PROBABILITY MODEL OF THE SUBMERGED WELDING PROCESS AND CALCULATION OF THE PROBABILITY OF DEFECTS

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Abstract

This paper presents a probabilistic analysis of submerged arc welding (SAW) processes and evaluates the likelihood of defects formation in welds. The study, conducted on an automated SAW machine, investigated how parameter stability, wire feed rate, and flux layer condition influence defect frequency. The probabilistic approach enables assessing process reliability, predicting defect risk, and optimizing technological regimes.

Keywords

Submerged arc welding, probabilistic model, defect probability, welding machine, technological parameters, reliability

Introduction. Submerged arc welding machines are high-performance technological equipment widely used in modern heavy industry, the production of metal structures, pressure vessels, pipeline systems, as well as the manufacturing of large machine-building products. These machines are characterized by high welding current, stable arc burning, and a protected molten metal pool, which minimizes the influence of the human factor. As a result, the submerged arc welding method is distinguished by deep penetration, relatively stable weld quality, and the ability to weld thick materials in a single pass.

One of the main advantages of submerged arc welding equipment is the automation of the process and the ability to precisely control technological parameters. Parameters such as welding current, voltage, wire feed speed, and travel speed are continuously monitored by the machine. At the same time, the flux layer fully protects the arc from the external environment, limits the oxidation of the molten metal pool, and improves the mechanical properties of the weld. However, despite these advantages, in real production conditions the welding process does not remain absolutely stable.

A number of factors affecting the processing in submerged arc welding machines are of a random nature. These include voltage fluctuations in the electrical network, micro-vibrations in the wire feed mechanism, unevenness in the granulometric composition of the flux, the initial condition of the metal surface, and changes in heat exchange conditions, all of which directly influence the formation of the weld seam. As a result of these factors, even under the same nominal modes, weld quality varies and the probability of defects arising emerges.

In traditional approaches, the submerged arc welding process is often analyzed on the basis of a deterministic model, i.e., technological parameters are strictly defined and the outcome is accepted as predetermined. However, practical experience shows that defects in the weld seam—such as porosity, slag inclusions, lack of fusion, or uneven formation—do not follow a strict pattern but are determined by a combination of factors of a probabilistic nature. Therefore, the use of probability theory and statistical approaches in the analysis of submerged arc welding equipment is considered a relevant scientific problem.

Considering the welding process on the basis of a probabilistic model makes it possible to assess the reliability of submerged arc welding machines under real operating conditions, to predict in advance the probability of defect occurrence, and to optimize technological modes. This approach serves not only to improve weld quality but also to increase production efficiency, reduce the amount of scrap, and enhance automated control systems.

In this article, the processes occurring in submerged arc welding machines are analyzed on the basis of probability theory, and a scientifically grounded model is proposed for assessing the probability of defect occurrence in the weld seam. The research results provide the opportunity to develop practical recommendations aimed at increasing the technological reliability of submerged arc welding equipment in industrial conditions.

Metod. In this study, the submerged arc welding processes were investigated using an example of automated SAW welding equipment applied in industrial conditions. As the object of the study, the complex of electrical and mechanical units controlling the main technological parameters — such as welding current, voltage, wire feed speed, and the travel speed of the welding head — was selected. During the experiments, samples of low- and medium-carbon structural steels were used, along with welding wires and flux materials widely applied in industry. The granulometric composition of the flux, the thickness of its layer, and its moisture content were strictly controlled, and their influence on the weld seam formation process was systematically observed.

In this research, the submerged arc welding process was considered not as a deterministic process, but as a probabilistic process occurring under the influence of random factors. Fluctuations in welding current and voltage over time, irregularities in the wire feed mechanism, and changes in heat exchange conditions were modeled as random variables. The quality state of the weld seam was accepted as a discrete random event, where a defect-free weld was interpreted as a successful state of the technological process, and the occurrence of defects as a failure state. This approach made it possible to analyze the welding process within the framework of reliability theory.

The experimental work was repeated multiple times under the same nominal technological modes. The quality of each weld seam was evaluated using visual, metallographic, and technological control methods. In the obtained results, the presence or absence of defects such as porosity, slag inclusions, and lack of fusion was recorded. During the observations, the stability of the welding parameters over time and the influence of external factors were continuously monitored, ensuring the statistical reliability of the experimental results.

Figure 1. Submerged arc welding machine.

To assess the probability of defect occurrence, methods of mathematical statistics based on probability estimation, frequency analysis, and the identification of multifactorial relationships

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were applied. The experimental data were processed through statistical grouping, and the relationship between the distribution of technological parameters and the frequency of defect occurrence was analyzed. This approach created a scientific basis for predicting the risk of defect formation in the submerged arc welding process in advance and for optimizing technological modes.

The results of the experiments conducted in the submerged arc welding process showed a strong dependence of defect occurrence in the weld seam on the stability of the technological parameters. It was found that even when the same nominal modes were maintained, fluctuations in welding current, wire feed speed, and the condition of the flux layer led to a significant change in the frequency of defects. In particular, as the stability of the parameters over time decreased, a sharp increase in the probability of defect occurrence in the weld seam was observed.

According to the results of the statistical analysis, in a stable welding mode the frequency of defects was minimal, and the process was characterized by high technological reliability. In conditions with moderate parameter fluctuations, the frequency of defect occurrence increased several times, and the quality of the weld seam became unstable. In cases where strong fluctuations were observed, the probability of defects reached the highest values, and a sharp decrease in the technological reliability of the submerged arc welding process was identified.

