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# Critical Analysis of Chemical Machining Setup Design using FMECA

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A B S T R A C T

*The Failure Mode, Effects, and Criticality Analysis (FMECA) approach enabled the prioritization of failure modes and implementation of targeted interventions, resulting in improved reliability, consistent machining quality, and process efficiency. This paper conducts a critical analysis of a chemical machining setup design using FMECA. The chemical machining is a material removal process where key parameters such as chemical concentration, temperature, and stirring play pivotal roles in product quality. The study identifies critical subsystems, including temperature monitoring, the main controller, and the stirrer, which are integral to maintaining process stability and quality. Quantitative assessment using the Risk Priority Number (RPN) revealed that temperature monitoring contributed approximately 47% to the overall system risk, highlighting its criticality. Corrective actions, including enhanced sensors, optimized stirring mechanisms, and improved insulation, significantly reduced RPN values. This analysis underscores the importance of robust design, precise parameter control, and predictive maintenance in chemical machining setups.*



## 1. INTRODUCTION

Failure mode and effect analysis (FMEA) technique is the process of reviewing as many components, assemblies, and subsystems as possible to identify early potential failure modes in a system and their effects and causes on the overall system or assembly. In FMEA techniques, initially the failure modes of each component and its effect on the system is recorded in FMEA worksheet. It was developed by reliability engineers in 1950's and initially used for reliability study of any system. FMEA technique can be applicable for any working system where if any one of the components fails what will be its effect on overall performance of the system, manufacturing process in which priority of process parameters is defined based on outcome parameters, initial design of system to identify the critical components in system.

Nadia Belu et. al [1] discussed the auto headlining and its functional design using FMEA technique. Designing of the autohead lining product considered the working environment and customer requirement such as isolating and protecting the binnacle and passengers against noise, shock, heat and must meet aesthetic requirements of the user. A FMEA worksheet prepared for above mentioned criterias during design of product with respect to constraints of its functioning and severity, occurrence and detections were defined to make a final decision about the product design criteria. J. Wurtenberger et. al. [2] studied the product development process dependency on level of information and quality of results available. Here FMEA technique is useful for early detection of mode of failure before the product development process to minimize the cost of rectification after failure. To identify an earlier mode of failure, the information of the product should be correct and of good quality. The quality of information depends upon the more specific answers to the questions like mode of failure, reason for occurrence, resulting damages, level of risk and remedies to resolve the problem. Use of pyramid model where at the bottom characterization of parts are considered and at top function part which is made up from all small sub assemblies and parts. Each sub level of the pyramid is characterized based on physical, chemical and biological effect on materials and geometrical parameters. The final decision on product development can be obtained by mapping the FMEA with characterized information received from pyramid levels. Benjamin Cabanes et. al. [3] elaborated application of FMEA in semiconductor industry for improving engineering reliability in product development. Author used C-K design theory as a theoretical framework. C-K design theory is both a unified theory of design and a theory of reasoning in design. C-K design theory allows to model innovative design as the interaction and the co-evolution of two interdependent spaces: the space of concepts [C] and the space of knowledge [K]. In this paper, C-K design theory is used both to analyze FMEA weaknesses and limits and to provide a new pragmatic tool for action.

Zhongi Wu et. al. [4] demarcated the system into three parts based on identification of potential failure modes a) entry point failure mode identification b) system failure mode identification and c) specification description of failure modes. For critical analysis of any system using FMEA, the entry point studies the physical interaction of subsystems and its functions in assembly, system failure mode identification uses the type of manufacturing methodology whereas specification description of failure modes focuses on documentation of manufacturing process. The information gathered from above methodology was critically analyzed using FMEA evaluation factors such as severity, occurrence and detection. L Y Zheng st. al. [5] developed a web based process management integrated system using FMEA applicable during process planning and product design. In this paper, shell design used in aerospace engineering was performed through integrated service. The integrated process is useful for gathering information related to process planning, product design and manufacturing. Hartomo Soewardi and Siska Ari Wulandari [6] analyzed the maintenance of sugar cane industrial machineries using FMEA. During study of sugar cane industry observed the various modes of failure such as broken hammer and cutter, loose mounting or in-balanced rotating parts which affects the overall performance of the system. Logic tree analysis (LTA) used to categorize the modes of failure to suggest the improvements. The improvement classification was based on safety, cost and type of problem. Author suggested periodic maintenance and proper documentation of it.

