

A Fuzzy FMEA-Based Approach for Risk Analysis in Car Body Spot Welding Processes

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Article Information	ABSTRACT
Article History Received : March 09, 2026 Revised : March 26, 2026 Published : April 10, 2026	The spot welding process using robotic systems is associated with a high risk of failure, including spot weld release, spatter, missed welds, unavailable weld spots, missing brackets, porous welds, double welds, incorrect weld positions, and sliding joint parts. This study aims to enhance risk assessment in spot welding by integrating fuzzy logic inference with Failure Mode and Effects Analysis (FMEA) to overcome the limitations of conventional FMEA in handling uncertainty and ambiguity. The proposed model incorporates fuzzy representations of severity, occurrence, and detection parameters to calculate the Fuzzy Risk Priority Number (FRPN) through three stages: fuzzification, fuzzy inference, and defuzzification. A case study was conducted in the spot welding process of automotive body components in Karawang, using real process data and expert validation. The results show that FRPN values range from 3.95 to 6.38, with the highest risks identified in spot weld release (FRPN = 6.38) and incorrect weld position (FRPN = 6.29), indicating that these failure modes are the top priorities for corrective actions. Furthermore, the fuzzy FMEA approach provides better discrimination of risk levels compared to conventional FMEA, particularly in differentiating failure modes with similar RPN values, thereby improving the accuracy and reliability of risk prioritization.
Keywords: <i>Fuzzy FMEA; Manufacturing process; Risk analysis.</i>	

INTRODUCTION

The automotive industry demands strict adherence to safety and quality standards, particularly for critical systems in car body components (Stasiak-Betlejewska & Ali, 2024)(Ali & Jaqin, 2024). Car body parts are essential in vehicle structures but are highly susceptible to dents, distortions, and cracks, making the stamping process critical. Defects during this process can lead to high scrap rates and reduced product quality (Sumasto et al., 2024)(Belyaeva et al., 2024). When a component fails to perform its intended function, it can compromise both vehicle performance and safety. Therefore, tools that can effectively identify potential failure risks during production are essential (Fadhllullah et al., 2024).

Although FMEA traditionally has advantages in preventing potential risks, it has weaknesses when applied (citation). These weaknesses include uncertainty and ambiguity in assessments, especially in determining the severity, occurrence, and detection weights (Razzaq et al., 2024)(Karatop et al., 2021). This results in inaccurate RPN values. A higher RPN value is considered to have a more significant potential for failure than a potential for failure with a low

RPN value. However, this traditional RPN model has attracted a lot of criticism (Ali & Jaqin, 2024; Chung et al., 2024; Valipour et al., 2022).

The integration of FMEA and fuzzy logic has been extensively developed by researchers to improve upon the weaknesses of traditional FMEA. Combined research on the FMEA method and fuzzy logic to assess risks in solar-powered pumps (Sun et al., 2025). This integration clarifies the uncertainty of failure risk assessment compared to traditional FMEA. In the field of occupational safety and health, the use of fuzzy logic creates artificial neural networks and genetic algorithms that can clarify uncertainty with the aim of improving work safety (Mitrakas et al., 2025). In the field of automotive research, the use of fuzzy logic and FMEA clarifies the uncertainty of experts in assessing the risk of production process failures (Razzaq, 2024). Fuzzy FMEA helps make accurate decisions on which failures to prioritize. The combination of AHP and FMEA for logistics industry optimization (Panudju et al., 2024). This combination of methods is more comprehensive for assessing failure risks because the decision-making results are more accurate.

This study uses a new approach employing fuzzy logic to analyze detection, severity, and occurrence parameters by refining existing literature with consideration of risk impact. Traditional FMEA risk assessment relies on expert experience. The data obtained is more difficult to process because the assessment data is in the form of linguistic assessments (Kodaloğlu et al., 2025). Therefore, this study converts linguistic data processed with fuzzy logic and parameters formed with fuzzy inference.