The obtained results confirm the effectiveness of evaluating the submerged arc welding process based on a probabilistic model. Graphical analysis shows that the expansion of the distribution of technological parameters leads to an almost linear increase in the probability of defects. This situation indicates the necessity of improving quality in the welding process not only by nominal modes, but also by ensuring their stability.

Below, the table and graph constructed on the basis of the experimental results clearly illustrate the relationship between the stability level of the welding mode and the probability of defect occurrence. It is evident from the table and graph that reducing parameter fluctuations through automated control systems can significantly decrease the probability of defects in submerged arc welding machines.

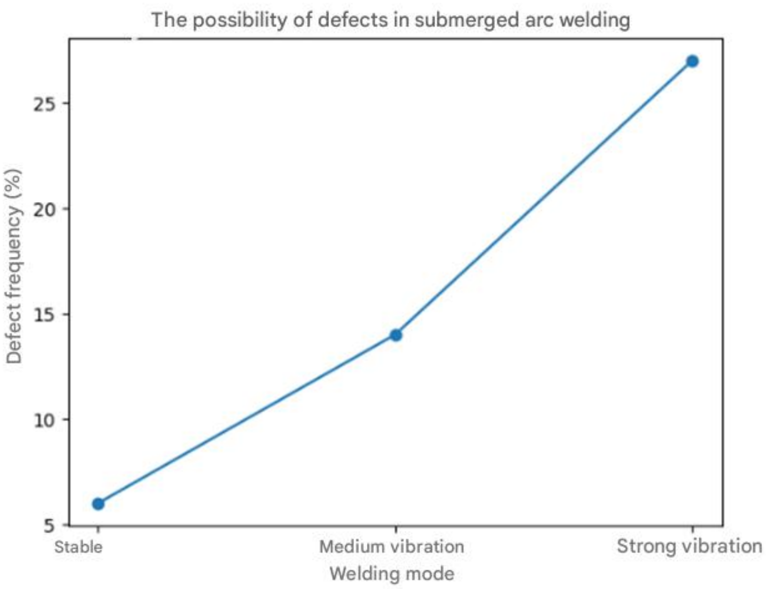

Figure 2. Graph of welding mode instability and the probability of defect occurrence.

Table 1

Welding Mode	Technological Parameters Condition	Defect Frequency, %

Stable mode	Minimal fluctuations	6
Moderate fluctuation mode	Parameters partially unstable	14
Strong fluctuation mode	Parameters unstable	27

Discussion. The obtained results confirm the necessity of considering the submerged arc welding process not merely as a set of strictly defined technological parameters, but as a complex technological system with multifactorial and probabilistic characteristics. The sensitivity of defect frequency identified in the experimental results to the stability of the parameters demonstrates that even minor fluctuations in submerged arc welding machines have a significant impact on weld quality. This situation creates differences that cannot be explained by traditional deterministic models and clearly demonstrates the scientific validity of the probabilistic approach.

Statistical analysis showed that, even when the average values of technological parameters are the same, the width of their distribution is one of the main factors determining the probability of defect occurrence. In particular, random fluctuations in welding current and wire feed speed lead to unstable formation of the molten metal pool, thereby increasing the probability of defects such as porosity and slag inclusions. These results indicate that the issue of ensuring quality in the submerged arc welding process cannot be limited solely to the selection of nominal modes.

The analysis of the obtained graphs and tables shows an almost monotonic increase in the probability of defects with increasing intensity of parameter fluctuations. This relationship confirms that the submerged arc welding process can be analyzed within the framework of reliability theory. When the occurrence of defects is regarded as a probabilistic event that leads the process to a partial or complete failure state, a new scientific approach is formed for assessing the technological reliability of welding machines.

Furthermore, the research results provide scientific justification for the importance of automated control and monitoring systems in submerged arc welding machines. It was shown that the probability of defects can be sharply reduced by detecting parameter fluctuations in real time and limiting them. This indicates that the digitalization of submerged arc welding equipment and its integration with intelligent control systems is a promising direction.

Based on the results of the discussion, it can be stated that the proposed probabilistic model enables the prediction of defect risks in the submerged arc welding process in advance. With the help of this model, technological modes can be selected not only from the standpoint of energy and productivity, but also on the basis of quality and reliability criteria. As a result, it becomes possible to reduce the amount of scrap in the production process, save material and energy resources, and increase the operational reliability of welded structures.

Conclusion. The conducted research has scientifically substantiated that the submerged arc welding process is a complex technological system with multifactorial and probabilistic characteristics. The results of the study showed that the occurrence of defects in the weld seam is determined not only by the nominal values of the technological parameters, but also by their stability over time and random fluctuations. In particular, it was found that changes in welding current, wire feed speed, and the condition of the flux layer have a decisive influence on the probability of defects.

Based on the proposed probabilistic model, the possibility of assessing the technological reliability of submerged arc welding machines has been created. The experimental results confirmed that as the fluctuations of the parameters increase, the frequency of defects rises significantly, which indicates that analyzing the welding process based on a deterministic approach is not sufficient. The probabilistic approach, in turn, enables scientifically grounded decision-making aimed at predicting weld quality in advance and reducing the risk of defects.

The research results confirm the importance of implementing automated control and monitoring systems in submerged arc welding machines. It was shown that by monitoring technological parameter fluctuations in real time and limiting them, it is possible to reduce the probability of defects, increase production efficiency, and decrease the amount of scrap. This approach also contributes to saving energy and material resources in industrial conditions.

In general, the analysis of the submerged arc welding process based on a probabilistic model holds significant scientific and practical importance for improving the quality of the weld seam, ensuring the operational reliability of welded structures, and developing modern digitized welding technologies. The research results can serve as a theoretical basis for the future development and optimization of intelligent welding systems.

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