## 2. METHODOLOGY OF FMECA

FMECA is used to get the probability of failure mode for calculated severity of functional system or sub-system. The supporting data of failure modes are used to perform the critical analysis of a system or sub-system and may get results in the form of qualitative or qualitative. Following are the steps used to do critical analysis using FMEA for any system or subsystem [7-9],

I. Initially the system is discretized into functional subsystems which affects the working or overall performance of the system in case of failure. The severity factors are defined to subsystems based on the category of failure (system failed completely, partially or with no major effect).
II. The block diagram of the system will be prepared based on modes of failure and identification of different causes of failure which is used for doing the critical analysis of subsystems.

III. Now the system will be analyzed based on the effect of failure on it such as system fails permanently, degradation of performance of system over a period, system works partially. The severity is calculated based on the classification of failure modes on the scale of 1-10 based on table-1.

**Table 1.** Classification of severity.

| Category | Description | Criteria |
| --- | --- | --- |
| I | Catastrophic | Permanent and sudden failure of a system which couldn't be corrected. Failure may not be safe and hazardous to the environment. |
| II | Critical | Major damage to the system which results in costly rectification of the system. |
| III | Marginal | Minor damage to the system due to failure which can be rectified. |
| IV | Negligible | No immediate effect on the system and can be rectified over a period. |

IV. The ability of the system to detect the method of failure, report and analysis must be verified. A system should be able to identify the normal, abnormal and incorrect conditions.

V. The above analyzed modes of failure need to be ranked according to its probability of occurrence as mentioned in table-2. The criticality analysis may be qualitative or quantitative.

**Table 2.** Levels of failure probability.

| Level | Description | Probability of failure |
| --- | --- | --- |
| A | Frequent | Happens continuously |
| B | Probable | Happens many times |
| C | Occasional | Happens sometimes |
| D | Remote | Unlikely but chance to happen |
| E | Improbable | Unlikely and assumed will not happen |

VI. For quantitative assessment of criticality, the type of severity, detection level and occurrence probability will be considered and based on that Risk priority number (RPN) calculated.

VII. After completing the quantitative assessment of criticality, the FMECA matrix is prepared according to severity and quantitative criticality from which design parameters of the system can be finalized. The finalization of the system includes the reliability recommendation of each component of the system, and a feedback system to monitor the working of components in critical or stressed conditions. RPN calculation is an alternative method to criticality analysis [10].

## 3. CRITICALITY ANALYSIS OF CHEMICAL MACHINING SETUP

Chemical machining is selective removal of material from metallic work surfaces using acidic or alkaline etching solutions under controlled process parameters. In this process, the surface from which material is required to be removed is exposed to the chemical solution at predefined and maintained temperature and stirred continuously. In chemical etching process following process parameters play major role as mentioned below [11-13].

a) Concentration of chemical solution - It plays an important role during machining process hence it reacts with the work surface and removes the material. During machining operation, the removed material is stored and circulated in a process which reduces the concentration of chemical solution which needs to be continuously monitored and maintained.

b) Temperature of chemical solution during machining process - Chemical solution is heated in the range of 47$^0$C to 57$^0$C which increases the material removal rate (MRR). Higher the MRR lower will be surface finish (SF). So the temperature of chemical solution needs to be maintained to get better quality of product.

c) Monitoring and controlling the temperature of solution during machining process - in general, thermostats are used in most machines to regulate and maintain the required temperature.

d) Continuous stirring of chemical solution - It increases the MRR by removing/moving the removed material due to chemical reaction and exposes the new surface for etching and chemical reaction.

This paper focused on the critical analysis of components used in chemical machining setup which regulates the above parameters.

## 3.1 Working and block diagram of chemical machining setup

As explained, the chemical machining is selective removal of material from the exposed portion of the workpiece as shown in Fig.1. The workpiece is coated with photoresist material which is not required to be machined and immersed in chemical solution typically used are $FeCl_3$ and $CuCl_2$. The chemical solution reacts with workpiece surface and material removed as by products.

