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Iryna Zakharova*

Doctor of Technical Sciences, Professor
Pryazovskyi State Technical University
49000, 29 Hohol Str., Dnipro, Ukraine
https://orcid.org/0009-0000-5403-2153

Serhii Shchetynin

Doctor of Technical Sciences, Professor
Pryazovskyi State Technical University
49000, 29 Hohol Str., Dnipro, Ukraine
https://orcid.org/0000-0003-1404-4285

Vira Shchetynina

Doctor of Technical Sciences, Professor
Pryazovskyi State Technical University
49000, 29 Hohol Str., Dnipro, Ukraine
https://orcid.org/0000-0001-6714-498X

Anton Zusin

PhD in Technical Sciences, Associated Professor
Pryazovskyi State Technical University
49000, 29 Hohol Str., Dnipro, Ukraine
https://orcid.org/0009-0002-0659-9299

Iryna Volenko

PhD in Technical Sciences, Associated Professor
Pryazovskyi State Technical University
49000, 29 Hohol Str., Dnipro, Ukraine
https://orcid.org/0009-0003-7871-9226

Use of robotic and automated systems in welding and restoration of parts

Abstract. The research was aimed at analysing the use of robotic systems in welding and surfacing processes of mechanical engineering to increase the productivity, accuracy, and economic efficiency of production operations. The study used methods of comparative analysis, economic analysis, and risk analysis to assess the effectiveness of implementing robotic systems in the welding process and investigate their impact on costs, product quality, and working conditions. Analysis of the effectiveness of implementing robotic technologies has shown that automation of these processes reduces the likelihood of defects in welds and surfaced coatings, ensuring stable quality at all stages of production. The use of robotic systems such as ABB IRB 6700 and Fanuc ARC Mate 100iD allowed achieving precise control over welding and surfacing parameters, in particular, temperature, material feed rate, and current. Robotic welding and surfacing systems, in particular, from Fronius, KUKA and YASKAWA, are actively used in the energy, metallurgy, nuclear and aviation industries to improve the accuracy, safety, and efficiency of production processes. The study included the development of energy-saving technology for surfacing rolls of rolling mills to improve their wear resistance and corrosion resistance using Tesla Weld SAW/MMA MZ 630 devices and the Tesla Weld R1 welding robotic arm to automate

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*Corresponding author

the process and ensure high quality of the deposited layer. It was noted that robotic systems can work with a wide range of materials, in particular aluminium, steel, and alloys, which expands the possibilities of using the technology in mechanical engineering. Due to the robotisation of welding and surfacing processes, a significant reduction in production costs is achieved, since the need for manual control and correction of the process is reduced. Automation allows surfacing on worn parts, which extends the service life of the equipment and reduces the cost of replacing it

Keywords: product quality; automation; materials; safety; economic efficiency; competitiveness

INTRODUCTION

Robotisation of production processes has become an important step in the development of mechanical engineering, especially in such energy-consuming and technologically complex operations as welding and surfacing. These processes require high accuracy, stability, and control, so automating the tasks associated with them can significantly improve production efficiency.

In mechanical engineering welding processes, the use of robotic systems has become one of the most important tasks, as they can significantly improve the productivity and quality of welding. However, there are a number of issues that require detailed study, in particular, on optimising the adaptation of robots to various materials and compounds. J. Kahnamouei & M. Moallem (2024) noted that robotic systems significantly reduced welding seam defects due to the high accuracy of automated processes. They also stressed the importance of adapting such technologies to different production conditions. C. Loukas *et al*. (2021) indicated a significant reduction in costs and increased productivity in mass production, due to the automation of welding processes. Their research has shown that the use of robotic systems has helped to optimise production lines and increase production volumes. C. Zheng *et al*. (2022) drew attention to the significant initial costs of implementing robotic systems, which are quickly recouped by reducing shortage costs and improving efficiency. They also emphasised that using a hybrid autonomous programming method for welding systems reduces setup time and improves accuracy. S. Murugan & P. Sathiya (2024) emphasised the importance of ensuring the safety of workers through the use of robotic systems in welding processes. They noted that automation made it possible to avoid dangerous contacts of people with high temperatures and harmful fumes.

P. Zhang *et al*. (2022) found that automation of welding processes allows precise control of the quality of welding seams in real time, which significantly reduces the likelihood of defects and increases the stability of the final product. M. Javaid *et al*. (2021) noted that robotic systems have helped to reduce environmental waste, as automation has contributed to more efficient use of materials. This allowed reducing the negative impact of production on the environment. X. Wang *et al*. (2021) investigated how robotic systems can reduce the time required to set up welding machines when working with different types of joints. This allowed maintaining a high speed of production processes and increasing their flexibility. D. Lee & K. Han (2024) emphasised that automation of welding processes significantly reduced the need for manual quality control. They also noted that this reduced the risk of human error and improved the accuracy of work. A. Mehta & H. Vasudev (2024) investigated the impact of automation on the stability and accuracy of welding processes, especially in the context of mass production of metal structures. They stressed that robotic systems have significantly improved quality and reduced production costs. Thus, although a number of aspects of welding automation have been studied, there are significant gaps in research on the impact of working conditions on the efficiency of robotic systems, adaptation to different types of materials, and the economic aspects of implementing such technologies in production. The purpose of the study was to comprehensively analyse robotic and automated systems as a tool for improving the efficiency and quality of welding and surfacing processes in mechanical engineering.

