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Ruslan Kulykovskyi — Candidate of Technical Sciences, Associate Professor, Vice-Rector for Scientific and Pedagogical Work and Issues of University Development Prospects, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: kulikovski@zp.edu.ua*, ORCID: 0000-0001-8781-2113

Denys Molochkov — Ph. D., Senior Lecturer, Department of Information Technologies in Electronic Devices, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: molochkov@zp.edu.ua*, ORCID: 0000-0002-9030-5371

Oleksandr Kostin — Candidate of Technical Sciences, Professor, Professor at the Department of Welding Engineering, Admiral Makarov National University of Shipbuilding, Mykolaiv, Ukraine, *e-mail: kostin.weld@gmail.com*, ORCID: 0000-0002-4739-660X

Volodymyr Martynenko — Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Electrical Power Engineering, Electrical Engineering, and Electromechanics, Mykolaiv National Agrarian University, Mykolaiv, Ukraine, *e-mail: martynenko@mnau.edu.ua*, ORCID: 0000-0003-4067-3640

Serhii Oleksiienko — Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Welding and Construction Technologies, Chernihiv Polytechnic National University, Chernihiv, Ukraine, *e-mail: sv.oleks@ukr.net*, ORCID: 0000-0001-5475-4439

OPTIMIZATION OF THE DIFFUSION BONDING PROCESS FOR A MULTILAYER JOINT IN 14Cr17Ni2 ALLOY

Purpose. *To optimize diffusion bonding technology for multilayer joints of aircraft engine components made of 14Cr17Ni2 alloy, minimizing material degradation and geometric distortions.*

Research methods. *Analysis of conventional (T1) and intensified (T2) diffusion bonding (using an intermediate nickel layer up to 10 μm). Parameters were optimized on laboratory samples and full-scale models; joint quality was assessed by metallographic analysis.*

Results. *T1 technology requires high pressure (15–20 MPa) at 950–1050 °C. Optimized T2 technology (with a Ni layer) showed superior results: welding temperature 950 °C, pressure 5 MPa, holding time 50 min. The Ni layer allowed for a 3-4 fold reduction in pressure, use of a lower welding temperature, maintained high joint quality, and ensured deformation ≤4%. Metallography confirmed the absence of defects in the microstructure. The reduced welding temperature of 950°C prevents post-weld hardening of the 14Cr17Ni2 alloy.*

Scientific novelty. *Optimal parameters for diffusion welding of multilayer joints of 14Cr17Ni2 alloy at low pressure using a thin Ni interlayer have been determined, ensuring defect-free, high-quality joints with significantly reduced welding pressure and temperature. The optimal interlayer thickness allows leveraging the contact strengthening effect to achieve a joint with strength comparable to the base material.*

Practical value. *T2 diffusion bonding technology ensures reliable manufacturing of precision multilayer components from 14Cr17Ni2 alloy with minimal thermo-mechanical impact and reduced manufacturing complexity (lower pressure equipment). This is a promising and economically viable solution for the aviation industry, for components requiring high precision and performance under extreme conditions.*

Key words: *diffusion bonding, 14Cr17Ni2, interlayer, relative plastic deformation, surface activation.*

Introduction

The advancement of the aviation industry in the 21st century is characterized by the intensive implementation of the latest scientific and technological achievements. A prominent example is the development and application of methods for obtaining permanent joints of structural materials, particularly in the solid phase [1]. Among such methods, diffusion bonding holds a special place. It's a high-technology solid-phase process based on atomic diffusion and local plastic deformation at elevated temperatures. This process ensures the production of high-quality permanent joints for a wide range of materials and is crucial for manufacturing high-precision components due to minimal welding deformations [1].

The object of this study is multilayer joints of 14Cr17Ni2 alloy, produced by diffusion bonding for the "Amplifier Block" component (Fig. 1). This component is a two-stage amplifier of command signals in the automatic control system of aircraft engine valves and operates under exposure to air at compressor command pressure over a wide temperature range, from -60 to +500 °C. Alloy 14Cr17Ni2 is classified as difficult-to-weld, and welded joints in the heat-affected zone exhibit reduced corrosion

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resistance [2]. The high precision and reliability requirements for such components, combined with the material's specific characteristics, necessitate a thorough selection and optimization of their joining technology.

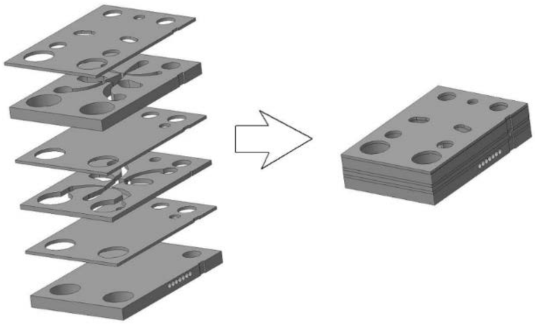

Figure 1. Multilayer structure of the Amplifier Block

The aim of this work is to develop and optimize the technological process of diffusion bonding for the "Amplifier Block" made of 14Cr17Ni2 alloy. This process aims to ensure the formation of a high-quality joint while minimizing the negative impact on the material's properties and the product's geometric parameters, specifically by reducing the main process parameters through a justified selection of an intensification method.