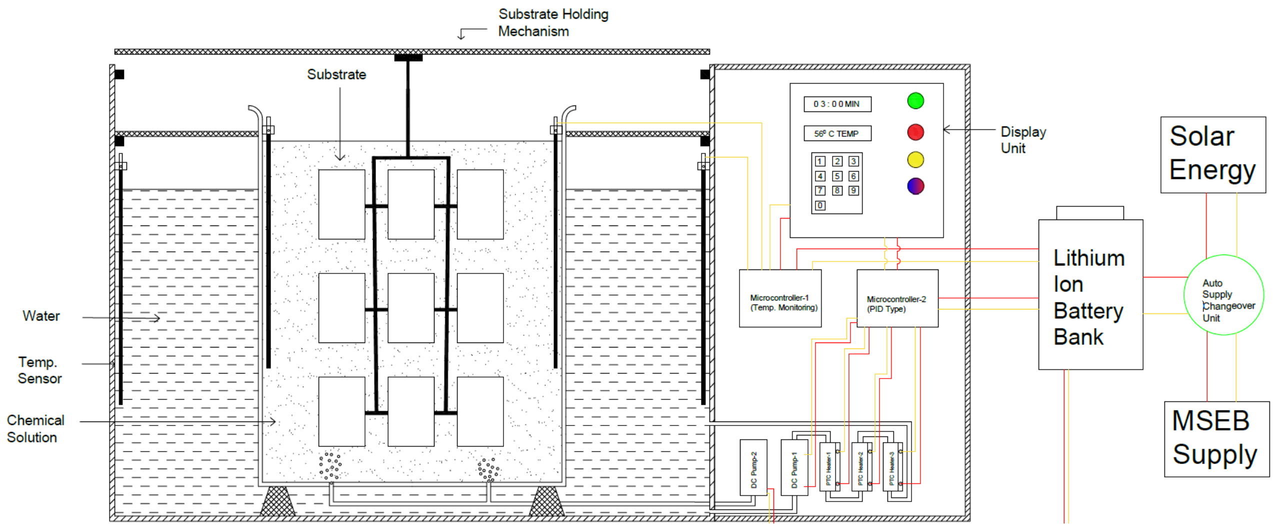



**Fig. 1.** Proposed Chemical Machining Setup.

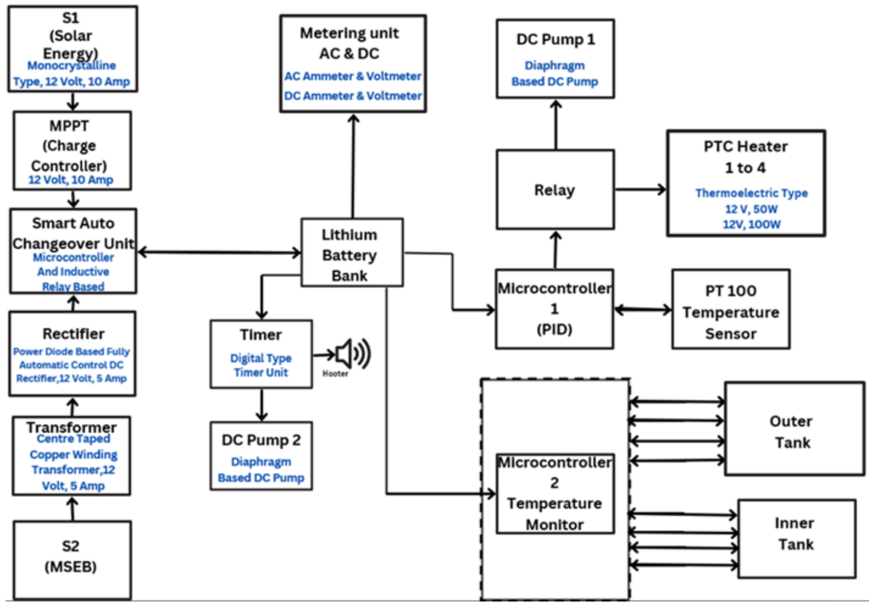



**Fig. 2.** Block diagram of chemical machining setup.

The setup of chemical machining consists of functional parts such as microcontrollers, temperature sensor which monitors temperature of solution, stirrer. The quality of the manufactured product using chemical machining setup depends upon the accuracy and working condition of all functional parts. In the chemical machining setup, the stirrer helps to remove the byproduct developed from the chemical reaction and remove it to get new surface exposed for reaction purpose, temperature sensor sends the signal to microcontroller for desired temperature and maintains it, control panel controls the time of chemical reaction and input of time and temperature. If any of the components of the setup malfunction it will result in poor quality of product manufactured. The design of chemical machining setup has the two different types of power supply which includes direct AC supply from transmission lines and DC supply obtained from solar panels. The AC and DC supply charges the lithium-ion battery and same can be used for the overall system.