MATERIALS AND METHODS

The method of comparative analysis helped to evaluate the efficiency of robotic systems in comparison with conventional welding processes, where operators play the main role. By comparing the operation of robots such as ABB IRB 6700, Fanuc ARC Mate 100iD, and Kawasaki RA06L with manual welding, the level of accuracy and stability of the welding seams was determined. The ABB IRB 6700 is a powerful robotic system that is known for its versatility and ability to perform precise welding operations. Due to its high manoeuvrability and ability to work in confined spaces, the robot provides high welding accuracy even in difficult or hard-to-reach places. This allows producing compounds that meet the highest quality standards, and also reduces the likelihood of defects that occur due to the human factor. Fanuc ARC Mate 100iD specialises in welding operations and is one of the most popular robots in the industry. Its ability to quickly adapt and accurately perform complex welding seams can significantly reduce processing time and increase production efficiency. This system provides high process stability, which is critical for the production of parts operating under heavy loads, where any error can lead to serious breakdowns.

The Kawasaki RA06L, with its high speed and precision, is also an essential element for ensuring a continuous welding and surfacing process. Based on the ability to perform precise movements in three axes, this robot can provide the highest quality of connections and improve the efficiency of restoring parts. Its ability to accurately implement programme instructions allows maintaining a constant quality of welds, which is critical for ensuring the strength of structures. To analyse the impact of robotic systems on welding processes in mechanical engineering, data from real manufacturing companies that have implemented systems such as ABB IRB 6700, Fanuc ARC Mate 100iD and Kawasaki RA06, and companies that use conventional welding methods, were used. As part of the analysis, the technical characteristics and performance of these systems were studied to optimise welding processes.

Motor Sich Joint Stock Company (n.d.) (Ukraine) has implemented ABB IRB 6700 for welding automation. According to reports, the plant managed to significantly reduce the cost of materials and energy, and improve the quality of welding. The use of this system ensured the stability of processes and reduced the likelihood of defects. Fanuc Corporation (n.d.) (Japan), installed Fanuc ARC Mate 100iD to perform welding on complex parts. Reports indicate an increase in the efficiency of the system in conditions of large production volumes and minimisation of defects. Due to the high accuracy of settings, this system adapts well to working with different materials, which expands its capabilities. Kawasaki Robotics (n.d.) (Japan) uses Kawasaki RA06 to perform welding operations with various metals, in particular, titanium alloys. Analysis of the reports showed a significant improvement in the accuracy and stability of welding seams, which is especially important for the production of high-tech parts. Joint Stock Company Kharkiv Tractor Plant (n.d.) (Ukraine), which operates according to classical welding methods, without the use of robotic systems, in its reports notes higher costs for materials and energy, and an increased risk of defects due to the human factor. In addition, the processes at this enterprise are less stable than automated systems.

In the study, an energy-saving technology for surfacing working rolls of rolling mills was developed to increase their wear resistance and corrosion resistance, and reduce the energy intensity of the process. The method of high-speed submerged arc surfacing was used, which provided resistance to abrasive wear and thermal loads. To implement the process, Tesla Weld SAW/MMA MZ 630 devices and the Tesla Weld R1 robotic welding manipulator were used, which allow automating the process and ensuring a stable temperature regime to achieve high quality of the deposited layer. This approach to analysis allowed identifying the advantages of implementing robotic systems in welding processes.

RESULTS

In today's machine-building industry, the accuracy and efficiency of production processes are critical factors for achieving high product quality and reducing costs. Robotic systems have a significant impact on improving productivity and accuracy, especially in processes such as welding and surfacing. With the introduction of advanced automation technologies such as ABB IRB 6700, Fanuc ARC Mate 100iD, and Kawasaki RA06L robots, manufacturers can significantly improve the efficiency of their production lines.

In general, the introduction of robotic systems in welding and surfacing processes not only improves the accuracy of operations, but also reduces the impact of the human factor, which reduces the risk of errors and defects (Pires *et al.*, 2022). The high stability of robots ensures consistent product quality, which is essential for market competitiveness. Restoration of parts, welding of complex joints, and the production of high-tech products – all this has become possible due to the use of robotic systems, which are being improved every year, providing more and more opportunities to improve the quality and efficiency of production. Thus, robotic systems are able to adapt to different types of materials and joints, which allows them to work in small-scale production conditions without significant settings (Table 1).

Table 1. Adaptation of robots to different types of materials and joints to ensure stable welding seam quality

Material type	Robotic system	Adaptation parameters	Impact on seam quality
Steel	ABB IRB 6700, Fanuc ARC Mate 100iD	Temperature, electrode feed rate	High welding accuracy, minimal defects
Stainless steel	Kawasaki RA06L	Feed rate, voltage regulation	Maintaining joint strength, absence of corrosion
Aluminium	ABB IRB 6700	Temperature control, acceleration of the welding process	Seam strength, avoiding overheating
Titanium	Fanuc ARC Mate 100iD	Fine-tuning of current and temperature	High quality welded joint
Brass	Kawasaki RA06L	Gas flow control, welding speed	Clean seam, absence of defects

Source: compiled by the authors

Some robotic systems cannot work with certain materials due to their physical properties, such as low or high thermal conductivity, melting point, sensitivity to overheating, or susceptibility to corrosion. For example, materials with low thermal conductivity (for example, titanium) require special settings for welding parameters, since insufficient heating can lead to joint defects. However, some robots may not have sufficient accuracy or adaptability to specific materials, which limits their use in certain production conditions. Automatic parameter adjustment is one of the biggest advantages of modern robotic systems. Robots are equipped with systems that automatically adjust parameters for each specific process, allowing them to work with different types of materials, from steel to aluminium, with different thicknesses and complex geometries. This is especially important when it comes to surfacing, which requires precise control of the material supply and temperature conditions.

For welding processes, robots such as the FANUC ARC Mate 100iD have built-in systems that allow automatically adjusting the voltage and wire feed rate, depending on the thickness and type of material. This allows performing high-quality welding at different stages of production, without having to manually adjust the parameters for each individual stage. This flexibility allows significantly reducing the preparation time for work and increasing the speed of production. Surfacing, which is often used to restore parts, also benefits from automatic parameter adjustment. The ABB IRB 6700 can quickly adapt its settings to changing operating conditions, which allows maintaining a stable process even under different temperature conditions or when changing the shape of parts. If it is necessary to repair complex or large-sized products, the operation can be configured so that the system maintains the optimal material feed rate and its distribution by the surface of the part.