The formation of a permanent joint in the solid phase is based on fundamental physicochemical principles, which include the stages of physical contact formation, electronic interaction, and the development of diffusion processes [3]. This requires not only the bringing together of surfaces but also activation energy (thermal and/or mechanical) [4]. Under real conditions, the process is complicated by the presence of microroughness and various films on the surfaces. The formation of a joint is thermodynamically favorable when the surface free energy of the system decreases. This energy depends on the material's structure and temperature but is practically independent of pressure, although adsorbed gases significantly reduce it [5]. The thermodynamic feasibility of joining similar materials is evident, whereas for dissimilar materials, it is determined by the possibility of a chemical reaction and a change in Gibbs energy.

The process of joint formation during diffusion bonding occurs in three conventional stages. Physical interaction involves bringing atoms close enough for quantum-mechanical interaction and overcoming microroughness through local plastic deformation. The next stage, activation of contact surfaces, involves the formation of active centers through the transition of the system to a higher energy activated state, where physicochemical interaction occurs at sites of crystal structure defects. The final stage, volumetric interaction in the contact zone, includes the formation of strong chemical bonds, the development of diffusion (self- and interdiffusion, accelerated by increasing temperature and along grain boundaries and surfaces) and relaxation processes, leading to the homogenization of the joint [6].

The key parameters determining the quality of a diffusion bonded joint are surface cleanliness and roughness, the composition of the welding atmosphere, the thermal cycle (welding temperature), an applied pressure, and welding duration [7–11]. Alloys with a high chromium content, such as 14Cr17Ni2, are characterized by the formation of thermodynamically stable oxide films on their surfaces, which complicate welding and traditionally necessitate the use of high temperatures and significant plastic deformation for their disruption [2, 12, 13]. This, in turn, can negatively affect the material properties and product accuracy.

To enhance the efficiency of the diffusion bonding process for 14Cr17Ni2 alloy and achieve the required joint quality at reduced technological parameters, various intensification methods aimed at activating physicochemical processes during the three main stages of joint formation were analyzed. Known methods, such as cyclic pressure variation, the application of ultrasonic vibrations, the imposition of tensile forces, impact pressure, controlled forced deformation, as well as the influence of electric or magnetic fields, or ionizing radiation, can activate the formation of physical contact, the disruption of surface films, and mass transfer in the joint zone [14, 15]. This, in turn, may allow for a reduction in the process temperature or duration. However, a comprehensive analysis of these methods in relation to the stated task – the fabrication of multilayer precision components from 14Cr17Ni2 alloy – revealed a number of significant limitations. Specifically, many of the listed approaches lead to substantial plastic deformation of the welded parts, which is unacceptable for precision products. Furthermore, they do not always ensure that the joint strength is equal to that of the base metal when the welding temperature is significantly lowered, and often require the development of complex technologies, the creation of specialized high-precision equipment, and precision tooling, which is associated with considerable material costs.

Considering these limitations and the necessity to meet a set of requirements, such as minimal deformation, high joint quality, and the possibility of reducing the welding temperature, pressure, and time, the application of intermediate plasticizing layers was chosen as the most promising intensification method. This method allows for a reduction in chemical heterogeneity in the joint zone, improvement of conditions for the disruption of oxide films and the formation of physical contact due to the plastic deformation of the interlayer itself, minimization or complete elimination of significant plastic deformation of the main components, and a substantial reduction in the temperature, pressure, and holding time of diffusion bonding, while ensuring the attainment of joints with properties close to those of the base material [16]. The use of intermediate non-fusible layers, particularly those of plastic metals such as nickel, is an effective method for intensifying the diffusion bonding process and reducing its energy-force parameters. Unlike fusible interlayers, which essentially bring the process closer to brazing and may not provide the neces-

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sary joint strength, non-fusible layers promote the formation of a high-quality metallurgical bond.

Nickel, as a transition d-metal, is characterized by high strength and ductility, which are maintained over a wide temperature range. It forms solid solutions or stable phases with most structural metals, including the components of 14Cr17Ni2 alloy, thereby avoiding the formation of brittle intermetallics in the joint zone [16]. Its enhanced deformability compared to many other metals promotes better formation of physical contact in the early stages of welding. Intermediate layers can be applied in the form of foils, powders, or thin coatings (electroplated or deposited). Foils, having a surface activity close to that of a bulk material and a significant thickness (0.05…1.0 mm), are primarily used to prevent the formation of undesirable phases. Powder interlayers, although possessing high free energy which promotes sintering, are difficult to apply as a uniform layer. Thin electroplated or deposited coatings, however, due to structural defects, a high surface-to-volume ratio, and small thickness, have significantly higher free energy compared to foils, which activates mutual diffusion processes [16]. Electroplated coatings also provide surface protection against oxidation and, due to tangential stresses at the "substrate-coating" interface, promote the disruption of oxide films and activation of the base metal surface. In view of these advantages, this particular method was chosen for forming the nickel intermediate layers.