The literature has shown the benefits of fuzzy logic and FMEA in various fields, but there is a significant gap in the combined application of the two in the automotive industry. This study addresses this gap by combining fuzzy logic and FMEA to solve potential risk in the welding process of car component production. The methodology used has the advantage of improving the accuracy of risk assessment and providing tools for quality assurance experts to make priority action decisions. With the advantages of combining the FMEA and fuzzy logic methods and overcoming their limitations, this research has an impact on the advancement of risk assessment methods in the automotive industry sector.

RESEARCH METHODS

Material

In the preparation stage of traditional Failure Mode and Effect Analysis (FMEA), this study was conducted through several systematic steps to ensure data validity. First, direct observations were carried out on the car body production process. Re-evaluated after 6 months starting from the raw material stage to the final quality inspection stage, in order to obtain a comprehensive understanding of the process flow (Najafpour et al., 2017). Second, based on the results of these observations, potential failure modes and their corresponding effects were identified (Valdes, 2014). Third, to obtain objective assessments of the FMEA parameters, interviews were conducted with 10 experts who possess relevant experience and expertise to determine the values of severity, occurrence, and detection. This approach was employed to ensure that the resulting data have an adequate level of accuracy and reliability (Goble, 2012).

In determining the priority of potential failures, it is determined from the RPN value which is calculated based on the Risk-indexed parameters Detection, Severity, Occurrence (Duan et al., 2024). Welding spot failure data were evaluated using the FMEA framework as shown in Table 1, where Risk Priority Numbers (RPN) were calculated based on severity, occurrence, and detection ratings (Ccopa Ibarra et al., 2024).

Table 1. Failure Mode and Effect Analysis Welding Spot

Potential Failure	The Impact of Failure	S	Causes	O	Detection	D	RPN
Spot Releases	Safety risk	7	Cup tip out / dirty, There is a gap in the part Cup tip is tilted / not centered	7	Tagane test	5	294
Spot Spater	Endangering the operator	5	There is a gap in the spot area. (accuracy part defect)	5	Visual Inspection dan marking check	5	125
Missed Spot	The strength of the small welding part	7	The positioning gun is not right.	3	Visual Inspection dan marking check	6	105
Spot Not Available	Performance part has decreased	7	The spot process was missed.	3	Visual Inspection and marking check	5	126
Bracket Not Available	Part cannot be processed assembly	7	Bracket not installed	3	Visual Inspection and marking check	5	105
Hollow spot	Performance part has decreased	7	Overheating / over parameter	3	Visual Inspection and marking check	5	105
Double spot	Appearance part defect	5	The cup tip is not in the center	3	Visual Inspection and marking check	5	75
Wrong Position Spot	Performance part has decreased	5	The position of the gun is not correct during the process	3	Visual Inspection and marking check	5	245
Sliding joint part	Part cannot be processed assembly	7	Pin out, broken pin, no pin, sliding pin	5	Visual Inspection	7	175

Method

Fuzzification of inputs and output

The stages of the fuzzy FMEA system include fuzzification of inputs and outputs, definition of fuzzy rules, combination of fuzzified inputs and rule consequences—the fuzzy inference process, and defuzzification of outputs from Godina's adapter, as shown in Figure 1.