Fronius has developed robotic pipeline welding systems that are important elements in the energy sector, especially on oil and gas platforms, and in chemical and petrochemical plants. One of these systems is Fronius TPS/I, which provides high welding accuracy in difficult conditions, automating the processes of filling joints on pipelines (Pires *et al*., 2022). These pipelines require special strength and tightness, as they transport liquid or gas under high pressure, which places high demands on the quality of welding seams. The system is capable of operating in confined spaces, which is especially important for welding pipes in hard-to-reach areas, such as underwater parts of pipelines or in cramped conditions on oil platforms. Based on its characteristics, Fronius TPS/I ensures efficient and accurate welding even in such extreme conditions, which significantly reduces the time required for repair work and increases the reliability of pipelines.

Robotic surfacing systems are actively used in the metallurgical industry, for restoring or strengthening structures, such as rolls or other components that are subjected to heavy mechanical loads (Puzyrov & Hrechka, 2024). One of these innovative systems is Fronius CMT, which allows precise surfacing, even on thin metals, without overheating the material (Ocansey *et al*., 2024). This is especially important for maintaining stable performance in metallurgical processes, where the metal can be subjected to heavy loads and high temperatures. Fronius CMT works on the principle of minimising the thermal impact on the material, which prevents overheating and deformation. This technology significantly improves the quality of the deposited metal, reduces the likelihood of cracks and defects, and reduces the cost of materials and energy. The use of robotic systems for the restoration of metallurgical structures can increase production efficiency, increase the service life of equipment, and reduce the cost of replacing worn parts.

In the nuclear industry, welding components of nuclear reactors requires maximum accuracy and reliability of connections, since any defect can lead to serious consequences (Ali *et al*., 2022). For this purpose, robotic welding systems are actively used, which can work in confined spaces and with high requirements for seam accuracy. For example, KUKA offers specialised work to perform welding operations on structures that are used in nuclear installations (Kołodziejczak *et al*., 2022). The system is capable of welding structures made of high-alloy steels that can withstand high temperatures and radiation loads. Such robots can be used for welding pipes, reactor vessels, and other key components that are exposed to heavy loads. Since precision and tightness of joints are crucial for safety in the nuclear industry, robotic systems allow achieving high precision joints that meet all safety requirements.

In the aviation and space industries, welding is an important process for manufacturing high-precision structures from materials such as titanium and other light alloys. Robotic welding systems are used to ensure high joint strength with minimal deformation, which is critical for components exposed to high loads. YASKAWA uses its robotic systems for precise welding of aviation components (Vasilev *et al*., 2021). They use both laser welding systems and conventional TIG or MIG welding methods, which allows maintaining high quality welds, even with large production volumes. These systems provide the precision, stability, and high quality of connections that are necessary to ensure the safety and reliability of aviation and space structures, where even minor defects can lead to serious consequences. Welding technologies in the aviation and space industries allow producing lightweight but strong structures that meet high requirements for reliability and safety.

The development of energy-saving technology and equipment for surfacing working rolls of rolling mills is an urgent task, since it helps to increase their corrosion resistance, crack resistance, wear resistance, and reduces the energy intensity of the process and the cost of rolled metal (Hnatenko, 2024). For efficient operation of the roll, it is necessary to ensure high strength of its working surface, and resistance to abrasive wear, thermal loads, thermal cyclic influences, and corrosion. These characteristics can be achieved by using the high-speed submerged arc surfacing method. The working roll of the rolling mill is shown in Figure 1 and is presented as a cylindrical part with a deposited reinforced layer, which provides increased wear resistance and durability during operation.

The most common technologies are those based on automatic submerged arc surfacing. This is because this method of surface restoration has a number of significant advantages over other methods. The advantage of this recovery method is the high productivity of the process, combined with high-quality surfacing, stability of mechanical properties, and chemical composition of the deposited layer, and reduced consumption of welding materials and electricity compared to other surfacing methods. The technology of electric arc surfacing allows mechanising both basic and auxiliary operations, which contributes to the automation of the process. This greatly simplifies the work of service personnel and improves the working conditions of workers.

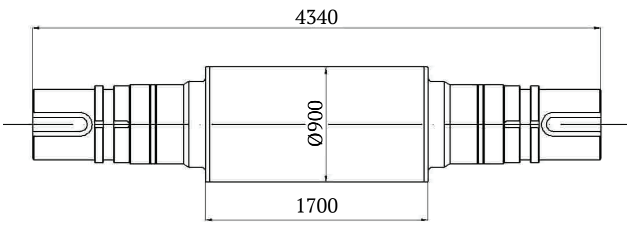

Figure 1. Working roll of the rolling mill
Source: R. Srinivasulu *et al*. (2022)

It is recommended to use the Tesla Weld SAW/MMA MZ 630 automatic submerged arc welding machine. This is a universal equipment designed for automatic surfacing under a layer of flux. The device is widely used in the production of building structures, shipbuilding, the manufacture of petrochemical tanks, and vessels operating under high pressure and temperature, and in bridge welding, heavy and metallurgical equipment, and all types of composite steels. In addition, the MZ 630 can be used for manual arc surfacing and air planning. The use of this device provides a number of advantages. During automatic submerged arc surfacing, the arc burns stably in the slag cavity, which is held by plasma flows, gases and vapours of the electrode and base metal.