Materials and methodology

The object of the research was multilayer joints fabricated from 14Cr17Ni2 martensitic-ferritic stainless steel, which is considered difficult-to-weld. The studies were conducted on model samples simulating the design of the "Amplifier Block" component – an assembly of six rectangular plates with dimensions of 38×58 mm and individual plate thicknesses ranging from 1 to 4.2 mm. The total thickness of the assembly before bonding was 12.8 mm. Samples of various sizes were used for the experimental investigations. Initial development of the parameters for technology T1 (conventional diffusion bonding) was performed on 15×15 mm plates of 14Cr17Ni2 alloy with thicknesses of 1 to 4.2 mm. For technology T2 (bonding with an intermediate nickel layer), 20×15 mm plates of similar thickness were used. Verification of the optimized parameters was carried out on full-scale 38×58 mm plates.

The roughness of the surfaces to be bonded did not exceed Ra=1.25 µm (according to ISO 21920-2). Mechanical surface preparation was performed by grinding using an abrasive wheel with a vulcanite bond and a grit size ensuring the specified roughness (F150 and finer according to ISO 8486-1 for bonded abrasives). Surface cleaning before bonding involved sequential wiping with technical grade acetone and technical grade ethyl alcohol. In the case of technology T2, a nickel layer up to 10 µm thick was electrodeposited on each side of the mechanically processed and cleaned workpieces. For samples used during the T2 regime development stage, the nickel layer thickness was 8–15 µm.

Initial development of optimal parameters for technologies T1 and T2 was conducted on a modernized USEPVN-4N diffusion bonding unit with radiation heating. Verification of the optimized regimes on full-scale samples was performed on a UDSV-DT diffusion bonding unit with an induction heating source. Validation of the technological process according to technology T2 was carried out using SECO/WARWICK vacuum high-temperature furnaces. To prevent adhesion between the elements of the welding fixture and the model assembly, their contact surfaces were treated with an aqueous solution of boron nitride.

The development of the diffusion bonding technology was carried out in two main directions. The first direction, technology T1 – conventional, aimed to determine the optimal parameters (temperature, pressure, holding time) for bonding without the use of intensification measures. The investigated parameters included a welding temperature (T_w) in the range of 850–1100 °C, a pressure (P_w) from 5 to 20 MPa, and a holding time (t_w) from 20 to 50 minutes. The vacuum level was maintained at not less than 10^{-3} mm Hg. Cooling of the parts was carried out in vacuum down to a temperature of 100°C.

The second direction, technology T2 – utilizing nickel interlayers, aimed to reduce the bonding pressure and temperature. The welding temperature (T_w) ranged from 900 to 950 °C. The bonding pressure (P_w) varied in the range from 1 to 10 MPa. The bonding time (t_w) was varied from 25 to 65 minutes. Fixation of the assembly elements before bonding was achieved using tensioning steel strips, resistance welded to the ends of the assembled stack. The thermal cycle included preheating to 600 °C with a holding time of 30 minutes, subsequent heating to the bonding temperature at a rate of 6–8 °C/min, holding at the bonding temperature and pressure, and subsequent furnace cooling to 70–100 °C.

The quality of the diffusion bonds was evaluated by deformation control, metallographic analysis, and visual inspection. Deformation control consisted of measuring the thickness of the samples before and after bonding using an MK-25 type micrometer. The displacement of the pressing system rod during bonding was also recorded. The maximum permissible shortening of the component after bonding was not to exceed 0.5 mm. Metallographic analysis was performed to detect defects such as lack of fusion, cracks, and kissing bonds, and to evaluate the microstructure of the joints. Metallographic sections were prepared by mechanical means. For etching the metallographic sections, a reagent consisting of 20 g of copper sulfate, 100 cm³ of hydrochloric acid, and 100 cm³ of ethyl alcohol was used, applied by swabbing. Microstructural investigation and photography were conducted using an NU 2 metallographic microscope.

Results and discussion

The development of optimal parameter combination for diffusion bonding of 14Cr17Ni2 alloy using the conventional technology (T1), i.e., without the application of intermediate intensifying layers, was conducted in two

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stages. The aim was to determine such combinations of temperature, pressure, and holding time that would ensure the formation of a high-quality, defect-free joint with an acceptable level of part deformation.

In the first stage, the dependence of the relative deformation (ε) of 14Cr17Ni2 alloy on the welding time (t_w) was determined at fixed values of temperature (T_w = = 1000 °C) and pressure (P_w = 20 MPa) (Fig. 2). It was established that the formation of the welded joint begins after only 5 minutes of holding time. This time corresponds to the completion of the transient creep stage, characterized by a continuous decrease in the deformation rate, and the transition to the steady-state creep stage. A high-quality, defect-free welded joint was formed with a holding time of 20 minutes or more. Thus, although increasing the holding time at given T_w and P_w typically enhances the joint strength up to a certain limit, after which its growth ceases, it also leads to a continuous increase in the deformation of the workpieces. Analysis of the quality of the obtained joints and the level of deformation showed that the optimal welding time under these conditions should be considered t_w = 20 min. Under this parameter values, the absence of defects in the welded joint is ensured, and an acceptable level of deformation (ε = 3 %) is achieved, which meets the requirements for the investigated component.