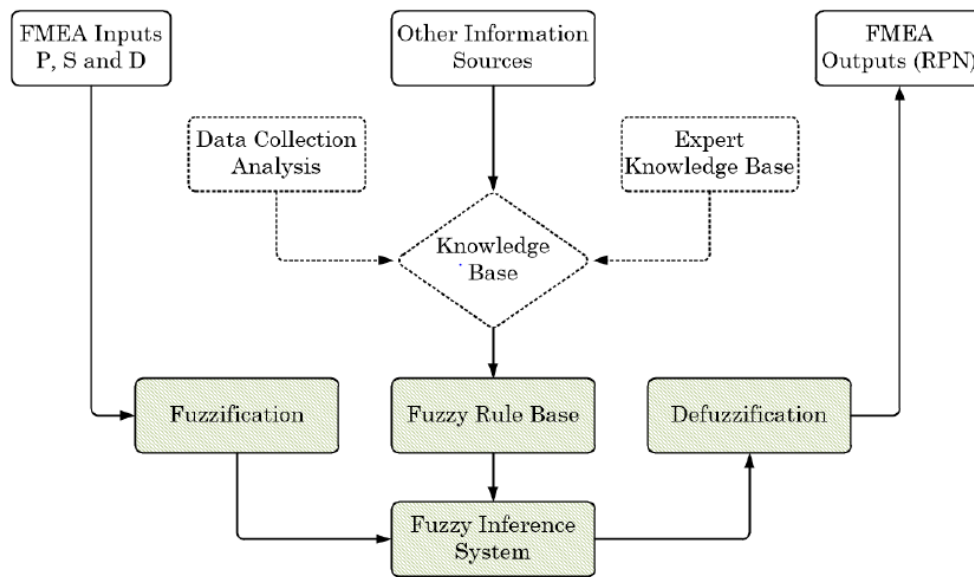


Figure 1. Fuzzy inference system

The fuzzification process converts numerical values into linguistic values that indicate the degree of membership of a fuzzy set. Fuzzification softens the boundaries of severity, occurrence, and detection values from rigid to ambiguous. Razzaq et al, 2024 (Razzaq et al., 2024) grouped Occurrence Criteria there are 10 ranks where the probability of occurrence is > 1 in 4 and > 1 in 6 failure category is very high, the possibility of 1 in 15 and 1 in 25 category is high, the possibility of 1 in 100 and 1 in 300 category is moderate, the possibility of 1 in 1500 category is low, the possibility of 1 in 2000 is very low and the possibility of 1 in 2500 category is remote. Detection Criteria has a rating of 1 - 10 which consists of linguistic almost certain, very high, high, moderately high, moderate, low, very low, remote, very remote, almost impossible where each Linguistic has evaluation criteria. While for Severity Criteria there is also a rating of 1 - 10 which consists of none, very minor, minor, very low, low, moderator, high, very high, hazardous warning, hazardous. FMEA risk scale presented in Table 2 (Karatop et al., 2021)

Tabel 2. Fuzzy Output Setting

Rating Scale	S	O	D	FRPN
10	Medium	High	Medium	Medium
9	Low	Very High	Low	Medium
8	Critical	Very High	Low	Very High
7	High	High	Medium	Very High
6	Medium	Medium	High	High
5	Low	Low	Very High	Low
4	Medium	Very High	Very High	Very High
3	High	High	High	Very High
2	Medium	Medium	Medium	Low
1	Low	Low	Low	Low

Fuzzy rules are useful for inferring expert judgment information that aims to reproduce human reasoning in solving complex systems (Godina et al., 2021). The data was obtained based on interviews and discussions. Figure 2 shows the combination of inputs and outputs of fuzzy inferences processed using MATLAB 2018a.

