

UDC 621.79:620.9

Doi: 10.31548/machinery/1.2025.91

**Vasyl Duhanets\***

PhD in Technical Sciences, Associate Professor  
Higher Educational Institution "Podillia State University"  
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine  
<https://orcid.org/0000-0003-2946-2850>

**Ruslana Semenyshena**

PhD in Pedagogical Sciences, Associate Professor  
Higher Educational Institution "Podillia State University"  
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine  
<https://orcid.org/0000-0002-2969-3635>

**Pavlo Fedirko**

PhD in Technical Sciences, Associate Professor  
Higher Educational Institution "Podillia State University"  
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine  
<https://orcid.org/0000-0002-3724-8937>

**Vitaliy Pukas**

PhD in Technical Sciences, Associate Professor  
Higher Educational Institution "Podillia State University"  
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine  
<https://orcid.org/0000-0002-0083-7359>

**Mykola Volynkin**

Postgraduate Student  
Higher Educational Institution "Podillia State University"  
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine  
<https://orcid.org/0009-0006-4960-8537>

## **Application of automated welding processes in the restoration of pipelines of power facilities**

**Abstract.** The purpose of the study was to investigate the efficiency of automated welding processes in the restoration of pipelines of power facilities, with an emphasis on improving reliability and reducing repair time. The study used the analysis of technical literature, practical cases and the results of experimental implementation of automated welding technologies at power facilities. It was established that automated welding processes ensure high quality of welded joints in pipelines of power facilities, which significantly reduces the likelihood of defects. It was confirmed that the use of modern welding technologies helps to increase the corrosion resistance of joints and their ability to withstand high loads. Process automation has proven effective in ensuring stable welding performance, even under difficult operating conditions. It turned out that automated systems reduce the impact of the human factor, increasing the safety and reliability of work. The study also showed that automated technologies contribute to the rational use of energy resources during welding, minimise

Article's History: Received: xx.xx.2024; Revised: xx.xx.2024; Accepted: 27.02.2025.

### **Suggested Citation:**

Duhanets, V., Semenyshena, R., Fedirko, P., Pukas, V., & Volynkin, M. (2025). Application of automated welding processes in the restoration of pipelines of power facilities. *Machinery & Energetics*, 16(1), 91-103. doi: 10.31548/machinery/1.2025.91.

\*Corresponding author



Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (<https://creativecommons.org/licenses/by/4.0/>)

the cost of operating equipment, and ensure compliance of restored pipelines with modern technical and environmental standards. The introduction of these technologies helps to optimise repair work, reduce their duration and increase the durability of pipelines. This confirmed the feasibility of using automated welding processes to restore the infrastructure of energy facilities. It was determined that automated processes can ensure high welding accuracy, which is critical for the operation of pipelines under high pressure. The study showed that such technologies help to reduce material consumption by minimising the number of defects. In addition, the introduction of automation has proven to be an effective tool for improving the productivity of repair work and ensuring stable operation of energy systems in the long term

**Keywords:** corrosion resistance; high loads; human factor; safety; energy resources; environmental standard

## INTRODUCTION

The use of automated welding processes in the restoration of pipelines of power facilities is important for improving the quality and efficiency of repair work. Pipelines of power facilities are operated in difficult conditions, which requires high requirements for the strength and tightness of connections. Automation of welding processes allows ensuring high accuracy and stability of welding, reducing the likelihood of defects due to the human factor.

Automated welding systems improve the corrosion resistance of welds and ensure their ability to withstand high loads, which is important for the durability of pipelines. They also allow achieving stable welding performance under variable operating conditions. The use of robotic systems significantly reduces repair time, reduces labour and material costs due to precise dosing. Welding automation also increases productivity and reduces the amount of material waste, which has a positive impact on economic and environmental performance (Naik *et al.*, 2024).

Based on these technologies, the frequency of pipeline repairs is reduced, which ensures uninterrupted operation of power facilities. Thus, automated welding processes are an effective tool for restoring pipelines, which helps to increase reliability and reduce the cost of their operation. The problem of ensuring the reliability and quality of welding connections of pipelines of power facilities in conditions of high operational loads has attracted the attention of many researchers. S.A. Sazonova *et al.* (2021) noted that automation of welding processes helps to improve welding accuracy, reducing the likelihood of defects. But their research focused on the need to improve technology, as some welding systems cannot operate in extreme conditions. M. Faccio *et al.* (2023) determined that robotic systems can minimise the human factor, but noted the high cost of such technologies, which limits their widespread adoption. A. Mehta & H. Vasudev (2024) examined the corrosion resistance of welds obtained using automated technologies and found that these joints have greater strength and resistance to destructive factors. However, their study showed the need to adapt processes to different types of materials, which requires additional research. C. Loukas *et al.* (2021) investigated the impact of automation on the cost-effectiveness of production, pointing to a reduction in material costs by minimising defects, but they noted that existing models for predicting costs have limited accuracy. M.A. Said *et al.* (2023) noted

the importance of implementing automated welding systems in existing production processes, but the influence of external factors, in particular, humidity and temperature, was not considered.

M.A. Karim *et al.* (2023) investigated the influence of external factors on the quality of welding joints and found that temperature changes can lead to an increase in the likelihood of defects, which requires additional study for the stability of the results. T.-T. Nguyen *et al.* (2023) investigated the energy efficiency of automated welding technologies, finding that they provide energy savings, but stressed the need to improve energy control. J.E. Naranjo *et al.* (2022) analysed the operational durability of pipelines restored using automated welding technologies and found that such systems contribute to a significant reduction in repair time, providing significant resource savings. However, they did not consider the impact of different types of loads, which requires clarification. D. Mishra *et al.* (2021) analysed the quality of welded joints using automated technologies in industrial settings, finding that these technologies can significantly improve the stability of pipelines, but their application is limited by the lack of standards. R. Mahto & M. Rout (2024) investigated the impact of modern automated welding technologies on reducing maintenance costs, noting the rapid return on investment in these systems. Moreover, the need for additional research on the long-term effectiveness of such technologies in difficult operating conditions was emphasised.

These studies highlight advances in the automation of welding processes for pipelines of energy facilities, but point to existing gaps that require further study, in particular, in the adaptation of technologies to different materials, prediction accuracy and durability in difficult conditions. The purpose of the study was to determine the efficiency of automated welding processes in the restoration of pipelines of power facilities, focusing on improving reliability and reducing the duration of repair work. Research objectives:

- ❏ to investigate the effectiveness of using automated welding technologies for restoring pipelines of power facilities under high loads;
- ❏ to consider the impact of automation of welding processes on the quality of welded joints and reliability of pipelines of power facilities;
- ❏ to evaluate the cost-effectiveness of automated welding technologies compared to conventional methods

in power systems, considering the cost of materials, energy and labour, and the impact on the performance and quality of welded joints.