### 3.2 Reasons affecting the quality of product and working of overall system

The quality of the chemically machined surface mainly depends upon the controlled parameters such as time, temperature, concentration, and continuous stirring of the chemical. The time of etching and concentration of chemical solution are independent parameters and could be controlled easily without any requirement of the control system. The control of temperature plays a major role in etching/machining of the component and its quality. Table-3 listed the different subsystems and components of the chemical machining setup which precisely controls the temperature of etching [14,15].

**Table 3.** Reasons affecting the quality of product.

| Major Components of Chemical Machining Setup Affecting the Quality of Product | | | Effect on Quality of Product |
|---|---|---|---|
| Temperature Monitoring System | Main Controller | Insulation | |
| • Incorrect Measurement of Temperature due to chemical deposition on Temperature Sensor<br>• Non-Uniform distribution of temperature of water and chemical bath.<br>• Loss of temperature signal in ADC (Analog to digital converter). | • Loss of signal to all electronics components of the system.<br>• Incorrect input and output of process parameters.<br>• Non-working of system indicators | • Heat transfer or water leakage through insulation. | Uncontrolled etching rate which compromises the quality of surface finish.<br><br>Non-working of stirrer causes the non-uniform chemical concentration which results in non-uniform MMR at different locations. |

The role of major components of chemical machining setup in controlling temperature which results in good surface finish as discussed below;

a) Temperature Monitoring System: As temperature plays an important role in etching rate, it should be controlled very precisely. The increase in temperature results in higher etching rate/ MRR which decreases the surface finish.

b) Main Controller: The main control system sends and receives the signal as per required temperature and time. The main control system controls the time required for machining and in case of uncontrolled time of machining, the large deviations in dimensions of components machined are observed.

c) Insulation: It avoids the transfer of heat and maintains the temperature.

All components of the etching system are linked to a lithium-ion battery for power supply. This battery is charged through both direct AC supply and solar DC power supply, which is regulated by an automatic changeover unit. The functionality of the entire system relies on effective charging and its associated parameters. Should any charging unit fail, it could lead to a complete system failure.

### 3.3 Quantitative assessment of criticality

The quantitative assessment of criticality of product calculated based upon the ratings given to severity, occurrence, detection and Risk Priority Number (RPN) as mentioned below [16].

a) Severity (S) is the hazard potential of the failure to the individual component and the system as a whole. It is numerically rated from 1 to 10, with 1 meaning no or very minor harm to the system and 10 for extremely dangerous effect on the system.

b) Likelihood of Occurrence (O) gives how likely a failure will occur. Again, a rating of 1 to 10 is assigned where 1 meaning “very unlikely to occur” and 10 meaning “failure is inevitable and persistent”.

c) Likelihood of detection (D) gives how likely the current control will detect the failure mode. Similar to above two parameters, a numerical rating of 1 to 10 is assigned to it, where 1 meaning “the failure will be detected very likely” and 10 meaning “the failure can’t be detected with current controls”.

d) Risk Priority Number (RPN) is the multiplication of the Severity, likelihood of occurrence and likelihood of detection. RPN is written as

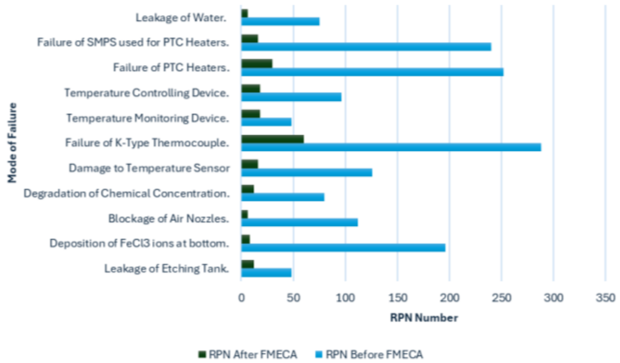
RPN = (Severity Rating) × (Likelihood of Occurrence rating) × (Likelihood of Detection rating)

Prioritizing Failure Modes by ranking their calculated RPN, giving priority to those with higher values and developing corrective actions by identifying and implementing corrective and preventive measures for the prioritized failure modes, including process improvements and quality controls. Monitoring and verification by carrying out the corrective actions and monitor their effectiveness to ensure a reduction in potential risk.