Current supply to the wire is carried out at a distance of 40 mm from the product, which allows welding at currents up to 3,000 A without overheating the electrode. Moreover, the current density reaches 200-250 A/mm^2, and the melting coefficient of the electrode increases to 16-19 g/A·h due to additional heating of the electrode by the current passing through it. This allows achieving a surfacing capacity of up to 15.2 kg/h. The high current density increases the arc pressure and penetration depth, which allows surfacing with low running energy and high speed. As the surfacing rate increases, the crystallisation rate ($V_{CR} = V_{S}$-Cosα), which leads to grinding of the microstructure. During submerged arc surfacing, due to the high current density, the pinch effect and magnetic pressure increase, which leads to the separation of the drop from the end of the electrode. With this, the influence of the gas flow increases, the processes of gas formation and evaporation in the drop increase. Thus, submerged arc surfacing results in fine-droplet transfer of electrode metal, and transfer in vapours. The frequency of crystallisation decreases, which leads to the development of a finely sutured crystallised seam, as a result of which the slag crust is easily removed.

Automatic submerged arc welding, due to its high current density, fine-drop transfer, and steam transfer, is approaching nanoprocesses where atoms are affected. During automatic submerged arc surfacing, the wire is fed automatically, considering the melting rate, which allows maintaining a constant arc length. The crack resistance and wear resistance of the deposited metal are improved during high-speed surfacing with low linear energy due to an increase in the crystallisation rate of the liquid metal, microstructure grinding, and reduced welding stresses.

Surfacing with low linear energy is an energy-saving process, as it helps to reduce electricity consumption, which, considering the increase in energy costs, significantly increases the efficiency of the surfacing process. A general view of the YAMZ-236 engine cylinder liner is shown in Figure 2, which shows its design features, including cooling channels, dimensions and shape that provide optimal conditions for engine operation.

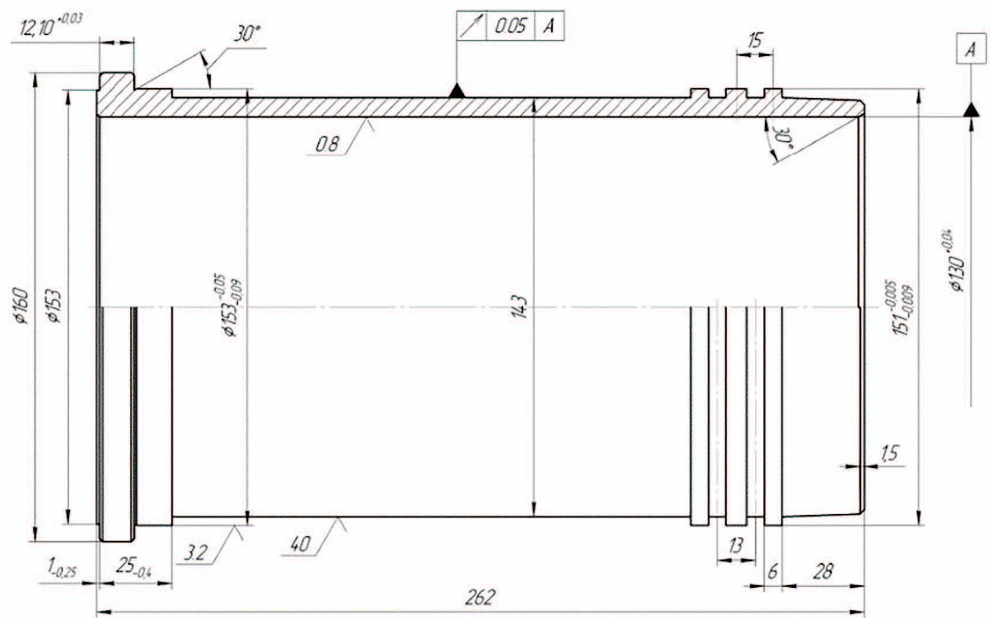

Figure 2. General view of the YAMZ-236 engine cylinder liner
Source: R. Srinivasulu *et al*. (2022)

The traditional method of surfacing consists in restoring the surfaces of parts by applying a metal layer by welding. The main advantage of this method is the ability to restore a significant amount of worn surfaces, which makes it particularly effective for repairing crankshafts that are subjected to intense mechanical loads. Surfacing is usually carried out using special welding materials that provide increased wear resistance and corrosion resistance. An important factor is the correct choice of surfacing modes, such as wire feed rate, temperature regime and cooling, as they determine the quality of the resulting layer (Zhang *et al.*, 2022).

For surfacing, a plasma arc was chosen as an energy source that ensures stable heating and high quality of the metal layer. This method allowed achieving optimal fusion of the base metal with the additive material, reducing the likelihood of defects such as pores or microcracks, and ensuring an even temperature distribution in the surfacing zone. The additive material was chosen considering the operating load conditions of the crankshaft: a steel-based alloy with the addition of chromium and molybdenum was used, which contributes to the development of highly wear-resistant phases in the deposited layer. The thickness of the surfacing layer was controlled in the range of 2-3 mm to avoid increasing the mass of the part and preserve the necessary geometric characteristics of the surface.

The temperature regime during surfacing has been optimised to ensure deep penetration of the base metal without the risk of thermal deformations. In the course of research, it was found that the temperature in the welding bath should be maintained in the range of 1,400-1,600°C to ensure high-quality diffusion adhesion between the base material and the deposited layer. The heating temperature of the additive material varied depending on its composition and for steel alloys with a high content of chromium and molybdenum was 1,450-1,550°C. To prevent local overheating and the development of thermal cracks, temperature control using optical pyrometry was used, which helped to maintain a stable thermal balance in the surfacing zone. The speed of movement of the energy source during surfacing was crucial to ensure even heat distribution and prevent the development of defects such as pores or microcracks. It was determined that the optimal speed of the energy source is 10-15 mm/s, depending on the shaft diameter and the type of filler material.