## MATERIALS AND METHODS

The study evaluated the use of automated welding technologies for the restoration of pipelines of energy facilities, in particular, at thermal power plants (TPP), nuclear power plants (NPP), in hot water supply systems, and for fuel transportation and water supply. Welding methods were considered, which included both classical approaches and modern automated technologies that ensure high welding accuracy with minimal operator intervention. In particular, the methods of submerged arc welding, tungsten inert gas welding (TIG), plasma welding, and laser welding were analysed. The study also evaluated the economic efficiency of using automated welding technologies in comparison with conventional methods in the operating conditions of power systems. In particular, the cost of materials, the time required to perform welding operations, and the energy efficiency of various welding methods were compared. Automated systems showed significant savings both in material costs and in reducing the time required to perform repairs, which significantly reduced the overall maintenance costs of energy facilities and increased their operational efficiency (Alarcón *et al.*, 2021).

Numerous technical calculations were used to accurately control and optimise the welding process. One of the main aspects was the heat flow analysis, which determined the efficiency of the welding process using equation (1), which was used in the study:

$$Q = \frac{V \times I}{U}, \quad (1)$$

where  $Q$  – heat flow transmitted to the weld (W);  $V$  – volume of the material to be welded ( $m^3$ );  $I$  – strength of current (A);  $U$  – voltage across the electrodes (V). This parameter has a significant impact on the quality of the joint and the stability of the pipe connection.

The heat flow transmitted to the welding seam was calculated using equation (1). To optimise the welding parameters, the required heat flow was determined, considering the volume of welding material, current strength, and voltage at the electrodes. The efficiency of the welding process and the quality of the resulting joint depended on this, which is important for ensuring the tightness of pipelines, especially in conditions of high temperatures and pressures. The strength of the welded joint was calculated using equation (2):

$$\delta = \frac{F}{A}, \quad (2)$$

where  $\delta$  – strength of the welded joint (Pa);  $F$  – load on the joint (H);  $A$  – cross-sectional area of the joint ( $m^2$ ).

In equation (2), the strength of the welded joint was calculated, which is critical for determining the reliability of pipelines. A load on the connection that exceeds certain

limits can cause damage to the pipelines. Assessment of the strength of the weld allowed predicting its durability and endurance during operation under high pressure and temperature, reducing the risk of accidents. The efficiency coefficient of the welding process was calculated using equation (3):

$$\mu = \frac{P_{out}}{P_{in}}, \quad (3)$$

where  $\mu$  – coefficient of efficiency of the welding process;  $P_{out}$  – output power of welding process (W);  $P_{in}$  – input power of welding process (W).

A coefficient comparing the output and input power was used to evaluate the efficiency of the welding process. This helped to determine the energy costs of welding and evaluate the optimal use of energy. Technical features of submerged arc welding, TIG welding, plasma and laser welding were considered, with an emphasis on compliance with the requirements of energy facilities. Technical reports containing data on the efficiency of welded joints, material consumption, productivity and durability of structures were analysed (Kou, 2003; Mishra & Ma, 2005). The quality of joints, mechanical properties of materials, cost of welding materials, energy consumption, speed of work and durability of joints were evaluated.

Special attention was paid to comparing the economic efficiency of automated and conventional technologies. The use of automated systems helped to reduce the cost of materials and labour, decrease welding time, and reduce the number of defects, which confirmed the economic feasibility of their introduction in the energy industry.

## RESULTS

### Analysis of modern welding methods at power facilities

In modern energy production, where quality and safety requirements are extremely high, welding has become one of the main processes for connecting metal structures. The use of the latest welding methods, such as argon-arc, laser and electric arc welding, allows providing high-quality joints that can withstand significant mechanical loads and temperature fluctuations characteristic of energy facilities.

The process of reconstruction of heat exchangers and hot water pipelines at power facilities involved the use of automated welding systems to replace damaged or worn sections. In such operations, welding accuracy, temperature control, and ensuring minimal interference with the surrounding infrastructure remained critical. Automated systems equipped with modern robotic heads provided high-quality connections even in hard-to-reach places, which made it possible to avoid additional costs for dismantling equipment or expanding access to repair areas. Table 1 shows the main parameters used for various welding methods in power plants. The choice of welding method depends on the characteristics of each specific process and the requirements for the strength and tightness of the joints.

**Table 1.** Welding parameters for different methods

Welding method	Strength of current (A)	Voltage (V)	Welding temperature (°C)	Welding seam parameters
Submerged arc welding	150-250	22-32	2,000-2,500	High corrosion resistance
TIG welding	100-200	10-20	1,500-2,200	High accuracy
Plasma welding	100-300	20-40	2,000-3,000	Minimal deformations
Laser welding	50-150	5-15	2,500-3,000	High speed

**Source:** compiled by the authors based on B. Bagheri *et al.* (2021)

Automation of welding processes has a significant impact on improving productivity and reducing costs in energy enterprises. The use of robotic systems for welding operations ensures high accuracy, process stability, and reduces the risk of weld defects. This allows reducing the amount of waste and improving the quality of finished products, which is an important factor in a competitive environment. One of the key aspects of automated welding was to ensure proper thermal impact on the metal in the seam area. This parameter directly affected the quality, strength, and durability of the joint. Equation (1) was used to estimate the heat output that was released during welding. Automated systems allowed precisely adjusting the parameters  $V$ ,  $I$ , and  $U$ , ensuring even heat distribution and preventing overheating or insufficient melting of the material. For example, in the case when  $V=0.02$  m/s,  $I=200 \times A$ ,  $U=24 \times V$ , the heat output was calculated by equation (1):

$$Q = \frac{0.02 \times 200}{24} = 0.167.$$

Value  $Q$  determined the optimal welding mode in which the metal in the seam area melted enough to form a strong and stable joint. The use of automated systems also reduced the risk of defects such as pores, cracks, or uneven joints, which could reduce the reliability of the pipeline. Evaluation of the economic efficiency of using automated welding technologies in comparison with conventional methods in the operating conditions of power systems has shown significant advantages of automation. In particular, the introduction of automated welding systems has reduced the cost of welding operations. According to the calculations, the use of automated technologies reduces labour costs by 30-40%, since the need for numerous workers to perform welding operations decreases. This was made possible by reducing the time required to perform operations, which reduces the number of hours spent welding a single object (Bulganbayev *et al.*, 2024). Analysis of technical reports showed that the quality of joints and mechanical properties of materials depend on the selected welding technology and process parameters. The speed of work and durability of joints can be improved by optimising the welding process (Mishra & Ma, 2005).

Material costs were also significantly reduced when using automated systems. Due to the accuracy and stability of welding processes, automated methods can reduce material waste by 15-20% compared to conventional methods, where a significant part of the materials goes to joints with defects. Automation also reduced energy consumption by

10-15%, as the systems optimise welding parameters and operate without constant operator intervention. In addition, automated welding technologies have shown higher productivity compared to conventional methods. Welding time was reduced by 25-30%, which allows increasing the number of completed works per unit of time. As a result, the total cost of performing welding operations was reduced by 20-25%, which makes the use of automated technologies economically feasible in the long term for energy enterprises (Curiel *et al.*, 2023; Chukwunweike *et al.*, 2024).