In the second stage of research, with a fixed optimal welding time of t_w = 20 min, an experiment was conducted to determine the optimal range for varying the welding pressure P_w and temperature T_w. Welding temperature is a critical parameter as it determines the plasticity of the metals and the rate of diffusional exchange between the contacting surfaces. Even small changes in temperature can significantly affect the kinetics of joint formation. An increase in pressure, in turn, promotes an improvement in joint quality. However, excessively high pressure can cause an undesirable level of plastic deformation of the parts, changes in their shape, or even failure. During the experiments, the welding temperature was varied in the range from 850 to 1100 °C, and the pressure was varied from 5 to 20 MPa (Fig. 3).

At a welding temperature T_w = 850 °C and a pressure P_w = 20 MPa, a relatively low level of deformation (ε = =1.6%) was ensured. However, metallographic analysis revealed lack of fusion (Fig. 4a). This indicates an insufficiency of temperature or holding time for the given pressure. At lower pressures (P_w = 5–15 MPa) and a temperature of 850°C, only adhesion of the welded plates was observed. These plates, as shown by the microsection, were separated by an oxide strip (Fig. 4b) and easily detached from each other upon an attempt to separate them.

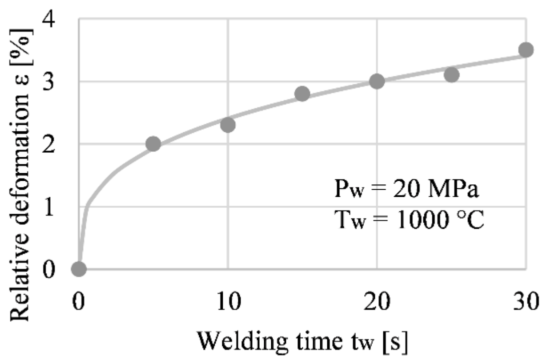

Figure 2. Strain (ε) of 14Cr17Ni2 alloy samples as a function of welding time (t_w)

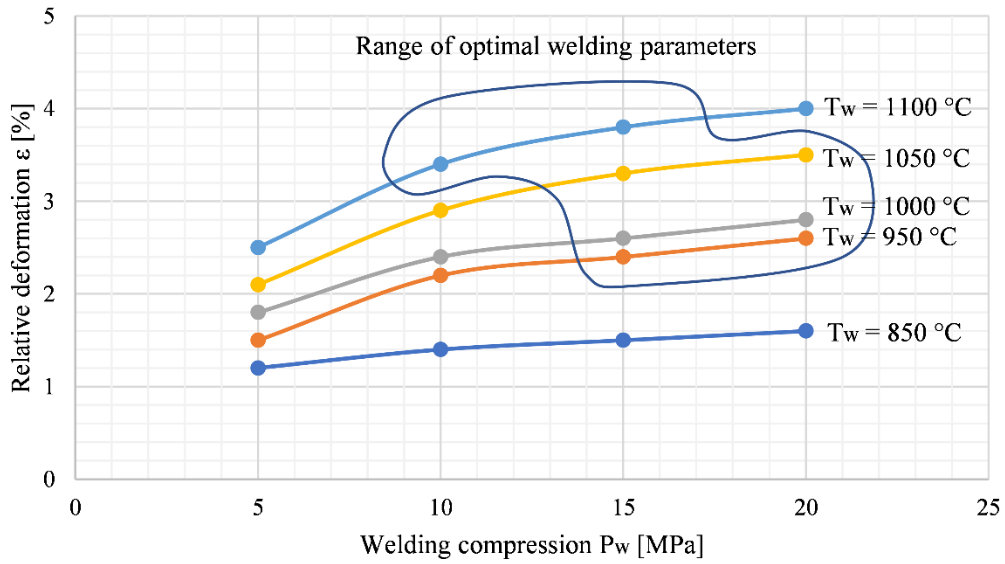

Figure 3. Effect of applied pressure (P_w) on plastic strain (ε) of 14Cr17Ni2 alloy samples

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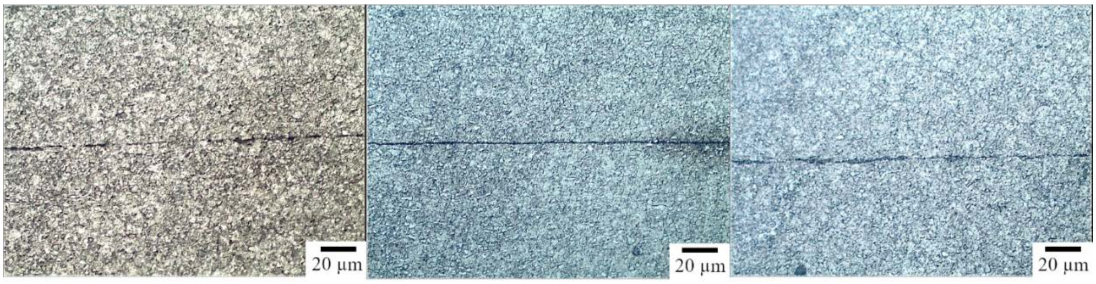