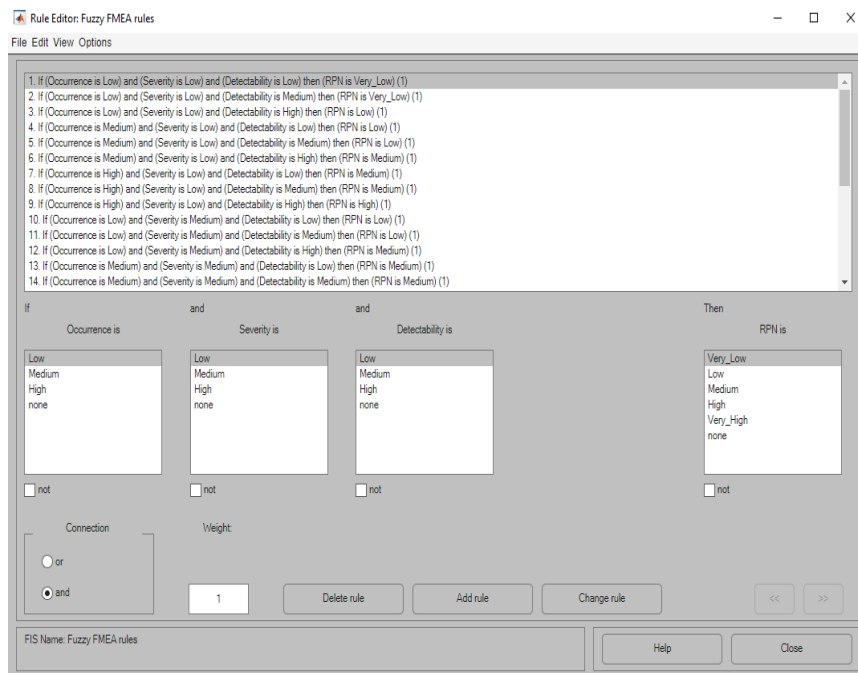


Figure 2. Partial View of The Inference Rules in MATLAB 2018

Fuzzy Inference System

Figure 3 show The Fuzzy Inference Process used technique provides an overview of the potential occurrence of possible failures indicated by the same RPN value. This technique is useful for reducing the problem of prioritizing RPN values. Razzaq et al 2024 (Razzaq et al., 2024) made an equation to calculate the RPN value on the number of potential failures with detection, occurrence and severity represented by K_{xy} where $x = 1, 2, 3, \dots, n$ and $y = 1, 2, 3, \dots, n$. then the order scale of detection, occurrence and severity is shown in table 1,2,3.

$$RPN = \prod_{x,y=1}^n K_{xy} \quad (1)$$

Where $1 \leq x \leq y; 1 \leq y \leq n;$

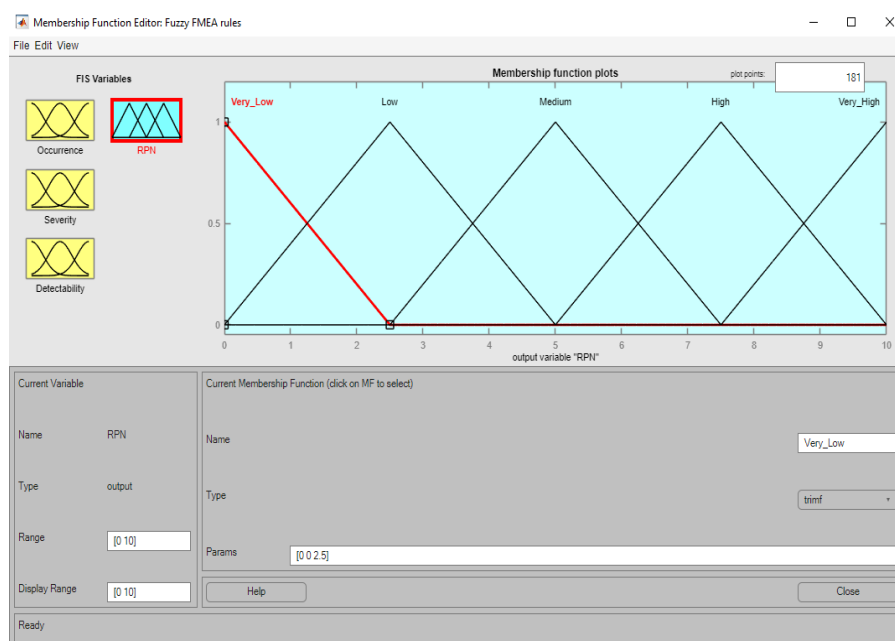


Figure 3. Surface Reviewer

Defuzzification

Defuzzification is the final stage in the fuzzy inference process, where the values of the process set are converted back to real units. This process produces a ranking of potential failure risks. There are several defuzzification methods based on the literature (Ahmed et al., 2021)(Kalaifarasi et al., 2021). The defuzzification method must be able to reduce disambiguity (produce a single value), plausibility (center of area), and computational simplicity (Borges et al., 2018). The method used is the center of gravity (COG), which has the advantages of sensitivity to the length and width of the overall fuzzy region, as well as subtle variations in the expected final value for the output value, among other characteristics (Yuan et al., 2011)(Sain & Mohan, 2021). COG calculates the average of the fuzzy region that explains the output with the x-axis point dividing the fuzzy region into two equal subregions, as shown in equation (2):