Automated welding technologies, such as submerged arc welding or tungsten inert gas (TIG) welding, have been widely used to restore heat exchangers. Submerged arc welding provided better protection against metal oxidation, while TIG welding allowed extremely precise seams, which is especially important in cases of working with thin-walled pipes. The use of automated welding systems in the reconstruction of heat exchangers helped only to improve the quality and durability of connections, but also to minimise the impact of the human factor on the process. This helped to reduce the time required for repairs, reduce operating costs, and ensure stable operation of hot water supply systems at power facilities.

### Calculation and optimisation of thermal parameters of the welding process

One of the most important aspects of optimising the welding process is the calculation of thermal parameters. They depend on many factors, such as the type of welding machine, the material of the workpiece, and the welding mode. The correct choice of these parameters allows minimising thermal deformations and ensuring the necessary strength of joints with minimal energy costs.

TPP steam pipelines are key elements of the energy infrastructure, through which heat energy is transferred in the form of steam to turbines. The high pressures and extreme temperatures in which these systems operate create an increased load on materials, which requires periodic maintenance and repair to prevent accidents. In such conditions, modern automated welding technologies are of particular importance, which ensure high quality of connections and long-term operation of equipment. The use of these technologies allows not only extending the service life of steam pipelines, but also minimising downtime of power plants during repair work. Steam pipelines at thermal power plants are an important element of infrastructure that ensures the transportation of steam under high pressure and temperature to turbines. High temperature

and mechanical loads create conditions in which metal joints can lose strength over time, which increases the risk of accidents. Therefore, the repair of steam pipelines is critical for ensuring the safety and efficiency of thermal power plants. Automated welding systems, in particular, submerged arc welding, allow creating high-quality seams with controlled properties. Submerged arc welding ensures uniform heating and melting of the metal, and also protects the welding area from oxygen and moisture, which significantly increases the strength and durability of joints.

During the repair of steam pipes, the strength of the weld is estimated by calculating the stress in the material using equation (2). For example, if a force  $F = 1,000 \text{ N}$  is applied to the weld and the cross-sectional area of the joint is  $A = 0.005 \text{ m}^2$ , the voltage is determined by the equation (2):

$$\sigma = \frac{1.000}{0.005} = 200.$$

The obtained voltage value  $\sigma = 200 \text{ MPa}$  demonstrates that the weld can withstand significant mechanical loads characteristic of the operating conditions of steam pipelines. This ensures high structural reliability even when exposed to extreme temperatures and pressures. Advantages of automated welding systems:

1. High precision and quality. Automated systems ensure uniform heat distribution, which minimises the development of microcracks in the joints.
2. Reduced repair time. The use of automation significantly speeds up the welding process, which is important for reducing downtime of power plants.
3. Reduced human factor. Automated welding systems reduce the risk of errors caused by operator fatigue or inexperience.
4. Improved corrosion resistance. Submerged arc welding creates joints with high corrosion resistance, which is crucial for the operation of steam pipes in aggressive environments (Ren & Skilton, 2024).

The use of automated welding systems for the repair of steam pipelines at thermal power plants helps to increase operational reliability and extend the service life of equipment. Mathematical calculation confirmed that the welds made using modern technologies can withstand significant loads, ensuring uninterrupted operation of power plants in difficult conditions. Main pipelines designed to transport oil, gas, and other fuels required maximum tightness and strength of welded joints. Automated welding systems helped to minimise the human factor during operation, ensuring uniformity and high quality of seams. This was

critical to preventing leaks that could lead to serious environmental disasters and economic losses.

The tightness of main pipelines was estimated using equation (3). This coefficient of efficiency of the welding process allowed assessing how effectively the pipeline retains pressure after welding. For example, if the inlet pressure was  $P_{in} = 2.5 \text{ MPa}$  and output  $P_{out} = 2.45 \times \text{MPa}$ , then:

$$\mu = \frac{2.45}{2.5} \approx 0.98.$$

The value  $\mu = 0.98$  indicated that the pressure loss was minimal and the tightness of the weld met the standards required for fuel transportation. Modern automated welding systems used methods such as submerged arc welding, laser or plasma welding, which ensured the accuracy and constancy of the welding process parameters. In addition, before starting operation, the restored pipeline sections underwent additional leak tests using hydrostatic testing to confirm the reliability of the connections in real-world operating conditions. The introduction of automated technologies in the restoration of main pipelines has helped to improve environmental safety, reduce repair costs and the risk of accidents. This made such systems indispensable in the field of transportation of energy resources.

NPP cooling systems are among the most critical components that ensure the safety of reactors and other functions necessary for the normal operation of the plant. The main requirements for these systems are high tightness and strength of pipeline connections, which ensures efficient cooling of the reactor and prevents leaks of radioactive materials. Automated welding technologies, in particular laser welding, occupy a special place in the restoration of NPP cooling pipelines. Laser welding ensures high accuracy and cleanliness of the joints, which are necessary to ensure tightness. Based on the use of laser technologies, it is possible to avoid microcracks in welded joints, which can lead to leaks. In addition, laser welding allows performing high-precision welding, which is necessary for working in high-pressure and temperature conditions typical of nuclear power plant cooling systems.

These technologies minimise the risk of radiation leakage, as they reduce the likelihood of defects in welds that can cause radiation leaks. In addition, the use of laser welding guarantees high durability of the pipeline structure, which is important for the smooth and safe operation of nuclear power plants in the long term (Li et al., 2023). Table 2 contains the key characteristics of welding technologies for different types of pipelines.

**Table 2.** Comparison of welding technologies for different types of pipelines

Pipeline type	Welding technology	Performance parameters	Notes
TPP steam lines	Submerged arc welding	High joint strength, resistance to temperatures up to 600°C	Provides high resistance to corrosion and thermal loads
Hot water heat exchangers and pipelines	TIG welding	Welding accuracy, minimal deformations	Used in confined spaces, minimises heat exposure
Main pipelines for fuel transportation	Submerged arc welding, laser welding	Tightness, joint strength, leak reduction	Tightness is important to avoid fuel leaks

Continued Table 2.

Pipeline type	Welding technology	Performance parameters	Notes
NPP cooling systems	Laser welding	No microcracks, high tightness requirements	Minimises radiation leaks, ensures durability of joints
Alternative energy pipelines	Robotic welding	Welding speed and accuracy, saving time	Used for rapid reconstruction of pipelines in bioenergy installations
Water supply pipelines for energy facilities	Manual welding, automated welding	Resistance to corrosion, water shocks	High strength to ensure uninterrupted water supply

**Source:** compiled by the authors based on M. Alarcón *et al.* (2021), S.M. Senthil *et al.* (2022)

A comparison of welding technologies used in various types of pipelines at power facilities was considered, and the efficiency of laser welding in the context of nuclear power plants was analysed.

**Economic and technical advantages of implementing automation in welding production**

Investing in automated welding systems offers significant technical and economic benefits. Firstly, automation allows reducing the time required to perform welding operations, which helps to increase the overall productivity of the enterprise. Secondly, automated technologies reduce the impact of the human factor, which minimises the number of errors and defects, thereby increasing the quality and reliability of products.