a b c

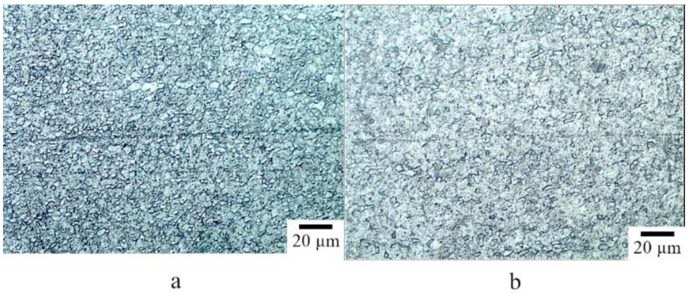
Figure 4. Microstructure of the welded joint of 14Cr17Ni2 alloy at [T_w = 850°C; P_w = 20 MPa; t_w = 20 min] (a); [T_w = 850°C; P_w = 5 MPa; t_w = 20 min] (b) and [T_w = 950°C; P_w = 5 MPa; t_w = 20 min] (c)

Increasing the welding temperature to T_w = 950 °C at a pressure P_w = 5–10 MPa did not ensure the required joint quality due to lack of fusion and adhesion (Fig. 4c). Conversely, at P_w = 15–20 MPa and a temperature of 950°C, high-quality joints with mutual diffusion of the joined materials across the entire contact zone were successfully obtained (Fig. 5a). The relative deformation of the joints in this case did not exceed 2.6 %. Similar joint quality was also observed when welding at a temperature of 1000 °C; the maximum relative deformation was 2.8 %. Further increasing the temperature to T_w = 1050 °C ensured a high-quality welded joint and a change in relative deformation to 3.5% at P_w = 20 MPa and 3.3% at P_w = 15 MPa (Fig. 5b). When welding at lower applied pressures, a defective welded joint was formed. A temperature of 1100 °C and a pressure in the range of P_w = 10–20 MPa ensured a defect-free joint. In this case, welding with an applied pressure P_w = 20 MPa led to an increase in the deformation of the welded joint to more than 4 %. According to the requirements for the fluidic amplifier block, the permissible level of deformation is not more than 4 %. This threshold was exceeded only when welding with the parameters T_w = =1100 °C, P_w = 20 MPa, and t_w = 20 min.

Analysis of the joints in the test samples, obtained by conventional diffusion bonding of 14Cr17Ni2 alloy, allowed for the determination of the following recommended regime parameters: welding temperature T_w = 950–1050°C, pressure P_w = 15–20 MPa, and holding time t_w = 20 min. If welding is performed at a higher temperature of T_w = 1100°C, the welding pressure should be within the range of P_w = 10–15 MPa and the holding time t_w = 20 min to avoid excessive deformation. Thus, the application of "conventional" diffusion bonding technology for 14Cr17Ni2 alloy requires the use of a universal diffusion bonding unit capable of providing a relatively high range of welding pressure (10–20 MPa).

The use of intermediate soft interlayers is a known method for intensifying the diffusion bonding process, allowing for a reduction in process temperature and pressure. In this work, an electrodeposited nickel interlayer with a thickness of 8–15 µm was chosen to intensify the diffusion bonding process of 14Cr17Ni2 alloy and minimize the thermo-mechanical impact on the material. The development of welding regimes for technology T2 was carried out with the aim of determining the minimum possible applied pressure while ensuring a high-quality joint. The welding temperature was reduced to 900°C, which allows for the avoidance of additional heat treatment cycles for the welded joint, as hardening of 14Cr17Ni2 alloy is recommended from temperatures of 970°C and above. The welding pressure P_w was varied in the range from 1 to 10 MPa, and the welding time t_w was changed from 30 to 65 minutes depending on the pressure.

At a pressure P_w = 1 MPa and a holding time t_w = 65 min, the deformation of the welded assembly was ε = 0.8%. However, this regime did not ensure the required quality of the welded joints, as metallographic analysis revealed adhesion of the plates (Fig. 6a), complete (Fig. 6b) or partial lack of fusion (Fig. 6c). The thickness of the intermediate nickel layer in the joint was 21–24 µm. Such a result indicates that a pressure of 1 MPa is insufficient to ensure proper physical contact and surface activation, even with a prolonged holding time and the presence of a plastic nickel interlayer.



a b

Figure 5. Microstructure of the welded joint of 14Cr17Ni2 alloy at [T_w = 950 °C; P_w = 15 MPa; t_w = 20 min] (a) and [T_w = 1050 °C; P_w = 15 MPa; t_w = 20 min] (b)

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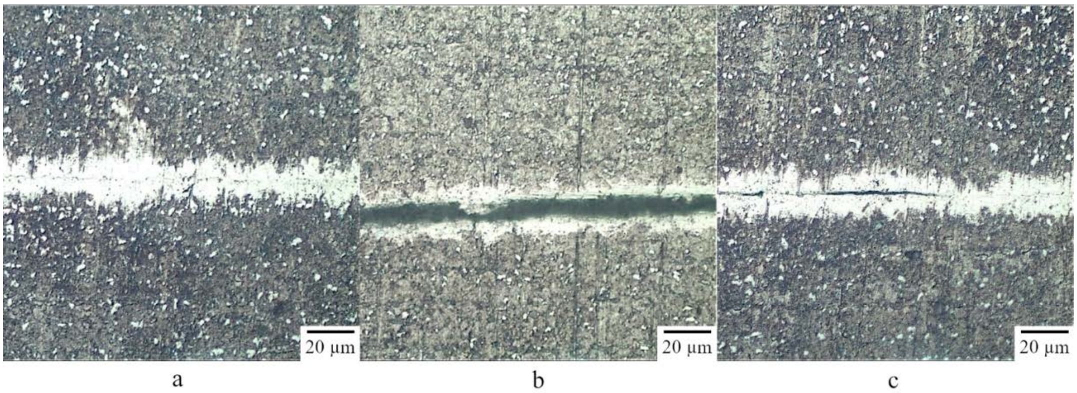