Where x is support value where the membership function reaches its maximum value, $\mu_i(x)$ is membership degree of the function.

$$\text{COG} = \frac{\sum \mu_i(x) \times \mu_i}{\sum \mu_i(x)} \quad (2)$$

Fuzzy Risk Priority Number (FRPN) is used to determine corrective actions to address potential failures. The FRPN value is determined based on the severity, frequency, and detection values calculated by setting linguistic variables. Severity, frequency, and detection use a scale of 1 to 10 (Şengül et al., 2015)(Dumitrascu & Dumitrascu, 2024). MATLAB R2018a has developed a Fuzzy-FMEA assessment model with an inference system calculation mechanism as shown in Figure 4.

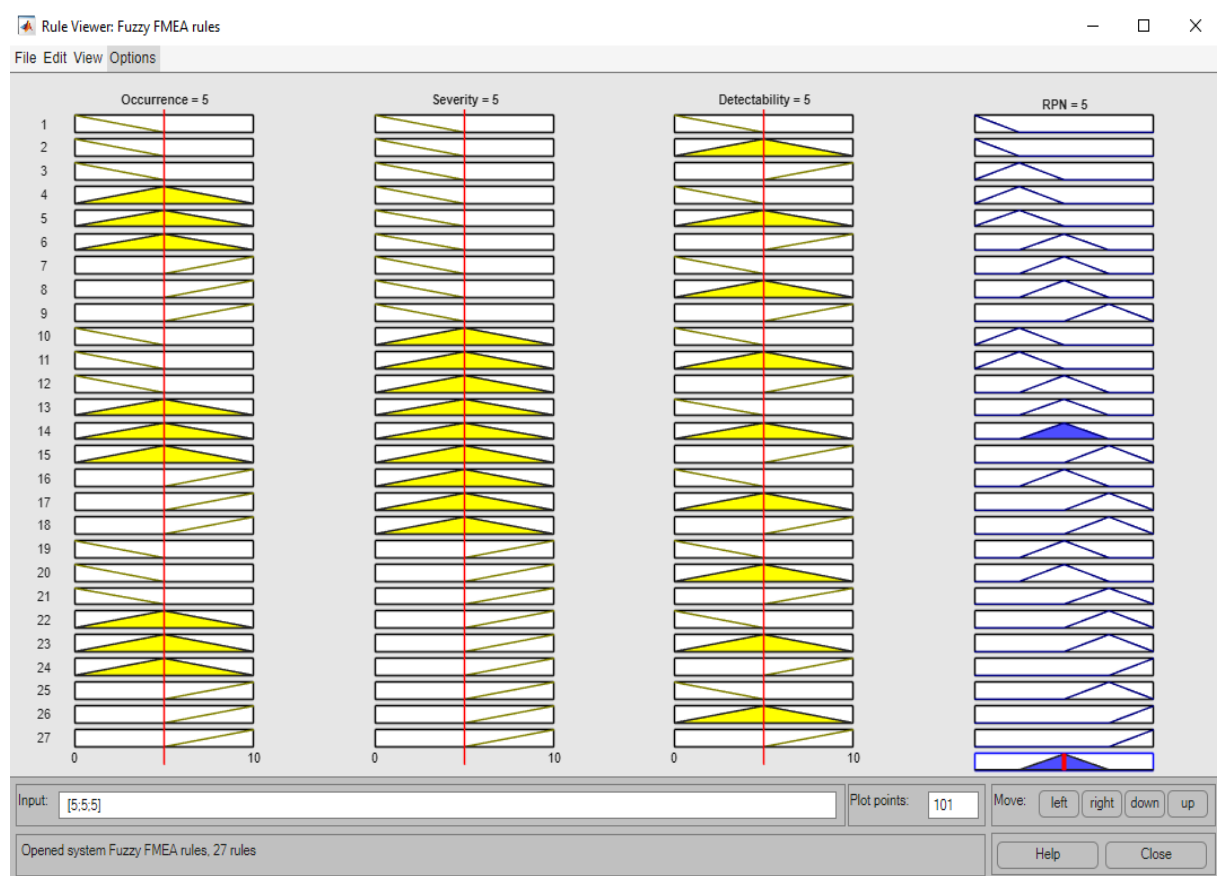


Figure 4. Defuzzification Result

RESULTS AND DISCUSSION

Result comparison and validation between the fuzzy-FMEA and conventional FMEA method