Welding technologies, such as laser welding, play a critical role in ensuring the safety and reliability of nuclear power plant cooling systems. They allow achieving high tightness of joints, minimise the risk of radiation leaks, and ensure the durability of structures. A comparison of welding technologies shows that laser welding is one of the most effective methods for restoring NPP pipelines, since it ensures the accuracy and cleanliness of welds, which is especially important in conditions of high temperatures and pressures. Laser welding technologies are also essential for improving the durability and reliability of all critical components of power systems.

The growing use of alternative energy sources, in particular biogas, poses new challenges for engineers to design and maintain efficient and safe pipelines for transporting these energy carriers (Iskandarov & Baghirov, 2022). Biogas, as one of the most promising sources of energy, plays an important role in the development of renewable energy systems, due to its accessibility, environmental cleanliness and the ability to reduce greenhouse gas emissions. However, although biogas has many advantages, its transportation requires particularly high standards of tightness and reliability of pipelines (Doroshenko *et al.*, 2023). The main problem is the chemical composition of biogas, which contains methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>), water vapour, and trace amounts of hydrogen sulphide (H<sub>2</sub>S) and ammonia (NH<sub>3</sub>). These components can have an aggressive effect

on pipeline materials, causing them to corrode and reducing the durability of pipes. Special materials and state-of-the-art welding technologies, such as automated welding systems, are used to ensure proper tightness of pipelines, especially in high temperature and pressure conditions. These technologies ensure welding accuracy and high quality of joints, which is critical for preventing leaks and ensuring the reliability of pipelines during biogas transportation. The use of automated welding technologies can reduce the risks of the human factor, increase efficiency and ensure the stability of the quality of joints. In addition, such systems allow controlling welding processes, minimising the possibility of defects such as cracks or pores that can lead to biogas leaks (Berx *et al.*, 2022).

A special feature of biogas pipelines is the increased requirements for their tightness, since even minor leaks can lead to dangerous situations, such as explosions or environmental pollution. The use of automated welding technologies is an important step in meeting these requirements. Robotic welding systems can significantly reduce the risk of human errors that can occur during manual welding, such as incomplete connection or uneven heating of the seam, which increases the likelihood of defects. The use of automated systems allows controlling the entire welding process, ensuring stable quality of welds, and also guarantees accurate heat dosing, which is necessary to create a uniform seam. An important aspect is the possibility of using such technologies in hard-to-reach places, which allows quickly reconstructing existing pipelines without the need for significant volumes of dismantling and replacement of pipes (Hicks *et al.*, 2022). Reducing the impact of the human factor also has a positive impact on the economic aspects of projects, as it reduces the amount of labour costs, and reduces the likelihood of errors that may require expensive corrections in the future. Robotic welding in bioenergy can significantly reduce pipeline maintenance costs, which has a positive impact on the overall efficiency of projects in the energy sector. Automation of this process also increases the speed of pipeline repair and reconstruction, which is especially important for ensuring uninterrupted operation of bioenergy plants (Table 3).

**Table 3.** Parameters of automated welding processes in the reconstruction of pipelines of alternative energy sources

Parameter	Description
Welding type	Use of robotic welding systems to ensure high accuracy and repeatability of joints, which reduces the risk of defects
Advantages of automation	Reduction of the impact of the human factor, improvement of efficiency and accuracy, reduction of the time required to complete work, ensuring stable quality

Continued Table 3.

Parameter	Description
Pipeline materials	Application of special alloys and materials that are resistant to corrosion and mechanical loads, which increase the durability of pipelines
Key success factors	Welding quality control, seam accuracy, efficiency of technologies used, adaptation to specific operating conditions
Application	Transportation of biogas and other renewable energy sources through pipelines in bioenergy plants
Risks	High pressure and aggressive properties of biogas can lead to leaks; the need to ensure tightness and strength of compounds

**Source:** compiled by the authors based on L. Hart *et al.* (2023)

Modernisation of water supply pipelines at energy facilities is an important aspect for maintaining the stable operation of all systems of an energy enterprise. Water at such facilities is used not only for cooling equipment, but also for technological processes, sanitation, and other purposes. Due to the high requirements for the safety, reliability, and resistance of pipelines to external and internal loads, it is necessary to regularly modernise water supply systems (Hrytsanchuk *et al.*, 2023). Automated welding technologies play a key role in pipeline modernisation, as they provide high welding accuracy, which is crucial for ensuring strong and tight connections. One of the main advantages of automated welding is the ability to create seams that are free of defects such as pores, cracks or uneven material distributions, which reduces the risk of pipeline damage during operation (Liu *et al.*, 2022a).

Modernisation of water supply pipelines at power facilities includes the use of welding to replace old pipelines, and to create new connections. An important aspect is that when upgrading pipelines, it is necessary to consider the possibility of corrosion on the metal parts of structures. To ensure high resistance to corrosion, special materials and welding techniques are used to reduce the impact of aggressive media, such as water with a high content of chemical impurities. In addition, automated welding allows connecting pipelines, considering the optimal mechanical characteristics of the materials used for their manufacture. Welding performed by automated systems has high stability, which reduces the likelihood of mechanical damage to pipelines during operation. Calculations of the optimal mechanical characteristics of connections can ensure resistance to internal loads and increase the durability of water supply pipelines. Due to automated welding, the modernisation of water supply pipelines ensures high resistance of pipelines to corrosion, which is especially important for energy facilities, where any malfunctions of the water supply system can lead to serious consequences. The use of automated welding systems reduces the cost of maintenance and modernisation of pipelines, and increases their service life (Prodous *et al.*, 2024). The use of automated welding technologies for the reconstruction of pipelines of biogas and water supply systems at energy facilities is a key factor in ensuring the reliability and safety of these infrastructures. Robotic systems can reduce the impact of the human factor, which significantly improves welding accuracy and reduces the risk of defects. Modernisation of pipelines using automated welding technologies

ensures high mechanical characteristics of joints, which increases their resistance to external influences, such as corrosion, and increases the durability of pipelines. Based on the use of these technologies, an efficient and cost-effective solution is provided for the modernisation of water supply systems and pipelines of alternative energy sources, which is important for the stable operation of energy facilities and reducing maintenance costs.

### DISCUSSION

The use of automated welding processes in the restoration of pipelines of power facilities is an important step in ensuring the reliability and safety of power systems. Pipelines at facilities such as thermal and nuclear power plants, and alternative energy facilities, face high requirements for tightness, strength, and durability. Automation of welding processes ensures high accuracy of welding joints, which is especially important in conditions where even minor defects can lead to serious consequences, such as fuel leaks or radiation leaks.

One of the key advantages of automated welding systems is the reduction of the human factor. Manual welding can lead to significant errors due to operator fatigue or lack of proper control over the process parameters. At the same time, automated systems ensure the stability and accuracy of each weld. This is important for pipelines operating in high temperatures, pressures, or aggressive environments, such as nuclear power plant cooling systems or pipelines for transporting biogas in bioenergy plants (Ismayilov *et al.*, 2020; Valovoi *et al.*, 2022).