Figure 6. Welding defects: adhesion (a), complete lack of fusion (b) and partial lack of fusion (c) at T_w = 900 °C; P_w = 1 MPa; t_w = 65 min

Increasing the pressure to P_w = 3 MPa with a holding time t_w = 60 min led to a deformation of the welded assembly of ε = 2.8%. This regime ensured the formation of a complete welded joint without zones of lack of fusion or continuous adhesion. However, in separate sections of the weld seam, the presence of voids (pores) located along the joint line was observed. The thickness of the intermediate layer in the joint was 22–30 µm. This indicates that a pressure of 3 MPa is closer to optimal but still does not guarantee complete densification and elimination of all microporosities.

Upon further increasing the pressure to P_w = 5 MPa with a holding time t_w = 35 min, the deformation of the welded assembly was ε = 3.5%. Under this regime, a high-quality joint was obtained: defects characteristic of lower pressures, such as voids along the joint line, adhesion, and lack of fusion, were absent. Practically all five joints of the multilayer assembly were characterized by a uniform, defect-free microstructure along the entire length of the seam (Fig. 7). The thickness of the intermediate layer in the joints was 20–25 µm, which is somewhat less than when welding under previous regimes, and is explained by the increased plastic deformation of the soft nickel interlayer under the influence of higher pressure. This regime is optimal from the standpoint of joint quality and an acceptable level of deformation.

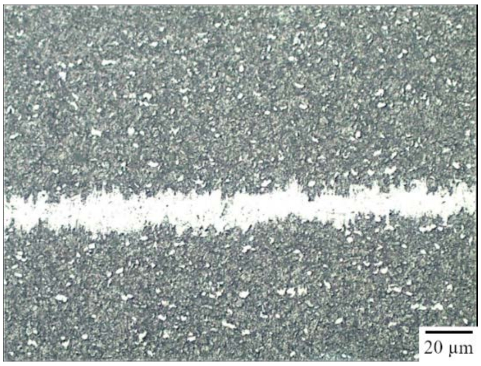

Figure 7. Microstructure of the diffusion bonded joint of nickel-plated 14Cr17Ni2 alloy at T_w = 900 °C; P_w = 5 MPa; t_w = 35 min

Welding an assembly of nickel-plated workpieces at a pressure P_w = 10 MPa and a holding time t_w = 25 min led to a significant increase in the deformation of the welded assembly to ε = 6.17%, which exceeds the maximum permissible threshold of 4% for the “Amplifier Block” component. Although all welded joints were characterized by a defect-free structure, a significant reduction in the thickness of the intermediate layer to 10–15 µm was observed. Although such a reduction in interlayer thickness can positively influence the joint strength due to the effect of contact hardening of soft interlayers, excessive deformation makes this regime unacceptable for this component.

An important aspect of using thin soft interlayers is the effect of their contact hardening, where the mechanical properties of the metal in a thin layer, rigidly bonded to a less plastic base material, significantly exceed the properties of this metal in its free state [17]. With a decrease in the relative thickness of the interlayer, its strength characteristics increase hyperbolically until the strength of the interlayer reaches the strength of the base metal. This means that to realize the advantages of contact hardening and ensure high joint strength while preserving the plasticizing role of the interlayer, it is necessary to use the thinnest possible layers. This very phenomenon can contribute to increasing the strength of joints, especially those obtained at a pressure of 10 MPa, but excessive product deformation is unacceptable. The desire to obtain the benefits of the contact hardening effect without excessive deformation was taken into account when selecting the target thickness of the electrodeposited nickel layer of approximately 10 µm on each surface to be welded for the main experiments on full-scale samples.

To confirm the stability of the developed regimes and identify a possible scale factor, verification was performed on full-scale samples (38×58 mm) using the UDSV-DT unit with an induction heating source. The regime that showed the best results on laboratory samples was chosen: T_w = 900 °C, P_w = 5 MPa, t_w = 35 min. The results showed that welding an assembly of nickel-plated full-scale workpieces using these parameters led to a deformation of the welded assembly of ε = 3.5%. Metallographic analysis confirmed that all five joints of the assembly are characterized by a uniform, defect-free microstructure along the entire

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length of the seam (Fig. 8). This indicates that the developed diffusion bonding regimes using a nickel interlayer are reproducible and ensure the formation of a high-quality welded joint regardless of the type of heating source and sample size.