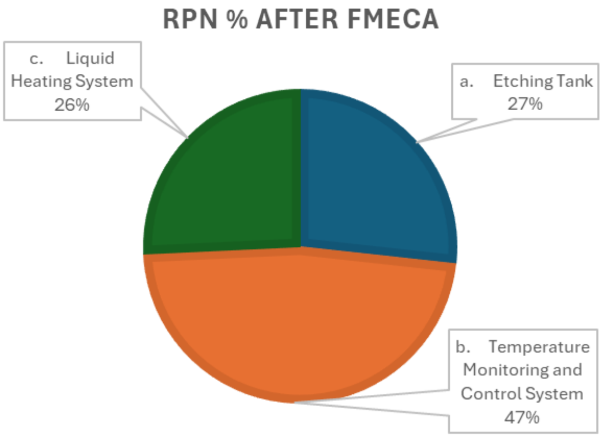
**Table 4.** FMECA Calculation of Chemical Machining Setup [17,18].

| Mode of Failure | Effect of Failure | S | Causes of Failure | C | Current Control Methods | D | RPN | Recommended Action | S | O | D | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **a. Etching Tank** | | | | | | | | | | | | |
| Leakage of Etching Tank. | Dilution of Chemical Solution, Wastage and Chemical Solution Effect on Other Electrical Components. | 8 | Excess Temperature and Pressure of Chemical Solution. | 3 | Joints Filled with Glues. | 2 | **48** | Use of Epoxy for Joint Filling and Periodic Inspection of Joints. Use of brackets for stronger joints. | 3 | 2 | 2 | **12** |
| Deposition of $FeCl_3$ ions at bottom. | No Uniform Chemical Concentration, Higher Etching Rate at Bottom of Workpiece. | 7 | No Proper Stirring of Chemical Solution. | 7 | Manual Stirring. | 4 | **196** | Placing the Air Nozzles at Bottom of Chemical Container. | 4 | 2 | 1 | **08** |
| Blockage of Air Nozzles. | Problem in Formation of Air Bubbles and Effect on Stirring Action which Results in Etching Rate/ MRR. | 8 | Deposition of $FeCl_3$ ions at Opening of Nozzles. | 7 | Manual Cleaning. | 2 | **112** | Periodic Replacement of Air Nozzles and Manual Cleaning. | 3 | 2 | 1 | **06** |
| Degradation of Chemical Concentration. | Reduces Etching Rate/ MRR. | 4 | Accumulation of Removed Material in Chemical Solution. | 4 | Change of chemical Solution when Material Removal Rate is Low. | 5 | **80** | Periodic Change of Chemical Solution based on MRR and Time Required for Etching or Addition of $FeCl_3$ ions to increase concentration. | 2 | 2 | 3 | **12** |
| Damage to Temperature Sensor | Improper Signal Sent to Main Controller. | 7 | Etching of Sensors used for Measuring Chemical Temperature. | 9 | Visual Inspection. | 2 | **126** | Visual Inspection and Trimming of Ends of Sensors. | 4 | 4 | 1 | **16** |
| **b. Temperature Monitoring and Control System** | | | | | | | | | | | | |
| Failure of K-Type Thermocouple. | Required Temperature will not be Maintained, Reduced Surface Finish. | 8 | Chemical Etching of Thermocouple. | 9 | Trimming the Ends of Thermocouple. | 4 | **288** | Covering of Ends of Thermocouple with Milinex Paper and Periodic Cleaning. | 3 | 4 | 5 | **60** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature Monitoring Device. | Temperature of Outer Tank and Inner Tank will not be Displayed. | 4 | Etching of Input Terminals due to Fumes of Chemical Solution. | 4 | Periodic Cleaning of Device. | 3 | **48** | Use of Separate / Enclosed Compartment for Device. | 2 | 3 | 3 | **18** |
| Temperature Controlling Device. | Required Temperature will not be Maintained, Reduced Surface Finish. | 8 | Etching of Input Terminals due to Fumes of Chemical Solution. | 4 | Periodic Cleaning of Device. | 3 | **96** | Use of Separate / Enclosed Compartment for Device. | 2 | 3 | 3 | **18** |
| c. **Liquid Heating System** | | | | | | | | | | | | |
| Failure of PTC Heaters. | No Heating/ More time required for Heating of Water. | 9 | External Damage and Wire Cut. | 4 | Separate Mounting Arrangement | 7 | **252** | Separate Compartment for PTC Heater and Piping Assembly. | 5 | 2 | 3 | **30** |
| Failure of SMPS used for PTC Heaters. | No Power Supply to PTC Heaters. | 8 | Overload, Voltage Fluctuation and Overheating. | 6 | Openings for ventilation and cooling | 5 | **240** | Use of Exhaust for Cooling of SMPS. | 4 | 2 | 2 | **16** |
| Leakage of Water. | Heat Loss and Damage to Electrical Circuits. | 5 | Excess Water Pressure and Higher Flow Rate and Improper Coupling. | 5 | Visual Inspection and Repairing. | 3 | **75** | Proper Joints Filling and Periodic Testing. | 3 | 2 | 1 | **06** |