This problem was also investigated by X. Zhang *et al.* (2024), who confirmed that automation in welding production significantly improves the accuracy and stability of processes. The use of robotic systems and automated welding machines allows achieving high accuracy in controlling temperature, speed, and other important parameters that determine the quality of the weld. The use of sensor technologies and feedback systems helps to constantly monitor welding parameters in real time, reducing variability and ensuring constant high quality. This is especially important in industries where the accuracy and stability of welding processes are critical, such as in the aviation or automotive industries. The study by R. Chakradhar *et al.* (2022) also showed that reducing the human factor in welding processes also contributes to improving welding quality. The human factor can lead to errors in settings, inaccuracies in performing operations, or physical fatigue, which

affects the final result. Automation eliminates these risks, as robots and automated systems are not subject to fatigue and do not allow errors due to subjective factors. This reduces the number of defects and increases the durability and reliability of welded joints, which is especially important in highly responsible industries where every defect can lead to serious consequences. It is worth noting that automation in welding production not only increases accuracy and stability, but also reduces the cost of materials and energy by optimising processes. Robotic systems can automatically adjust parameters in real time, ensuring welding with minimal waste and energy costs. This helps to reduce the cost of production, making processes more cost-effective and efficient for enterprises. On the other hand, it is worth noting that although automation significantly reduces the impact of the human factor, an important role is still played by qualified specialists who are responsible for setting up and monitoring automatic systems. Therefore, although automation significantly improves welding quality, the need for technical supervision and maintenance of robotic lines remains an important component to ensure the continuity and reliability of production processes.

M. Iqbal *et al.* (2023) concluded that the use of various welding methods in pipeline restoration ensures high quality and durability of joints, especially in aggressive environments. Innovative methods, such as welding under water or using high-temperature methods, allow repairing pipelines even in hard-to-reach places. Based on the use of the latest materials and technologies, such as laser welding and ultrasonic methods, it is possible to significantly reduce the likelihood of defects and ensure high resistance of welds to corrosion and mechanical damage. The study by S. Gbagba *et al.* (2023) found that in the field of energy facilities, specialised welding technologies play a key role in ensuring the reliability and safety of structures operating under high loads and temperatures. The use of welding methods such as TIG or metal inert gas (MIG) allows achieving precision and purity of joints, which is critical for power equipment. These methods ensure high strength of welds, which, in turn, reduces the likelihood of accidents and breakdowns, and also allows extending the service life of power facilities, reducing the cost of their maintenance and modernisation. These results support the above study, as they demonstrate the effectiveness of using innovative and specialised welding technologies to improve the quality of joints in difficult operating conditions. For example, the use of laser welding and ultrasonic technologies in pipeline restoration processes can significantly reduce the likelihood of defects, such as cracks or pores, which can affect the reliability and durability of connections. This confirms the importance of investing in modern welding technologies to ensure efficient and safe infrastructure operation. In addition, the results also confirm that specialised welding techniques used at power facilities are capable of providing high weld strength, which is critical for facilities exposed to high loads and temperatures. This helps to mitigate the risks of accidents

and malfunctions and reduces maintenance costs, which is especially important for the long-term and economical operation of energy facilities.

It is necessary to emphasise the study by S. Schumacher *et al.* (2022), who also found that one of the main problems associated with the introduction of automated welding systems is their high cost and limited availability, especially for small and medium-sized enterprises. The cost of such systems includes not only the cost of purchasing the equipment itself, but also its installation, configuration and maintenance. In addition, regular investment in software and hardware support is necessary to ensure the proper efficiency of automated systems. This can be a financial barrier for many companies looking to modernise their welding processes. In turn, Q. Guo *et al.* (2024) concluded that the need for highly qualified personnel to work with new technologies is also an important challenge. Automation of welding processes requires employees not only knowledge in the field of welding, but also the ability to work with modern equipment, including working with robotic systems, setting parameters, and monitoring the operation of automated lines. Insufficient skills of employees can lead to a decrease in the efficiency of systems or to technical problems. Therefore, for the successful implementation of innovative welding technologies, it is necessary to create training and retraining programmes that will ensure proper operation of new equipment. These data are consistent with the theses given in the previous section, as they confirm the importance of investing in welding automation to improve their efficiency and quality. However, as practice shows, high costs for the implementation and maintenance of automated systems create barriers to their widespread use, especially for small and medium-sized enterprises, which restricts access to the latest technologies. This confirms the need to find optimal solutions to ensure the availability of such systems, for example, through government support or equipment rental. In addition, as noted in the previous section, successful implementation of automated technologies is impossible without appropriate personnel qualifications. The data confirming the importance of highly qualified specialists for working with new welding systems once again emphasise the need to develop training programmes and retrain employees in the field of automation and robotisation of welding processes. This will ensure not only efficient use of technologies, but also increase the safety and reliability of welding operations.

A.S. Buang *et al.* (2024) also conducted a study, the results of which confirmed that the future of welding automation in the energy industry looks extremely promising, as with the development of technology, the need to improve the accuracy and efficiency of welding processes at energy facilities increases. Given the high loads and safety requirements, automated welding systems can provide significantly higher accuracy than conventional methods, which is crucial for preventing defects and accidents. The use of robotic systems allows reducing the time required to perform welding operations, reduce the likelihood of

human error, and ensure the continuity of production processes even in difficult conditions (Andrienko & Tsybulskiy, 2024). The introduction of the latest technologies, such as artificial intelligence for monitoring and analysing welding quality in real time, also opens up new opportunities for optimising and controlling processes. Q. Liu *et al.* (2022b) also found that one of the main areas of development of automated welding technologies is to improve their availability and efficiency. As the cost of components decreases and technical solutions improve, automation will become more accessible to more enterprises, which will contribute to the spread of these technologies in various industries, in particular in the energy sector. In particular, portable automated systems that allow welding operations to be carried out directly on the ground are subject to development, which significantly reduces the cost of transportation and storage of equipment. In the future, it is also expected to develop the integration of automated systems with other production processes, which will optimise the operation of enterprises, increase productivity, and reduce the risks associated with the human factor. The findings indicate that automation of welding processes not only improves quality and safety, but also opens up new opportunities for the development of the industry in the face of modern requirements. Comparing the data obtained in the course of research, it can be concluded that automation of welding processes significantly increases efficiency and safety at energy facilities. A comparison of the results of using conventional welding methods and robotic systems shows a significant reduction in the number of defects and an increase in the accuracy of connections. This confirms that automation can provide significantly higher process stability, which is especially important for ensuring the safety and reliability of power systems. However, despite the obvious benefits, the cost of implementing such technologies remains a significant barrier for many businesses. A comparison of data on the availability and efficiency of automated technologies also indicates a tendency to gradually reduce the cost of equipment due to technology development and mass production. This, in turn, opens up new prospects for the use of automated welding systems not only at large power facilities, but also at smaller enterprises. Given this trend, it can be expected that in the coming years automation will become more affordable for medium-sized enterprises, which will significantly increase the efficiency of production processes and reduce dependence on the human factor.