When using automated surfacing systems, such as robotic manipulators (welding robotic manipulator Tesla Weld R1), adaptive speed control algorithms were used, which performed correction of movement parameters in real time to ensure a stable temperature. Technical parameters for optimising surfacing processes for restoring the crankshaft of the YAMZ-236 engine are shown in Table 2, which presents the main values of temperature, speed of the energy source, the composition of the filler material, and other important factors affecting the quality and efficiency of the process.

Table 2. Technical parameters for optimising surfacing processes for restoring the crankshaft of the YAMZ-236 engine

Parameter	Surfacing (plasma)
Temperature in the processing area, °C	1,400-1,600
Particle temperature, °C	1,450-1,550
Source speed, mm/s	10-15
Particle speed, m/s	-
Layer thickness, mm	2-3
Cooling temperature, °C	300-500
Structure control	Fine-grained

Source: compiled by the authors

Welding and surfacing in production are critical operations that require high precision and stability. Despite great advances in technology, welding and surfacing processes have always carried certain risks associated with the human factor. Incorrectly configured parameters, physical fatigue, inattention, or even just different skill levels of employees can lead to errors and defects that reduce product quality and affect its durability. The use of robotic systems in these processes can significantly reduce the impact of the human factor, ensuring more accurate and stable operation (Sun *et al.*, 2022).

One of the main advantages of robotic systems is their ability to work in difficult and hard-to-reach places where the human hand cannot reach or where welding, using conventional methods, is extremely difficult and dangerous (Table 3). Another important benefit is to reduce the impact of fatigue and stress on performing operations. People working in long-term welding conditions may lose concentration or make mistakes due to fatigue. Robots work without interruptions and maintain high efficiency throughout the entire production cycle. This is especially important in mass production, where a large number of identical parts require thousands of welding operations and each mistake can be expensive. Table 4 illustrates the cost-effectiveness of implementing robotic systems in the welding process for small and medium-sized manufacturers. Calculations include material costs, energy resources, labour costs, and defect correction costs, which allows evaluating the possible benefits of automating the welding process. Reduced costs for raw materials, energy and labour are achieved through more precise control of welding parameters and a reduction in the number of defects.

Table 3. Impact of automation on employee safety and reduction of risks associated with hazardous welding processes

Security factor	Without automation	With automation	Impact on employee safety
High temperature	Increased risk of burns	Robots perform tasks in dangerous conditions	Minimising risks for employees
Evaporation of harmful gases	High level of health impact	Robots work in sealed areas	Reducing employee health risks
Noise and vibration	Harmful to hearing and health	Reduced noise load	Improving working conditions
Need for physical activity	High workload for employees	Robots perform heavy physical work	Reduce the risk of injury and fatigue
Risk from mechanical damage	Frequent injuries during manual welding	Reducing the possibility of injury	Significant improvement in employee safety

Source: compiled by the authors based on S. Proia *et al.* (2021)

Table 4. Evaluation of the cost-effectiveness of implementing robotic systems in the welding process for small and medium-sized manufacturers

Parameter	Without a robotic system (UAH)	With a robotic system (UAH)	Cost reduction (%)
Material costs (UAH/month)	50,000	40,000	20%
Energy costs (UAH/month)	30,000	25,000	16.7%
Labor remuneration (UAH/month)	70,000	40,000	42.9%
Costs for correcting defects (UAH/month)	15,000	5,000	66.7%
Total expenses (UAH/month)	165,000	110,000	33.3%

Source: compiled by the authors based on D. Okumus *et al.* (2023)

The introduction of robotic systems allows you to reduce the cost of raw materials due to the precise adjustment of parameters, which reduces the amount of waste. In addition, automation of the process reduces the risk of defects, which leads to a significant reduction in the cost of correcting defects, which has a positive effect on the overall profitability of production. Considering these data, the introduction of robotic systems for small and medium-sized manufacturers can significantly reduce welding costs, increasing product efficiency and quality. Compared to conventional welding methods, the use of robotic systems offers significant advantages, in particular, in improving the efficiency of the process. However, to understand exactly how robotic systems can improve welding quality and reduce costs, it is important to evaluate key parameters such as welding time, material costs, energy consumption, and weld quality. Table 5 provides a comparison of these parameters for conventional and robotic welding methods, which helps businesses to make an informed choice of the technology that best meets their production requirements.

Table 5. Comparison of welding processes using conventional and robotic systems

Parameter	Conventional welding method	ABB IRB 6700	Fanuc ARC Mate 100iD	Kawasaki RA06
Welding time	60 minutes	40 minutes	45 minutes	50 minutes
Material costs	500 UAH/month	400 UAH/month	420 UAH/month	410 UAH/month
Energy consumption	100 kW/h	80 kW/h	85 kW/h	90 kW/h
Welding quality	Variable, depends on the technician	High accuracy, stability	High accuracy, stability	High accuracy, stability

Source: compiled by the authors

Robotic systems are significantly superior to conventional welding methods in several key parameters. They allow reducing the welding time, due to the accuracy of programmable movements and the absence of a human factor, which provides a significant reduction in the duration of the process. This, in turn, reduces the cost of energy and materials, as robotic systems optimise these resources. Precise control of welding parameters also minimises waste and defects, which helps to improve the quality of welds. The absence of human error and the ability of robots to perform precise movements even in difficult conditions provides consistent, high quality of welding. With the introduction of robotic systems, enterprises can achieve not only improved productivity, but also significantly reduced costs for materials, energy resources, and defect correction, making this welding method cost-effective for large and medium-sized industries. However, for small businesses that do not have significant financial resources, the initial investment in robotic systems can be large, so they should estimate the cost of implementing such technologies in terms of their long-term profitability.

The use of sensor technologies and control algorithms in robotic welding systems can significantly improve the accuracy, stability, and efficiency of welding processes. Various robotic systems use innovative technologies to optimise the welding process and reduce the number of defects. Table 6 shows the main technologies and algorithms that are used in each of the systems to achieve the best results.