Figure 8. Microstructure of the diffusion bonded joint of nickel-plated 14Cr17Ni2 alloy at T_w = 900 °C; P_w = 5 MPa; t_w = 35 min

Analysis of the joints in the test samples, obtained using an intermediate nickel layer, showed that the following main regime parameters are recommended for diffusion bonding of a multilayer joint of 14Cr17Ni2 alloy: $T_w = 900^{+20}_{-15}$ °C, P_w = 3–5 MPa, t_w = 35–40 min. The application of an electrodeposited nickel interlayer with a thickness of up to 10 µm per side is an effective intensification method, allowing for a significant reduction in welding pressure. This creates the prerequisites for the successful implementation of the technology under industrial conditions, ensuring high joint quality with minimal thermo-mechanical impact.

To confirm the effectiveness and adapt technology T2 to conditions approaching the actual production of the "Amplifier Block" component, a stage of welding full-scale model assemblies (six 38×58 mm plates) was conducted. Initially, when using parameters close to laboratory ones ($P_w \approx 5$ MPa, $T_w = 920^{+5}_{-10}$ °C, t_w = 40 min), a satisfactory overall deformation of the assembled stack was obtained (average thickness after welding 12.3 mm from an initial 12.8 mm, which meets the requirements of the design documentation). However, analysis of the condition of the internal elements of the welded product revealed their significant linear deformation (warpage) (Fig. 9a).

This prompted a correction of the welding regimes. By reducing the welding pressure by 10 % (to approximately 4.5 MPa), increasing the welding temperature to 950 °C, and increasing the holding time to 50 min, it was possible to obtain a high-quality welded joint of the model assembly without visible linear deformation of the internal elements (Fig. 9b). These corrected parameters ($T_w = 950^{+20}_{-15}$ °C, P_w = 4.5 MPa, t_w = 50 min) were determined as final for technology T2.

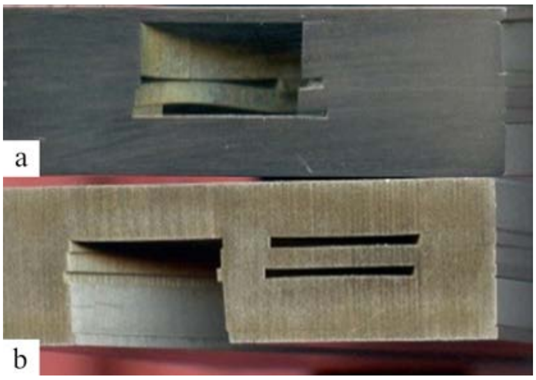

Figure 9. Model assembly with linear deformation of internal elements (a) and without (b)

Metallographic analysis of the welded joints, obtained on the model assemblies using the final T2 regimes, confirmed the high quality of all five seams in the assembly. The absence of defects such as "lack of fusion" and "adhesion" was observed, indicating the reliability and hermeticity of the joints. The thickness of the nickel interlayer in the joint zone varied from 13 to 15 µm (Fig. 10).

Thus, the development stage on full-scale model assemblies confirmed the advantages of technology T2 using nickel interlayers, enabling the production of high-quality multilayer joints of 14Cr17Ni2 alloy at significantly reduced pressures and optimized temperature-time parameters, which ensure minimal deformation and preservation of product accuracy. This demonstrates the high potential of this technology for manufacturing precision components in the aviation industry.

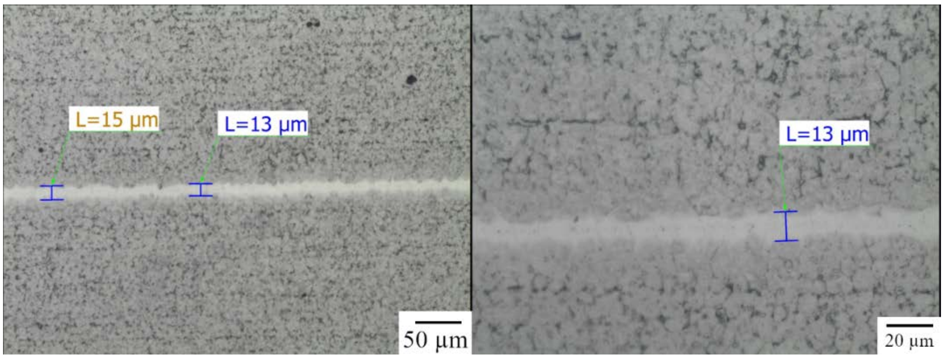

Figure 10. Microstructure of the welded joint of seam No. 5 of the component's model assembly: ×200 (left) and ×500 (right)

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Conclusions

As the result of this research, two approaches to the diffusion bonding of multilayer joints of 14Cr17Ni2 alloy were developed and optimized. The conventional technology (T1) allows for obtaining high-quality joints at a welding temperature T_w = 950–1050°C, a pressure P_w = 15–20 MPa, and a welding time t_w = 20 min. However, this technology requires high applied pressures, which can be critical for the accuracy of precision components and necessitates specialized equipment.