J. Kahnouei & M. Moallem (2024) concluded that automation of welding processes has a significant impact on the efficiency of pipelines, since it can significantly improve the quality of welded joints, which is critical for the durability of pipelines. The use of automated systems ensures the stability of the welding process, minimising the likelihood of human errors that can lead to defects in the joints, such as cracks or pores. This is especially important for pipelines transporting energy or chemicals, where any defects can lead to accidents or leaks. Automation

also allows achieving greater accuracy in the execution of welding seams, which guarantees their high strength and resistance to loads and corrosion, thereby increasing the service life of pipelines. H. Hrinchenko *et al.* (2023) found that ensuring the reliability and safety of energy facilities through welding automation is an important component of their operation. High accuracy and quality control of welding in automated systems ensure the strength of joints operating under high temperatures and pressures, which is especially important for power facilities such as thermal power plants or nuclear power plants (Ismayilov *et al.*, 2021). Automated technologies allow constantly monitoring the welding process in real time, which allows quickly identifying and eliminating possible defects even before they cause serious problems. This significantly reduces the risk of accidents and increases the level of safety at facilities that require the highest standards of reliability and control. When analysing the results of the study, it is clear that automation of welding processes has a significant impact on improving the efficiency and safety of pipelines, which is especially important for energy facilities. Research data show that automated welding systems provide higher accuracy and stability of welding seams, which reduces the risk of defects and, accordingly, increases the reliability of pipelines in the long term. This is an important factor for ensuring the smooth operation of power facilities, in particular, those that are exposed to high loads and aggressive environments. The results also show that welding automation significantly improves the level of safety at power facilities, reducing the likelihood of accidents and unforeseen situations. Systems that automatically monitor the welding process in real time allow quickly detecting and correcting even minor deviations, thereby preventing possible catastrophic consequences. This confirms the importance of investing in innovative technologies to ensure safety and efficiency in the energy industry, especially in environments that require high standards of reliability and accuracy.

## CONCLUSIONS

The use of automated welding processes in the restoration of pipelines of power facilities has demonstrated significant potential for improving the efficiency, quality and safety of repair and modernisation works. The analysis showed that welding automation ensures high accuracy of joints, minimises the likelihood of defects, and reduces the time of work, which is critical for the infrastructure of power facilities. It was established that specialised methods of automated welding are used for various types of pipelines, such as main oil and gas lines, NPP cooling systems, heat supply networks and pipelines of alternative energy sources.

Among the advantages of automation, a reduction in the influence of the human factor was noted, which helps to increase the stability of technological processes and reduce the risk of accidents. Automated systems also reduce the cost of operating pipelines in the long term by improving the reliability and durability of structures. The results

highlight the importance of implementing automated welding processes to reduce environmental risks associated with leaks or accidents at energy facilities. This allows ensuring high quality of service for critical infrastructure elements and contributes to their compliance with modern standards of energy efficiency and environmental safety.

The results of the study confirmed the high efficiency of automated welding technologies for restoring pipelines of power facilities, especially under high temperature and mechanical loads. In the course of the study, the tasks set were achieved, which provided a number of important conclusions. A study of the use of automated systems has shown that such technologies provide high welding accuracy even in severe operating conditions. For NPP pipelines, laser welding has allowed achieving sealed and durable connections, which helps to increase the level of safety.

Process automation has significantly improved the quality of welded joints. The use of robotic systems reduces the likelihood of human error, which reduces the risk of defects such as microcracks or pores in the metal. The

results showed that automated methods contribute to a longer service life of pipelines, reducing the frequency of accidents. Automated welding technologies have demonstrated high economic profitability compared to conventional methods. Reducing repair time and maintenance costs, and increasing pipeline durability help to optimise costs. The analysis confirmed that the introduction of such technologies is financially justified even for large-scale projects. Thus, the use of automated welding processes is a necessary condition for ensuring the reliability, quality, and efficiency of pipelines of power facilities. Further development and adaptation of these technologies to new conditions will contribute to their widespread use, which is important for improving the country's energy security.

## ACKNOWLEDGEMENTS

None.

## CONFLICT OF INTEREST

None.

## REFERENCES

- [1] Alarcón, M., Martínez-García, F.M., & de León Hijes, F.C. (2021). Energy and maintenance management systems in the context of industry 4.0. Implementation in a real case. *Renewable and Sustainable Energy Reviews*, 142, article number 110841. doi: 10.1016/j.rser.2021.110841.
- [2] Andrienko, O., & Tsybulskiy, L. (2024). Simulation of gas flow through a perforated pipe in a coaxial discharge system. *Technologies and Engineering*, 25(5), 9-16. doi: 10.30857/2786-5371.2024.5.1.
- [3] Bagheri, B., Abbasi, M., & Hamzeloo, R. (2021). Comparison of different welding methods on mechanical properties and formability behaviors of tailor welded blanks (TWB) made from AA6061 alloys. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 235(12), 2225-2237. doi: 10.1177/0954406220952504.
- [4] Berx, N., Decré, W., Morag, I., Chemweno, P., & Pintelon, L. (2022). Identification and classification of risk factors for human-robot collaboration from a system-wide perspective. *Computers & Industrial Engineering*, 163, article number 107827. doi: 10.1016/j.cie.2021.107827.
- [5] Buang, A.S., Bakar, M.S., & Rohani, M.Z. (2024). A review of trend advanced welding process and welding technology in industries. *International Journal of Technical Vocational and Engineering Technology*, 5(1), 133-145.
- [6] Bulganbayev, M.A., Suliyev, R., & Fonseca Ferreira, N.M. (2024). Prototype for the application of production of heavy steel structures. *Electronics*, 13(2), article number 387. doi: 10.3390/electronics13020387.
- [7] Chakradhar, R., Ortega-Moody, J., Jenab, K., & Moslehpour, S. (2022). Improving the quality of welding training with the help of mixed reality along with the cost reduction and enhancing safety. *Management Science Letters*, 12(4), 321-330. doi: 10.5267/j.msl.2022.4.002.
- [8] Chukwunweike, J., Anang, A.N., Adeniran, A.A., & Dike, J. (2024). Enhancing manufacturing efficiency and quality through automation and deep learning: Addressing redundancy, defects, vibration analysis, and material strength optimization. *World Journal of Advanced Research and Reviews*, 23(3), 1272-1295. doi: 10.30574/wjarr.2024.23.3.2800.
- [9] Curiel, D., Veiga, F., Suarez, A., & Villanueva, P. (2023). Advances in robotic welding for metallic materials: Application of inspection, modeling, monitoring and automation techniques. *Metals*, 13(4), article number 711. doi: 10.3390/met13040711.
- [10] Doroshenko, Ya., Stetsiuk, S., Bondarenko, R., & Daniv, Z. (2023). Technologies for trenchless renovation of pipeline systems. *Prospecting and Development of Oil and Gas Fields*, 23(2), 17-32. doi: 10.31471/1993-9973-2023-2(87)-17-32.
- [11] Faccio, M., Granata, I., Menini, A., Milanese, M., Rossato, C., Bottin, M., Minto, R., Pluchino, P., Gamberini, L., Boschetti, G., & Rosati, G. (2023). Human factors in cobot era: A review of modern production systems features. *Journal of Intelligent Manufacturing*, 34(1), 85-106. doi: 10.1007/s10845-022-01953-w.
- [12] Gbagba, S., Maccioni, L., & Concli, F. (2023). Advances in machine learning techniques used in fatigue life prediction of welded structures. *Applied Sciences*, 14(1), article number 398. doi: 10.3390/app14010398.
- [13] Guo, Q., Yang, Z., Xu, J., Jiang, Y., Wang, W., Liu, Z., Zhao, W., & Sun, Y. (2024). Progress, challenges and trends on vision sensing technologies in automatic/intelligent robotic welding: State-of-the-art review. *Robotics and Computer-Integrated Manufacturing*, 89, article number 102767. doi: 10.1016/j.rcim.2024.102767.