Table 6. Influence of sensor technologies and control algorithms on the welding process

Technology	ABB IRB 6700	Fanuc ARC Mate 100iD	Kawasaki RA06
Temperature sensors	High precision temperature control, which reduces defects	Precise temperature control for process stability	High temperature measurement accuracy, which minimises deviations
Positioning sensors	Improved positioning accuracy of welding elements	Positioning accuracy for stable connections	High-precision positioning to ensure accuracy
Adaptive management	Automatic parameter correction in real time	Support for stable welding parameters	Adaptive adjustment to maintain quality under different conditions
Management algorithms	Optimisation of speed and power depending on the material	Dynamic optimisation of parameters, depending on the conditions	Intelligent control, depending on the material parameters

Source: compiled by the authors

Each of the robotic systems has its own unique characteristics and approaches to the use of sensors and control algorithms. The ABB IRB 6700 is characterised by high temperature control accuracy and real-time automatic parameter correction, which minimises defects. The FANUC ARC Mate 100iD uses precise temperature control and dynamic parameter optimisation for stable welding performance. Kawasaki RA06 also provides high positioning accuracy and intelligent control, facilitating stable connections even in different conditions. The introduction of such technologies not only improves welding accuracy, but also reduces the likelihood of defects, increases productivity, and ensures stable quality at all stages of production. This is of great importance for manufacturing enterprises, where every detail is important to ensure high standards of quality and efficiency.

Restoration and repair of worn or damaged parts in the production process is important, as effectively extending the service life of equipment and machinery can significantly reduce the cost of new spare parts and improve economic efficiency. An important role in this is played by robotic systems that significantly expand the capabilities for performing tasks such as surfacing on worn parts, restoring their functional characteristics, and extending their service life. Robots allow automating these processes, ensuring high accuracy and stability, which is important when restoring parts that have suffered wear or damage (Epping & Zhang, 2018).

One of the main advantages of robotic systems is their ability to effectively perform surfacing on parts that have significant damage or wear, restoring their original functional characteristics. Surfacing is the process of applying material to the surface of a part to restore its geometry or functionality. Traditionally, this process was performed manually, which required highly qualified operators and was associated with a large amount of time. Due to robotic systems, this process can be automated, which ensures faster and more accurate execution of work, reducing the number of errors that can occur during manual operation.

Based on the ability of robotic systems to precisely control process parameters such as temperature, material feed rate, and stress, high surfacing quality can be achieved, which is critical for restoring the functional characteristics of parts. In the process of restoring parts, especially those that have undergone significant wear and tear, any inaccuracy can lead to inefficient restoration, which entails additional costs for new parts or repeated repairs. Robots that can automatically adjust parameters during operation, which allows achieving the required strength and durability of the deposited material, which significantly extends the service life of the restored part.

It is also important to note that using robotic systems to restore and repair parts reduces labour costs. Previously, to perform such operations, it was necessary to attract highly qualified employees, which was accompanied by high training and maintenance costs. Robots, due to their versatility and high accuracy, can perform these operations without human intervention, which significantly reduces labour costs and increases the efficiency of repairs.

In this way, robotic systems significantly expand the capabilities for efficient restoration and repair of worn and damaged parts, ensuring high accuracy, reducing costs, and increasing the cost-effectiveness of production. They allow preserving the functionality of parts used in difficult conditions and extending their service life, which is an important factor for reducing the cost of production and maintenance of equipment.

DISCUSSION

The use of robotic systems in mechanical engineering welding processes has demonstrated a significant improvement in the quality, speed, and safety of production. The results showed that the use of robotic systems, such as ABB IRB 6700 and Fanuc ARC Mate 100iD, improved the accuracy of welding operations, reduced the cost of materials, energy resources, and correction of defects, which was confirmed by data from real manufacturing enterprises that implemented these systems. This helped to ensure stable weld quality, minimise defects, and reduce the impact of the human factor on the final result. The adaptation of such robotic systems has reduced the likelihood of errors, which, in turn, has improved the overall efficiency of production processes in mechanical engineering.

This problem was also investigated by A. Sharma *et al*. (2021), where the results confirmed that improving the efficiency of welding processes through robotics in mechanical engineering can significantly reduce the impact of the human factor and ensure consistent quality of welds. Automation of welding allows optimising production time and reducing material costs, since robots can perform precise operations at high speed. It also helps to reduce the number of defects and increase overall production productivity. The study by S. Chen *et al*. (2022) also showed that universal recognition and positioning of angular welded joints using structured light significantly improves the accuracy of welding operations, especially in mass production environments. This allows robotic systems to ensure stable welding quality, even under variable conditions, minimising the likelihood of defects and reducing the cost of correcting defects.

Notably, the introduction of welding robots requires significant initial investment, which can become an obstacle for small and medium-sized enterprises. However, the long-term benefits of reducing production costs and improving product quality often justify these costs. In addition, automated systems can provide a high level of safety at work, as they reduce the need for human participation in potentially dangerous operations, such as working with high temperatures or toxic materials. The use of automated welding processes has also significantly reduced the cost of materials, energy and labour. Due to the high accuracy of controlling welding parameters, robotic systems allow optimising the amount of materials used and reducing the amount of waste (Kairat *et al*., 2023). In addition, the cost of correcting welding seam defects has significantly decreased, which previously required additional costs for manual inspection and refinement. Improving the efficiency of production lines has reduced overall production costs and improved the profitability of enterprises.

D. Ajiga *et al*. (2024) concluded that optimising the cost of materials through automation of welding processes can significantly reduce the amount of resources used, and improve the accuracy of the use of materials in the production process. Robotic systems can perform operations with minimal deviations, which reduces the cost of excess materials and ensures more economical use of resources. In addition, automation reduces the need for expensive materials, as robots can work efficiently with smaller portions of raw materials. The study by T. Aydinliyim *et al*. (2023) found that reducing the cost of defects and increasing the profitability of production are important advantages of automating welding processes. Due to the high accuracy and stability of robots, the probability of defects and the need to correct defects is reduced, which, in turn, lowers additional costs for repairs and alterations. This helps to increase the overall profitability of the enterprise, since reducing the cost of materials ensures more efficient use of resources and maximising profits.

