acidity/alkalinity and is critical for controlling cleaning and rinsing stages (Henkel, 2025).
- Conductivity reflects the concentration of dissolved ions and contamination levels (ASTM International, 2023).
- Fluorides influence etching rate and uniformity of aluminum surface treatment (Henkel Technologies, 2025).
- FA/TA (Free Acid/Total Acid) provides insight into bath activity and chemical balance (ASTM International, 2025).
- ME (Metal content) indicates dissolved aluminum concentration and bath saturation level (Ball Corporation, 2025a).

Continuous monitoring of these parameters enables timely chemical dosing adjustments and ensures process stability while minimizing resource consumption.

7.2. Laboratory (CPO)

Laboratory control in the CPO (Can Plant Operator) laboratory provides verification of chemical and process stability through standardized analytical methods. These include titration (FA/TA), ion-selective electrodes (fluorides), conductivity measurements, and spectrometric or gravimetric analysis for metal content. The laboratory serves as a reference system for validating in-line measurements and ensuring process compliance

with specifications. Its role is not only analytical but also operational, as CPO operators directly interpret results and initiate corrective actions when needed.

Table-based monitoring distinguishes between rinsing and chemical phases, where key parameters include pH, conductivity, chlorine content, FA, TA, RP, fluorides, and mobility enhancer concentration. Conductivity is a key indicator of water quality and contamination, while fluoride control is essential for consistent etching and conversion layer formation. FA/TA analysis provides insight into chemical balance, while derived indicators such as RP (TA–FA) and AR (TA/FA) are used to assess contamination and bath efficiency. Mobility enhancer (ME) concentration is determined by titration and ensures stable surface treatment in final rinsing stages.

7.3. Quality tests

Functional quality tests verify the effectiveness of the washer process on the treated aluminum surface and provide direct feedback on surface cleanliness, treatment uniformity, and coating readiness.

Water Break Test - Evaluates surface cleanliness by observing water film continuity. Immediate film break indicates contamination, while uniform film formation confirms proper cleaning.

Finger Wipe Test- Assesses residual particles or aluminum dust on the surface. It is a simple visual/physical inspection method dependent on operator experience.

Muffle Test - Evaluates conversion layer formation by thermal treatment at 538 °C. Color change intensity (golden tone) indicates treatment level.

Dome Stain Test- Assesses corrosion and staining resistance of the can dome area after immersion in borax solution at elevated temperature.

Pasteur Test- Simulates thermal processing conditions (95 °C, 30 min) to evaluate coating adhesion and resistance to delamination.

UV BRC Test - Checks UV coating coverage on the base rim area using UV inspection and chemical exposure (copper sulfate solution).

7.4. Product defects and corrective actions

Defects in the washer process are categorized into mechanical, chemical, and coating-related (oPRP) defects.

Mechanical defects result from transport and handling issues, leading to dents, scratches, moisture, or deformation. Corrective actions include adjustment of transport systems, vacuum transfer, blow-off units, and dryer settings.

Chemical defects arise from improper bath parameters (pH, fluorides, flow rates) and include overtreated or undertreated surfaces, stains, and abnormal test results. Corrective measures involve chemical balancing, nozzle replacement, and process optimization.

Coating/oPRP defects relate to final coating and include undercured lacquer, missing spray, foreign bodies, and neck peeling issues. These are controlled through coating system adjustments and equipment maintenance.

8. Experimental study – Etching rate test

8.1. Aim of the experiment

The objective of the experiment was to quantify the intensity of chemical etching of aluminum cans (etching rate) as a direct indicator of accelerator activity in the Washer etching stage. The result is expressed as the mass of removed aluminum per can (mg/can) and per unit surface area (mg/m²).

8.2. Materials and equipment

The experiment was conducted using standardized conditions and the following materials and equipment:

- Aluminum can type: STD 500 ml (total surface area 755 cm²)
- Calibrated analytical balance (accuracy ±0.001 g)
- Demineralized (DI) water for rinsing
- Drying equipment (ventilated oven) for consistent moisture removal
- Identification markings for samples
- Personal protective equipment (PPE)

8.3. Experimental procedure

The Etching Rate Test was performed according to established industrial methodology (Henkel, 2023), following these steps:

1. Five identical aluminum cans (STD 500 ml) were selected and individually marked.
2. After the first rinsing stage, cans were thoroughly dried and weighed to obtain the initial mass (m_1).
3. The same cans were reintroduced into the Washer system and passed once more through the etching stage.
4. After treatment, cans were dried again and weighed to obtain the final mass (m_2).

5. Mass loss per can (etching rate) was calculated: Attack (mg) = (Total Mass Before (g) – Total Mass After (g)) × 1000 (conversion from grams to milligrams).
6. The average value was calculated for all tested samples.

$$\text{Average Etching Rate} = \frac{(\text{Total Mass Before} - \text{Total Mass After})}{\text{Number of Tested Cans}} \times 1000 \quad (1)$$

7. Results were normalized per surface area:

$$\text{mg/m}^2 = \frac{\text{mg/can}}{0.0755\ \text{m}^2} \quad (2)$$

8.4. Reference values

According to industrial data and Henkel guidelines (Henkel, 2023), acceptable etching values for 500 ml cans are presented in Table 1.