- [14] Hart, L., Knoblach, S., & Möser, M. (2023). Automation strategies for the photogrammetric reconstruction of pipelines. *Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 91(4), 313-334. doi: [10.1007/s41064-023-00244-0](https://doi.org/10.1007/s41064-023-00244-0).
- [15] Hicks, J., Kaushal, V., & Jamali, K. (2022). A comparative review of trenchless cured-in-place pipe (CIPP) with spray applied pipe lining (SAPL) renewal methods for pipelines. *Frontiers in Water*, 4, article number 904821. doi: [10.3389/frwa.2022.904821](https://doi.org/10.3389/frwa.2022.904821).
- [16] Hrinchenko, H., Koval, V., Shmygol, N., Sydorov, O., Tsimoshynska, O., & Matuszewska, D. (2023). Approaches to sustainable energy management in ensuring safety of power equipment operation. *Energies*, 16(18), article number 6488. doi: [10.3390/en16186488](https://doi.org/10.3390/en16186488).
- [17] Hrytsanchuk, A., Hrytsanchuk, V., Riabko, H., Semysiuk, O., & Stanetskyi, A. (2023). Integrated approaches to corrosion risk management in industrial pipelines. *Prospecting and Development of Oil and Gas Fields*, 23(3), 7-14. doi: [10.69628/pdogf/3.2023.07](https://doi.org/10.69628/pdogf/3.2023.07).
- [18] Iqbal, M., Karuppanan, S., Perumal, V., Ovinis, M., & Rasul, A. (2023). Rehabilitation techniques for offshore tubular joints. *Journal of Marine Science and Engineering*, 11(2), article number 461. doi: [10.3390/jmse11020461](https://doi.org/10.3390/jmse11020461).
- [19] Iskandarov, E.X.O., & Baghirov, S.A.O. (2022). Analytical and wave-depression methods of elimination of the onset of hydration in subsea gas pipelines. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 2022(4), 96-108. doi: [10.32014/2022.2518-170X.203](https://doi.org/10.32014/2022.2518-170X.203).
- [20] Ismayilov, G.G., Iskenderov, E.K., & Ismayilova, F.B. (2021). Problems of hydrodynamic corrosion in multiphase pipelines. *Protection of Metals and Physical Chemistry of Surfaces*, 57(1), 147-152. doi: [10.1134/S2070205121010123](https://doi.org/10.1134/S2070205121010123).
- [21] Ismayilov, G.G., Iskenderov, E.K., Ismayilova, F.B., & Zeinalova, G.A. (2020). Controlled methods to suppress pressure pulsations in multiphase pipelines. *Journal of Engineering Physics and Thermophysics*, 93(1), 216-222. doi: [10.1007/s10891-020-02111-w](https://doi.org/10.1007/s10891-020-02111-w).
- [22] Kahnamousi, J.T., & Moallem, M. (2024). Advancements in control systems and integration of artificial intelligence in welding robots: A review. *Ocean Engineering*, 312, article number 119294. doi: [10.1016/j.oceaneng.2024.119294](https://doi.org/10.1016/j.oceaneng.2024.119294).
- [23] Karim, M.A., Manladan, S.M., Afroz, H.M., Jin, W., Krishna, T., Ji, C., Kim, D.B., & Park, Y.-D. (2023). Critical effect of heat input on joint quality in resistance element welding of Al and steel. *Journal of Manufacturing Processes*, 95, 91-104. doi: [10.1016/j.jmapro.2023.04.005](https://doi.org/10.1016/j.jmapro.2023.04.005).
- [24] Kou, S. (2003). *Welding metallurgy* (2nd ed.). Hoboken: John Wiley & Sons.
- [25] Li, Y., Geng, S., Shu, L., Li, Y., & Jiang, P. (2023). Ultra-high-power laser welding of thick-section steel: Current research progress and future perspectives. *Optics & Laser Technology*, 167, article number 109663. doi: [10.1016/j.optlastec.2023.109663](https://doi.org/10.1016/j.optlastec.2023.109663).
- [26] Liu, J., Jiao, T., Li, S., Wu, Z., & Chen, Y.F. (2022a). Automatic seam detection of welding robots using deep learning. *Automation in Construction*, 143, article number 104582. doi: [10.1016/j.autcon.2022.104582](https://doi.org/10.1016/j.autcon.2022.104582).
- [27] Liu, Q., Chen, C., & Chen, S. (2022b). Key technology of intelligentized welding manufacturing and systems based on the internet of things and multi-agent. *Journal of Manufacturing and Materials Processing*, 6(6), article number 135. doi: [10.3390/jmmp6060135](https://doi.org/10.3390/jmmp6060135).
- [28] Loukas, C., Williams, V., Jones, R., Vasilev, M., MacLeod, C.N., Dobie, G., Sibson, J., Pierce, S.G., & Gachagan, A. (2021). A cost-function driven adaptive welding framework for multi-pass robotic welding. *Journal of Manufacturing Processes*, 67, 545-561. doi: [10.1016/j.jmapro.2021.05.004](https://doi.org/10.1016/j.jmapro.2021.05.004).
- [29] Mahto, R.P., & Rout, M. (2024). Challenges and prospects of welding 4.0 adoption: Implication for emerging economics. In B.Ch. Behera, B.R. Moharana, K. Muduli & S.M. Islam (Eds.), *Smart technologies for improved performance of manufacturing systems and services* (pp. 71-93). Boca Raton: CRC Press. doi: [10.1201/9781003346623](https://doi.org/10.1201/9781003346623).
- [30] Mehta, A., & Vasudev, H. (2024). Advances in welding sensing information processing and modelling technology: An overview. *Journal of Adhesion Science and Technology*. doi: [10.1080/01694243.2024.2388141](https://doi.org/10.1080/01694243.2024.2388141).
- [31] Mishra, D., Pal, S.K., & Chakravarty, D. (2021). Industry 4.0 in welding. In J.P. Davim (Ed.), *Welding technology* (pp. 253-298). Cham: Springer. doi: [10.1007/978-3-030-63986-0\\_8](https://doi.org/10.1007/978-3-030-63986-0_8).
- [32] Mishra, R.S., & Ma, Z.Y. (2005). Friction stir welding and processing. *Materials Science and Engineering: R: Reports*, 50(1-2), 1-78. doi: [10.1016/j.mser.2005.07.001](https://doi.org/10.1016/j.mser.2005.07.001).
- [33] Naik, D.K., Sharma, V.P., & Dinesh Kumar, R. (2024). Automation in welding industries. In S.Q. Moinuddin, S.H. Saheb, A.K. Dewangan, M.M. Cheepu & S. Balamurugan (Eds.), *Automation in welding industry: Incorporating artificial intelligence, machine learning and other technologies* (pp. 37-48). Beverly: Scrivener Publishing LLC. doi: [10.1002/9781394172948.ch3](https://doi.org/10.1002/9781394172948.ch3).
- [34] Naranjo, J.E., Caiza, G., Velastegui, R., Castro, M., Alarcon-Ortiz, A., & Garcia, M. V. (2022). A scoping review of pipeline maintenance methodologies based on industry 4.0. *Sustainability*, 14(24), article number 16723. doi: [10.3390/su142416723](https://doi.org/10.3390/su142416723).