These results support the above study, as automation of welding processes does lead to a significant reduction in material costs and a reduction in the number of defective products. The use of robotic systems ensures a high level of accuracy, which allows optimising processes and significantly reducing waste. This approach not only improves production efficiency, but also helps to increase the company's competitiveness in the market by reducing costs and improving the quality of final products. The integration of robotic systems has also significantly improved employee safety. Robotic complexes have taken on the most dangerous operations, such as welding in hard-to-reach places or in high temperatures. This reduced the risk of injuries associated with physical exposure to high temperatures, electrical risks, and harmful fumes. However, as some researchers have noted, it is impossible to completely exclude the need for qualified personnel to configure and monitor the operation of such systems.

It is worth noting the study by S. Yang *et al.* (2022), who also found that reducing the risk of injury with robotic systems is one of the main advantages of automation in welding processes. Robots can perform dangerous operations, such as handling high-temperature materials or working in toxic fumes, which reduces workers' contact with hazardous factors. This reduces the likelihood of injuries and ensures greater safety at production sites. In turn, I. Sarivan *et al*. (2024) concluded that welding automation significantly improves occupational safety in mechanical engineering, as robots can replace humans in the most risky production areas. This not only reduces the number of accidents, but also reduces stress and physical activity on employees, which has a positive impact on their health and overall performance. The introduction of such technologies contributes to the creation of a safer working environment and increases the overall level of occupational safety at the enterprise.

These data correspond to the theses given in the previous section, as they confirm the importance of implementing automation to improve safety in production. Reducing the physical burden on employees and replacing their participation in dangerous operations with robots significantly reduces the likelihood of injuries and accidents (Bilenko *et al.*, 2023). Thus, automation not only increases the efficiency of production processes, but also contributes to the creation of a safer and healthier working environment. Another important aspect is the flexibility of robotic systems when configured to work with a variety of materials and compounds (Akberdin *et al.*, 2023). Due to the use of state-of-the-art sensor technologies and adaptive controls, systems such as the Kawasaki RA06L allow quickly adapting settings to work with a variety of metals, including aluminium, stainless steel, and alloys. This is an important factor for businesses operating in small-scale production, where materials and types of joints often change. Thus, robotic systems provide high stability and quality of welds with minimal reconfiguration time.

F. Rocha *et al*. (2021) also conducted a study, the results of which confirmed that the flexibility of robotic systems to work with different metals is an important advantage, since modern robots can be configured to handle different types of materials, such as steel, aluminium, or stainless steel. Due to the ability to adapt the software and change the operating parameters, robotic systems can perform welding operations with high accuracy on materials with different properties. This allows businesses to work efficiently with various types of metals without the need for significant additional settings or equipment changes. R. Abebe & M. Gopal (2023) also found that the effect of robot settings on welding materials lies in the ability to accurately adjust parameters of the welding process, such as temperature, material feed rate, and current intensity. These settings provide optimal conditions for working with each specific metal, which contributes to achieving maximum weld quality. Since different materials require different conditions to achieve perfect results, the precision of robot settings is key to ensuring the stability and durability of welds.

Comparing the data obtained in the course of research, it can be concluded that robotic systems show a significant improvement in adaptation to different materials, ensuring stable welding quality, even when changing the type of metal being processed. The high flexibility of such systems reduces reconfiguration time and minimises the need to change equipment for various tasks. This, in turn, increases production efficiency and reduces the cost of materials and processing, which confirms the potential of robotisation to optimise production processes. Analysis of the economic aspects of the introduction of robotic systems has shown that although the initial costs of automating welding processes can be high, their rapid payback is the result of a significant reduction in labour costs and a reduction in the number of defects. The use of robots reduces the time required to set up equipment, which also has a positive effect on the efficiency of production lines (Korzhyk *et al.*, 2017; Liashok & Tykhanskyi, 2024). According to research, enterprises that implemented automation were able to significantly increase production volumes without additional labour costs.

G. Pop *et al.* (2024) indicated that initial investments in robotic welding systems include high-tech equipment and software. However, these costs are quickly recouped by reducing operating costs, reducing the time required to set up and process materials, and reducing defects. Accordingly, payback usually occurs in a few years, which allows reducing overall costs and increasing the profit of the enterprise. According to X. Zhao *et al.* (2021), automation can significantly improve the speed and accuracy of welding operations, resulting in reduced material costs, reduced need for additional labour, and reduced order completion time. This significantly improves the profitability of enterprises, increasing their competitiveness. An analysis of the findings shows that although the initial costs of implementing robotic welding systems are high, the long-term benefits of reducing operating costs, reducing defects, and improving welding accuracy are far outweighed. The return on investment is faster, making these technologies beneficial for businesses looking to reduce costs and improve efficiency.

Thus, the use of robotic systems in mechanical engineering welding processes is an important step towards improving production efficiency. According to the results obtained, robotisation has significantly reduced costs, increased employee safety, and ensured high product quality. However, for maximum effect, it is important to consider all aspects of implementation, in particular, the initial costs, the need for qualified personnel, and technical requirements for adapting systems to different production conditions.

CONCLUSIONS

The use of robotic systems in welding processes of mechanical engineering can significantly improve production efficiency, due to the high accuracy and stability of operations. Robotic systems such as ABB IRB 6700, Fanuc ARC Mate 100iD and Kawasaki RA06 are used for automatic welding of various materials, ensuring precise execution of seams and joints. For example, the welding time with the ABB IRB 6700 is 40 minutes, which is 33% faster than with the conventional welding method (60 minutes). The cost of materials when using ABB IRB 6700 is reduced to 400 UAH/month, which is 20% less compared to conventional methods (500 UAH/month). In addition, due to the high accuracy of operation, energy consumption is reduced: the ABB IRB 6700 consumes only 80 kW/h, which is 20% less than the conventional method with 100 kW/h. This is especially important for welding in conditions of large production volumes, where it is necessary to achieve stable quality and high strength of joints.