To reduce the process parameters and minimize their impact on the material and product geometry, technology T2, utilizing intermediate layers of electrodeposited nickel up to 10 µm thick on the surfaces to be welded, was successfully applied. Optimization of technology T2 on laboratory samples demonstrated the possibility of obtaining high-quality joints at $T_w = 900^{+20}_{-15}$ °C, P_w = 3–5 MPa, and t_w = 35–40 min. Further development of technology T2 on full-scale model assemblies of the "Amplifier Block" component allowed for the correction and establishment of the final recommended parameters: temperature $T_w = 950^{+20}_{-15}$ °C, pressure P_w = 5 MPa, and holding time t_w = 50 min. This stage confirmed the effectiveness of the developed technology for complex multilayer structures, making it possible to eliminate the linear deformation of the internal elements of the assembly, which was observed in the initial development stages.

The application of a nickel interlayer demonstrated significant advantages, particularly a considerable reduction in the required welding pressure and temperature compared to T1, while maintaining high joint quality. This was possible due to the plasticizing effect of the nickel interlayer, which facilitates the formation of physical contact at lower pressures, activates diffusion processes at lower temperatures, and promotes the disruption of oxide films. Reducing the operating temperature to 900–950°C also allows for the avoidance of additional thermal impact in the form of hardening 14Cr17Ni2 alloy. The level of deformation under optimal T2 regimes (ε = 3.5% at P_w = 5 MPa) remained within permissible limits.

The optimized technological process of diffusion bonding for the fluidic amplifier block made of 14Cr17Ni2 alloy using technology T2 ensures the production of high-quality joints. The performed metallographic analysis of welded joints, fabricated using the final T2 technological process, showed the absence of defects such as “lack of fusion” and “adhesion”, which characterizes the high quality and hermeticity of the obtained welded joints. The magnitude of product deformation after welding is within the permissible limits of up to 4%.

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ОПТИМІЗАЦІЯ ПРОЦЕСУ ДИФУЗІЙНОГО ЗВАРЮВАННЯ БАГАТОШАРОВОГО З'ЄДНАННЯ ЗІ СПЛАВУ 14Cr17Ni2

Руслан Куликовський — канд. техн. наук, доцент, проректор з науково-педагогічної роботи та питань перспектив розвитку Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: kulikovski@zp.edu.ua*, ORCID: 0000-0001-8781-2113

Денис Молочков — доктор філософії, старший викладач кафедри інформаційних технологій електронних засобів Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: molochkov@zp.edu.ua*, ORCID: 0000-0002-9030-5371

Олександр Костін — канд. техн. наук, професор, професор кафедри зварювального виробництва Національного університету кораблебудування імені адмірала Макарова, м. Миколаїв, Україна, *e-mail: kostin.weld@gmail.com*, ORCID: 0000-0002-4739-660X

Володимир Мартиненко — канд. техн. наук, доцент, доцент кафедри електроенергетики, електротехніки та електромеханіки Миколаївського національного аграрного університету, м. Миколаїв, Україна, *e-mail: martynenko@mnau.edu.ua*, ORCID: 0000-0003-4067-3640

Сергій Олексієнко — канд. техн. наук, доцент, доцент кафедри технологій зварювання та будівництва Національного університету «Чернігівська політехніка», м. Чернігів, Україна, *e-mail: sv.oleks@ukr.net*, ORCID: 0000-0001-5475-4439

Мета. *Оптимізувати технологію дифузійного зварювання багатошарових з'єднань деталей авіадвигунів зі сплаву 14Cr17Ni2, мінімізуючи деградацію матеріалу та геометричні спотворення.*

Методи дослідження. *Аналіз традиційного (Т1) та інтенсифікованого (Т2) дифузійного зварювання (із застосуванням проміжного шару нікелю до 10 мкм). Параметри оптимізовано на лабораторних зразках та повнорозмірних моделях; якість з'єднань оцінено металографічним аналізом.*

Результати. *Технологія Т1 вимагає високого тиску (15–20 МПа) при 950–1050 °С. Оптимізована технологія Т2 (з шаром Ni) показала кращі результати: температура зварювання 950 °С, тиск 5 МПа, час витримки 50 хв. Шар Ni дозволив знизити тиск у 3-4 рази, використати нижчу температуру зварювання, зберегти високу якість з'єднання та забезпечити деформацію ≤4%. Металографія підтвердила відсутність дефектів у мікроструктурі. Знижена температура зварювання 950°С запобігає гартуванню сплаву 14Cr17Ni2 після зварювання.*

Наукова новизна. *Визначено оптимальні параметри дифузійного зварювання багатошарових з'єднань зі сплаву 14Cr17Ni2 при низькому тиску із застосуванням тонкого прошарку Ni, що забезпечує отримання бездефектних, високоякісних з'єднань зі значно зниженими тиском та температурою зварювання. Оптимальна товщина прошарку дозволяє використовувати ефект контактного зміцнення для отримання з'єднання з міцністю, аналогічною до основного матеріалу.*

Практична цінність. *Технологія дифузійного зварювання Т2 забезпечує надійне виготовлення прецизійних багатошарових деталей зі сплаву 14Cr17Ni2 з мінімальним термомеханічним впливом та зниженою складністю виробництва (обладнання для нижчого тиску). Це перспективне та економічно вигідне рішення для авіаційної промисловості, для деталей, що потребують високої точності та працездатності в екстремальних умовах.*

Ключові слова: *дифузійне зварювання, 14Cr17Ni2, прошарок, відносна пластична деформація, активація поверхні.*

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