The fuzzy FMEA method has advantages over traditional FMEA in that it has a higher sensitivity level. In addition, the combination of fuzzy logic and FMEA produces a more accurate RPN rating. This study obtained risk assessment results which are summarized in Table 3. Fuzzy output settings. These results show that fuzzy FMEA can improve on the shortcomings of traditional FMEA in the spot welding process.

Table 3. Fuzzy output settings

Potential Failure	The Impact of Failure	Causes	S	O	D	RPN	FMEA Ranking	Fuzzy RPN	Fuzzy FMEA Ranking	Fuzzy RPN Classification
Spot Releases	Safety risk	Cup tip out / dirty, There is a gap in the part Cup tip is tilted / not centered	7	7	5	294	1 st	6.38	1 st	Important
Spot Spater	Endangering the operator	There is a gap in the spot area. (accuracy part defect)	5	5	5	125	5 th	5	8 th	Low Important
Missed Spot	The strength of the small welding part	The positioning gun is not right.	7	3	6	105	6 th	5.12	5 th	Average Important
Spot Not Available	Performance part has decreased	The spot process was missed.	7	3	5	126	4 th	5.05	7 th	Low Important
Bracket Not Available	Part cannot be processed assembly	Bracket not installed	7	3	5	105	6 th	5.07	6 th	Low Important
Hollow spot	Performance part has decreased	Overheating / over parameter	7	3	5	105	6 th	5.18	4 th	Average Important
Double spot	Appearance part defect	The cup tip is not in the center	5	3	5	75	7 th	3.95	9 th	Low Important
Wrong Position Spot	Performance part has decreased	The position of the gun is not correct during the process	5	3	5	245	2 nd	6.29	2 nd	Important
Sliding joint part	Part cannot be processed assembly	Pin out, broken pin, no pin, sliding pin	7	5	7	175	3 rd	6.05	3 rd	Average Important

Table 4. Prioritization obtained by classic FMEA and fuzzy FMEA.

FMEA Ranking	Classic FMEA	Fuzzy FMEA
1 st	Spot Releases	Spot Releases
2 nd	Wrong Position Spot	Wrong Position Spot
3 th	Sliding joint part	Sliding joint part
4 th	Spot Not Available	Hollow spot

The results of this study demonstrate that the application of fuzzy FMEA provides a more robust and sensitive risk assessment compared to traditional FMEA, particularly in addressing uncertainty and improving the accuracy of risk prioritization. In conventional FMEA, the use of crisp values for severity, occurrence, and detection often limits the ability to distinguish between failure modes, especially when identical Risk Priority Number (RPN) values are obtained. This limitation was also observed in the present study, where the failure modes “Bracket Not Available” and “Hollow Spot” yielded the same RPN value of 105, potentially leading to ambiguity in decision-making. Such findings are consistent with previous studies, which have highlighted the limited discriminatory capability of traditional FMEA in complex manufacturing environments. By contrast, the implementation of fuzzy FMEA in this study effectively overcomes these limitations through the integration of fuzzy logic, utilizing linguistic variables and membership functions. This approach enables a more flexible and gradual evaluation of risk parameters, thereby improving the differentiation among failure modes. For example, although “Bracket Not Available” and “Hollow Spot” share identical RPN values under the traditional approach, the fuzzy FMEA method assigns distinct priority rankings, with “Hollow Spot” ranked fourth and “Bracket Not Available” ranked sixth. This outcome indicates that fuzzy FMEA reduces ambiguity and enhances the precision of risk prioritization, which is critical for determining appropriate corrective actions.