(a)




(b)

**Fig. 3.** (a) Comparison of RPN before and after FMECA and (b) Contribution Failure Type on System Based on RPN.

Table-4 shows the FMECA calculation based on the major components of chemical machining setup which consist of etching tank, temperature monitoring and control system and liquid heating system. For each major component of the system, the different modes of failures are considered and FMECA performed. The application of FMECA shows the significant reduction in the chances of failure as shown in Fig. 3 (a), whereas the contribution of temperature monitoring system is approximately 47% based on the RPN number calculations as shown in Fig. 3(b).

## 4. RESULTS AND DISCUSSION

The FMECA analysis of the chemical machining setup provided a structured assessment of the critical components and their impact on the system's performance. The findings emphasize the significance of temperature control, stirring efficiency, and system reliability in achieving optimal machining quality.

The quantitative assessment using the Risk Priority Number (RPN) shows that temperature monitoring plays a crucial role, contributing approximately 47% of the overall risk to system reliability. This highlights the susceptibility of the process to temperature deviations, which can arise from issues such as incorrect temperature measurements, non-uniform temperature distribution, or signal loss in the Analog-to-Digital Converter (ADC). These deviations lead to uncontrolled etching rates, negatively impacting surface finish and dimensional accuracy. Similarly, the stirrer, responsible for ensuring uniform chemical concentration and effective removal of reaction byproducts, was identified as a critical subsystem. A malfunctioning stirrer results in non-uniform Material Removal Rate (MMR), leading to inconsistencies across the machined surface. This reinforces the need for robust stirring mechanisms and monitoring systems. The main control system also emerged as a vital component, governing the process's precision by regulating machining time and temperature. Failures in the controller can lead to significant deviations in the dimensions of machined components and overall quality. Additionally, insulation was found to be essential for maintaining temperature stability, preventing heat loss, and ensuring consistent process conditions. The dual power supply system, utilizing both AC and solar DC power sources, contributes to system reliability. However, any failure in the lithium-ion battery or its charging mechanism could result in total system failure, underlining the importance of reliable power management. The analysis also identified the need for improved maintenance and inspection protocols for the power supply and charging units.

The application of FMECA demonstrated its effectiveness in identifying and prioritizing failure modes. Corrective actions, such as implementing advanced sensors, improving insulation, and optimizing stirring mechanisms, resulted in a notable reduction in RPN values, as depicted in Figure 3(a). This reduction indicates a significant decrease in the likelihood of system failures. The systematic prioritization of failure modes enabled targeted interventions, which improved the overall reliability and quality of the chemical machining process.

## 5. CONCLUSION

The FMECA analysis identified temperature monitoring as the most critical subsystem, contributing to 47% of the total risk due to its significant impact on etching rates and surface finish. Other essential components include the stirrer for maintaining chemical uniformity, the main controller for process regulation, and reliable insulation for temperature stability. The dual power supply system enhances reliability but poses a risk if the battery or charging system fails. By prioritizing failure modes using RPN and implementing targeted corrective actions, the study achieved improved process reliability and product quality. This analysis underscores the importance of precise control, robust components, and predictive maintenance for enhancing the chemical machining setup's overall performance.

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