Table 1
Reference values for STD 500 ml cans

Surface (cm²)	Min (mg)	Avg (mg)	Max (mg)	Min (mg/m²)	Avg (mg/m²)	Max (mg/m²)
755	7.2	9.0	11.0	95	119	146

8.5. Experimental results

Measured values for five samples are given in Table 2.

Table 2
Experimental results of five can samples

Can	Mass before (g)	Mass after (g)	Loss (mg)
Sample 1	11.994	11.985	9
Sample 2	11.997	11.989	8
Sample 3	11.986	11.978	8
Sample 4	11.933	11.925	8
Sample 5	11.950	11.940	10
Total	59.860	59.817	43
Average: mg/can	/	/	8.6

Average values:

- Total loss: 43 mg
- Average mass loss per can = 43 mg / 5 = 8.6 mg/can.
- Total surface area (both sides) = 755 cm² = 755 / 10,000 = 0.0755 m².
- Etching rate = 8.6 mg / 0.0755 m² = 113.9 mg/m² ≈ 114 mg/m².

The average result of 8.6 mg/can (114 mg/m²) falls within the Henkel reference range (7.2–11.0 mg/can) and is very close to the industrial target average of 9.0 mg/can (119 mg/m²). Therefore, the measured etching attack can be considered normal and acceptable when compared with the reference values. Although slightly below the target average, it remains well within the specified tolerance limits.

9. Discussion

9.1. Relationship between Washer performance and final can quality

The efficiency of the Washer process directly influences the final quality of aluminum cans. Each stage-pre-washing, surface preparation, conversion coating, rinsing, and drying-contributes to contaminant removal, preservation of surface properties, and preparation for coating and printing.

The Etching Rate Test showed an average mass loss of 8.6 mg/can (114 mg/m²), which lies within the reference range (95–146 mg/m²). This confirms stable and controlled etching conditions. Controlled etching is essential for forming a uniform conversion coating, which directly reduces defects such as dome stain and neck peeling, ensuring reliable coating adhesion and corrosion resistance.

9.2. Impact on downstream process efficiency

Washer performance significantly affects subsequent production stages. Properly cleaned and dried cans enable better coating adhesion, improved print quality, reduced drying time, and higher packaging efficiency.

The experimental results indicate that the balance between fluoride concentration and FA/TA ratio provides optimal etching intensity. Excessive etching may weaken the conversion layer, while insufficient etching can lead to poor adhesion and increased defect rates. The obtained values confirm that chemical process control was well optimized, supporting efficient downstream operations.

9.3. Process risks and critical control points (oPRP)

Washer process risks, defined as oPRP (Operational Pre-requisite Programs), include mechanical damage, improper chemical treatment, transport instability, and cross-contamination between stages.

The experiment confirms that fluoride concentration and FA/TA ratio are critical for etching stability. Devi-

ations in these parameters may result in defects such as dome stain, neck peeling, and failures in functional tests (muffle and pasteur). Continuous monitoring and rapid corrective actions are therefore essential to maintain process stability and reduce scrap rates.

9.4. Future development and innovation

Future development of Washer systems focuses on improving resource efficiency and process control. Advanced chemical dosing systems, water recirculation, improved blow-off technologies, and sensor integration enable more precise operation.

Digitalization and real-time monitoring support predictive control, improving process stability, reducing chemical consumption, and minimizing environmental impact while maintaining product quality.

9.5. Quality vs. sustainability balance

Optimization of Washer processes must balance product quality and sustainability. Reduced consumption of water and chemicals should not compromise surface preparation quality. A well-controlled process, combining precise chemical management and efficient resource use, enables high product quality, minimal defect rates, and sustainable production. Achieving this balance remains a key objective for future technological development.

10. Conclusion

10.1. Summary of key findings

The analysis of the Washer process confirms that the quality and stability of all stages-pre-washing, surface preparation, conversion coating, rinsing, and drying-are essential for achieving high-quality aluminum cans. Continuous control of key parameters such as pH, conductivity, FA/TA ratio, fluoride concentration, and mobility additives ensures the formation of a uniform protective layer.

The experimental results (Etching Rate Test) confirmed stable and controlled etching conditions, supporting proper surface preparation and reducing the occurrence of defects such as dome stain, neck peeling, and transport-related issues. This demonstrates the strong link between chemical process control and consistent product quality.

10.2. Importance of the Washer in quality and sustainability

The Washer system represents a critical stage in aluminum can manufacturing, directly influencing surface quality and preparation for coating, printing, and packaging. Proper process control reduces defect rates, improves operational efficiency, and optimizes the consumption of chemicals, water, and energy. As such, the Washer plays a dual role-ensuring high product quality while supporting sustainable manufacturing. Balancing these aspects is essential in modern industrial production.

10.3. Recommendations for process improvement

To further enhance Washer performance, the following measures are recommended:

- Implementation of advanced monitoring and automated chemical control systems
- Regular maintenance and calibration of sensors and measurement instruments
- Optimization of water recirculation and consumption
- Continuous training of personnel regarding oPRP control points and quality testing procedures
- Introduction of digital and predictive process control systems

For future research, it is recommended to perform the Etching Rate Test on a larger sample size (≥10 cans) to improve statistical reliability and more precisely define the relationship between etching intensity, chemical control, and product quality.

11. Acknowledgment

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