Furthermore, the observed shift in ranking, particularly the increase in priority of the “Hollow Spot” failure mode from sixth position in traditional FMEA to fourth position in fuzzy FMEA, highlights the higher sensitivity of the fuzzy approach in capturing subtle variations in risk levels. This finding is in agreement with prior research, including Ervural and Ayaz (2023), which reported that fuzzy inference systems improve the sensitivity of risk evaluation by accounting for the degree of membership of each parameter rather than relying solely on fixed numerical scales. Consequently, the resulting risk assessment is more representative of real-world conditions, especially in processes characterized by high uncertainty and variability, such as spot welding.

The findings of this study not only corroborate existing literature regarding the advantages of fuzzy FMEA over traditional methods but also provide empirical evidence of its effectiveness in the context of car body spot welding processes. By delivering a more accurate, sensitive, and less ambiguous evaluation of risk, fuzzy FMEA supports improved decision-making in prioritizing failure modes and formulating corrective actions, ultimately contributing to enhanced process reliability and product quality.

Risk Mitigation and Suggestion

Identification and evaluation of risks in the spot welding process have been carried out on the two most risky processes, namely Spot Releases and Wrong Position Spot. Based on this, preventive and corrective measures have been proposed to reduce the impact of these two risks.

Managing risk in the spot release

The cause of potential spot release can be caused by dirty / worn welding cup tips. Worn cup tips cause the weld quality to decrease because the worn electrode tip will change shape wider. Visually, the size of the nugget is not standard, it can be smaller or wider in diameter. In addition,

when the part receives the load that occurs, the strength of the connection becomes weak. Dirt contaminating the tip of the cup tip will become an electrical resistance between the workpiece and the electrode so that the electrical energy that will turn into heat is not efficient for metal melting. The heat from the electricity only burns the surface of the electrode and metal. A cup tip dresser or tip dresser is a tool that serves to clean the dirt or coating that is on the tip. Each cup tip has performed spot operations as many as 500 points so it needs to be dressed. In the case study, the cup tip dresser process uses the manual tip dresser method operated by the operator manually. This dresser method is intended for low production volume and maintenance activities.



Figure 5. Cup Tip

Managing risk in wrong position spot

The risk of wrong position spot can be prevented by performing regular calibration on the robot axis. This is to ensure that the robot performs welding operations accurately and precisely at the appropriate point. Calibration will correct position shifts on the tool center point (TCP) and return the axis to its reference position so that the robot's movements remain accurate (Galindo-Salcedo et al., 2022). For high-frequency robot welding operations, calibration can be scheduled weekly to inspect the Tool Center Point (TCP) to ensure there are no significant shifts in the welding point. Monthly or quarterly calibration is recommended for strict operations with many critical points. Annual calibration is sufficient for welding robots operating under stable conditions.

CONCLUSION

This study develops a fuzzy FMEA approach to evaluate potential failure risks in the spot welding process by integrating fuzzy logic with conventional FMEA. The proposed method addresses the limitations of traditional FMEA, particularly in handling ambiguity and improving the accuracy of risk prioritization. The results show that the fuzzy FMEA model produces more reliable and discriminative RPN values, enabling clearer identification of critical failure modes, including spot release, wrong position spot, sliding joint part, and hollow spot. In addition, the incorporation of expert knowledge through fuzzy inference enhances the representativeness of real process conditions. Therefore, this approach provides a more effective decision-support tool for prioritizing risks and determining appropriate mitigation strategies, contributing to improved reliability and quality in robotic spot welding processes.

Future research should prioritize the advancement of the fuzzy FMEA framework through several key directions. First, the development of more sophisticated risk factor weighting and aggregation techniques is necessary, particularly by exploring hybrid approaches that capture interdependencies and the relative importance of risk parameters, such as the integration of fuzzy SWARA, fuzzy TOPSIS, and picture fuzzy sets. Second, addressing uncertainty and subjectivity remains essential; thus, the incorporation of adaptive and data-driven models, such as the Adaptive Neuro-Fuzzy Inference System (ANFIS), is recommended to enhance the predictive capability and robustness of risk assessments under dynamic conditions. Finally, comprehensive validation through real-world and longitudinal case studies across diverse industrial sectors is required to assess the consistency, applicability, and generalizability of advanced fuzzy FMEA models, thereby strengthening their practical relevance and reliability.

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