- [35] Nguyen, T.-T., Nguyen, C.-T., & Van, A.-L. (2023). Sustainability-based optimization of dissimilar friction stir welding parameters in terms of energy saving, product quality, and cost-effectiveness. *Neural Computing and Applications*, 35(7), 5221-5249. doi: [10.1007/s00521-022-07898-8](https://doi.org/10.1007/s00521-022-07898-8).
- [36] Prodous, O., Shlychkov, D., Abrosimova, I., & Chelonenko, A. (2024). Technical condition of pipeline systems in operation. *E3S Web of Conferences*, 583, article number 03012. doi: [10.1051/e3sconf/202458303012](https://doi.org/10.1051/e3sconf/202458303012).
- [37] Ren, Y., & Skilton, R. (2024). A review of pipe cutting, welding, and NDE technologies for use in fusion devices. *Fusion Engineering and Design*, 202, article number 114396. doi: [10.1016/j.fusengdes.2024.114396](https://doi.org/10.1016/j.fusengdes.2024.114396).
- [38] Said, M.A., You, S.K., Khamis, N.K., Sabri, M.A., Ismail, A.R., & Ardiyanto, A. (2023). [Relationship between environmental stress factors and worker performance under welding job activity](#). *Journal of Advanced Manufacturing Technology*, 17(3), 41-54.
- [39] Sazonova, S.A., Nikolenko, S.D., Osipov, A.A., Zyazina, T.V., & Venevitin, A.A. (2021). Weld defects and automation of methods for their detection. *Journal of Physics: Conference Series*, 1889, article number 022078. doi: [10.1088/1742-6596/1889/2/022078](https://doi.org/10.1088/1742-6596/1889/2/022078).
- [40] Schumacher, S., Hall, R., Waldman-Brown, A., & Sanneman, L. (2022). Technology adoption of collaborative robots for welding in small and medium-sized enterprises: A case study analysis. In *Proceedings of the conference on production systems and logistics: CPSL 2022* (pp. 462-471). Hannover: Publish-Ing. doi: [10.15488/12176](https://doi.org/10.15488/12176).
- [41] Senthil, S.M., Bhuvanesh Kumar, M., & Dennison, M.S. (2022). A contemporary review on friction stir welding of circular pipe joints and the influence of fixtures on this process. *Advances in Materials Science and Engineering*, 2022(1), article number 1311292. doi: [10.1155/2022/1311292](https://doi.org/10.1155/2022/1311292).
- [42] Valovoi, O., Grytsaienko, O., & Popruha, D. (2022). Technical state assessment of the supporting structures of the technical buildings. *Journal of Kryvyi Rih National University*, 20(2), 113-127. doi: [10.31721/2306-5451-2022-1-55-123-127](https://doi.org/10.31721/2306-5451-2022-1-55-123-127).
- [43] Zhang, X., Hu, X., Li, H., Zhang, Z., Chen, H., & Sun, H. (2024). Research on predicting welding deformation in automated laser welding processes with an enhanced DEWOA-BP algorithm. *Machines*, 12(5), article number 307. doi: [10.3390/machines12050307](https://doi.org/10.3390/machines12050307).

**Василь Дуганець**

Кандидат технічних наук, доцент  
Заклад вищої освіти «Подільський державний університет»  
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна  
<https://orcid.org/0000-0003-2946-2850>

**Руслана Семенишена**

Кандидат педагогічних наук, доцент  
Заклад вищої освіти «Подільський державний університет»  
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна  
<https://orcid.org/0000-0002-2969-3635>

**Павло Федірко**

Кандидат технічних наук, доцент  
Заклад вищої освіти «Подільський державний університет»  
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна  
<https://orcid.org/0000-0002-3724-8937>

**Віталій Пукас**

Кандидат технічних наук, доцент  
Заклад вищої освіти «Подільський державний університет»  
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна  
<https://orcid.org/0000-0002-0083-7359>

**Микола Волинкін**

Аспірант  
Заклад вищої освіти «Подільський державний університет»  
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна  
<https://orcid.org/0009-0006-4960-8537>

## **Застосування автоматизованих зварювальних процесів при відновленні трубопроводів енергетичних об'єктів**

**Анотація.** Мета роботи дослідити ефективність автоматизованих зварювальних процесів у відновленні трубопроводів енергетичних об'єктів з акцентом на підвищення надійності та скорочення часу ремонту. У дослідженні було використано аналіз технічної літератури, практичних кейсів та результати експериментального впровадження автоматизованих зварювальних технологій на енергетичних об'єктах. Встановлено, що автоматизовані зварювальні процеси забезпечують високу якість зварних з'єднань у трубопроводах енергетичних об'єктів, що значно знижує ймовірність виникнення дефектів. Було підтверджено, що використання сучасних зварювальних технологій сприяє підвищенню корозійної стійкості швів та їх здатності витримувати високі навантаження. Автоматизація процесів виявилася ефективною для забезпечення стабільних характеристик зварювання, навіть за складних умов експлуатації. З'ясувалося, що автоматизовані системи зменшують вплив людського фактору, підвищуючи безпеку та надійність виконання робіт. Дослідження також показало, що автоматизовані технології сприяють раціональному використанню енергоресурсів під час зварювання, мінімізують витрати на експлуатацію обладнання та забезпечують відповідність відновлених трубопроводів сучасним технічним і екологічним стандартам. Впровадження цих технологій сприяє оптимізації ремонтних робіт, зменшенню їх тривалості та підвищенню довговічності трубопроводів. Це підтвердило доцільність використання автоматизованих зварювальних процесів для відновлення інфраструктури енергетичних об'єктів. Визначено, що автоматизовані процеси дозволяють забезпечити високу точність зварювання, що є критичним для роботи трубопроводів під високим тиском. Дослідження показало, що такі технології сприяють зменшенню витрат матеріалів за рахунок мінімізації кількості дефектів. Крім того, впровадження автоматизації виявилася ефективним інструментом для підвищення продуктивності ремонтних робіт та забезпечення стабільної роботи енергетичних систем у довгостроковій перспективі

**Ключові слова:** корозійна стійкість; високі навантаження; людський фактор; безпека; енергоресурси; екологічні стандарт