One of the biggest advantages of implementing robotic systems is increased economic efficiency. Using systems such as ABB IRB 6700, Fanuc ARC Mate 100iD and Kawasaki RA06L reduces the chance of defects, which reduces the cost of error correction and reduces material waste. For example, the cost of correcting defects is reduced by 66.7%, from UAH 15,000 to UAH 5,000 per month, which significantly reduces welding costs. Precise control of welding parameters, such as temperature, feed rate, and current, reduces raw material costs by 20%, from UAH 50,000 to UAH 40,000 per month, and also reduces energy costs by 16.7%, from UAH 30,000 to UAH 25,000. Automation of the process reduces the need for qualified employees, which also reduces labour costs by 42.9%, from UAH 70,000 to UAH 40,000 per month, while increasing productivity.

Robotic systems such as Fronius TPS/I and Fronius CMT significantly improve welding efficiency and accuracy in complex environments, particularly in pipeline welding and structural surfacing in metallurgy. Moreover, KUKA and YASKAWA robots provide high reliability and accuracy when performing welding operations in critical areas such as the nuclear industry and aviation.

As a result of the research, an energy-saving surfacing technology was developed, which provides high wear resistance and corrosion resistance of the working rolls of rolling mills, reducing the energy consumption of the process. The use of automated surfacing systems, such as the Tesla Weld SAW/MMA MZ 630 and the Tesla Weld R1 robotic welding manipulator, helps to improve the efficiency of the process and the quality of the deposited layers.

The introduction of such technologies also ensures high product quality. Robots can perform welding with constant accuracy, which is impossible to achieve with manual welding operations. Based on automatic parameter control, it is possible to achieve perfect welds that meet the requirements for strength and tightness, which is especially important for the production of machinery and equipment that operates in extreme conditions.

Due to these advantages, robotic systems are becoming an important element of modern mechanical engineering, which allows increasing the competitiveness of enterprises, reducing costs, and improving the quality of products. They provide not only economic benefits, but also contribute to the development of safe and efficient production processes. To further develop this topic, it is necessary to investigate the impact of integrating the latest sensor technologies and artificial intelligence on the efficiency and accuracy of robotic welding systems in various production conditions.

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CONFLICT OF INTEREST

None.

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Ірина Захарова
Доктор технічних наук, професор
Приазовський державний технічний університет
49000, вул. Гоголя, 29, м. Дніпро, Україна
https://orcid.org/0009-0000-5403-2153

Сергій Щетинін
Доктор технічних наук, професор
Приазовський державний технічний університет
49000, вул. Гоголя, 29, м. Дніпро, Україна
https://orcid.org/0000-0003-1404-4285

Віра Щетиніна
Доктор технічних наук, професор
Приазовський державний технічний університет
49000, вул. Гоголя, 29, м. Дніпро, Україна
https://orcid.org/0000-0001-6714-498X

Антон Зусін
Кандидат технічних наук, доцент
Приазовський державний технічний університет
49000, вул. Гоголя, 29, м. Дніпро, Україна
https://orcid.org/0009-0002-0659-9299

Ірина Воленко
Кандидат технічних наук, доцент
Приазовський державний технічний університет
49000, вул. Гоголя, 29, м. Дніпро, Україна
https://orcid.org/0009-0003-7871-9226

Використання роботизованих та автоматизованих систем у процесах зварювання та відновлення деталей

Анотація. Дослідження спрямоване на аналіз використання роботизованих систем у зварювальних і наплавлювальних процесах машинобудування з метою підвищення продуктивності, точності та економічної ефективності виробничих операцій. У дослідженні були використані методи порівняльного аналізу, економічного аналізу та аналізу ризиків для оцінки ефективності впровадження роботизованих систем у зварювальний процес і вивчення їх впливу на витрати, якість продукції та умови праці. Аналіз ефективності впровадження роботизованих технологій показав, що автоматизація цих процесів знижує ймовірність дефектів зварних швів і наплавлених покриттів, забезпечуючи стабільну якість на всіх етапах виробництва. Використання роботизованих систем, таких як ABB IRB 6700 і Fanuc ARC Mate 100iD, дозволило досягти точного контролю над параметрами зварювання та наплавлення, зокрема температурою, швидкістю подачі матеріалу і струмом. Роботизовані системи зварювання та наплавлення, зокрема від компаній Fronius, KUKA та YASKAWA, активно використовуються в енергетиці, металургії, атомній промисловості та авіації, для підвищення точності, безпеки та ефективності виробничих процесів. Дослідження передбачало розробку енергозберігаючої технології наплавлення робочих валків прокатних станів для покращення їх зносостійкості і корозійної стійкості з використанням апаратів Tesla Weld SAW/MMA MZ 630 та зварювального роботизованого маніпулятора Tesla Weld R1 для автоматизації процесу і забезпечення високої якості наплавленого шару. Відзначено, що роботизовані системи можуть працювати з широким спектром матеріалів, зокрема алюмінієм, сталлю та сплавами, що розширює можливості застосування технології у машинобудуванні. Завдяки роботизації процесів зварювання та наплавлення досягається значне зниження виробничих витрат, оскільки зменшується потреба в ручному контролі та корекції процесу. Автоматизація дозволяє здійснювати наплавлення на зношених деталях, що подовжує термін служби обладнання та знижує витрати на його заміну

Ключові слова: якість продукції; автоматизація; матеріали; безпека; економічна ефективність; конкурентоспроможність