UDC 338:658.5

Oleksandr Chechet	Deputy head of the production department at JSC “Motor Sich”, Zaporizhzhia, Ukraine, *e-mail: Chechetalex1979@gmil.com*, ORCID: 0009-0003-2070-9885
Ruslan Kulykovskyi	Candidate of Technical Sciences, Associate professor, Vice-rector, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: kulikovski@zp.edu.ua*, ORCID: 0000-0001-8781-2113
Serhii Chigileychik	Leading Researcher at ZMDB SE “Ivchenko-Progres”, Zaporizhzhia, Ukraine, *e-mail: ChigileychikSL@ivchenkoprogress.com*, ORCID: 0000-0002-2372-9078
Yurii Torba	Candidate of Technical Sciences, Deputy director at ZMDB SE “Ivchenko-Progres”, Zaporizhzhia, Ukraine, *e-mail: Torba.Yuriy@gmail.com*, ORCID: 0000-0001-8470-9049
Andrii Dobrovolskyi	Leading engineer at ZMDB SE “Ivchenko-Progres”, Zaporizhzhia, Ukraine, *e-mail: dobrovolskiyj5@gmail.com*, ORCID: 0009-0007-8015-821X
Nataliia Shyrokobokova	Candidate of Technical Sciences, Associate professor, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: nsonik11@gmail.com*, ORCID: 0000-0002-7009-6218

MICROPLASMA POWDER CLADDING FOR THE REPAIR OF TURBINE MONOWHEELS MADE OF NICKEL-BASED HEAT-RESISTANT ALLOYS

Purpose. *Theoretical justification and experimental development of a technology for the restoration of turbine blades of an aircraft engine, manufactured using the “blisk” process from heat-resistant nickel alloys, via the additive micro-plasma powder cladding method (MPC).*

***Research methods**. The study employed microplasma layer-by-layer powder cladding on the end faces of plates made of the ЖС32-ВИ alloy, using the specialised robotic system STARWELD 190H. The MPC process was carried out using direct current of positive polarity (currents of 2…50 A). High-purity argon was used as the plasma-forming and shielding gas. The dimensions of the test plates were115×15×2 mm. The cladding was carried out using a reciprocating motion. After cladding, the samples were subjected to heat treatment. The mechanical properties of the samples obtained by the additive growth method were determined on standard flat specimens.*

***Results**. Following mechanical testing, the specimens exhibited the following properties: average tensile strength* $\sigma = 1147$ *MPa and plasticity* $\delta = 9.5\%$*, whilst the requirements of the standard specify* $\sigma_{в} \geq 882$ *MPa and* $\delta = 6.0\%$*. The fracture surfaces exhibited a medium-grained structure. No defects were observed in the fracture surfaces. The microstructure of the sample material prior to heat treatment consists of* γ*-solid solution containing an intermetallic* γ' *phase, carbides, carbonitrides, and 5 μm-sized eutectic* (γ-γ') *phase, which is characteristic of the as-cast condition of the ЖС32-ВИ alloy. The microstructure of the sample material after heat treatment corresponds to the normal state of the ЖС32-ВИ alloy.*

***Scientific novelty**. When manufacturing turbine wheels by casting, one of the most serious problems is casting defects, such as cracks, porosity and cavities. The use of existing repair methods, which are based on welding or surfacing using argon arc welding, for example for blades, is limited by the high susceptibility of heat-resistant nickel alloys (ЖС3ДК, ВЖЛ12) to the formation of heat-fatigue cracks due to the high content of* γ' *phase. The proposed repair technology involves cutting the blade down to the location of the defect and subsequently restoring the blade profile layer by layer using the additive micro-plasma cladding method.*

***Practical value**. It has been established that the repair of aircraft engine turbine blades using the additive micro-plasma powder cladding method ensures high mechanical properties across the entire height of the grown blade without the occurrence of casting defects.*

***Key words**: turbine wheel, additive microplasma cladding, powder,* γ'*-phase, mechanical properties, microstructure.*

DOI 10.15588/1607-6885-2026-2-9

Introduction

One of the main areas of development for gas turbine engines is the improvement of their specific performance, including a reduction in their mass and dimensions [1]. The turbine wheels of small gas turbine engines are usually manufactured using the «blisk» process, meaning that the wheel blades and the disc section are formed as a single component (Figure 1). With this construction, the total mass of the turbine wheel is reduced compared to wheels that use individual working blades [2, 3].

The turbine wheel of a small gas turbine engine, manufactured using the “blisk” process, operates under significant thermomechanical stresses (the operating temperature of the wheel blades ~ 950 °C, maximum rotational speed of the wheel is 39000 r/min), in an environment of high-temperature combustion products from aviation fuel. Due to these demanding operating conditions, turbine wheels are manufactured from heat-resistant nickel alloys using high-precision casting [4–7].

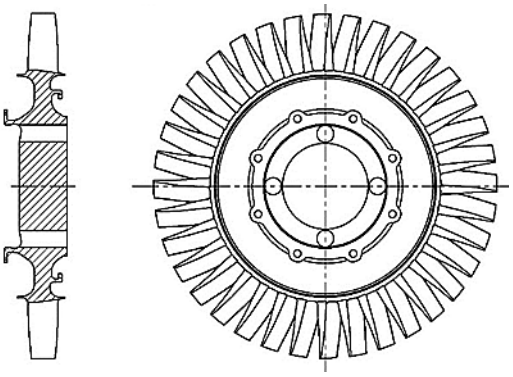

Figure 1. Turbine wheel manufactured using the “blisk” process

When manufacturing turbine wheels from heat-resistant nickel alloys ЖС3ДК and ВЖЛ12 using the casting process, difficulties arise due to the occurrence of casting defects such as cracks, porosity and cavities. It should be noted that most defects occur in the blades, particularly in the lower section near the base.

When attempting to repair such alloys using traditional methods, such as argon arc welding, cracks inevitably form in the heat-affected zone. The mechanisms behind their formation are varied: from liquation cracking during the welding process to strain-age cracking during subsequent heat treatment. This is due to the rapid kinetics of the precipitation of the strengthening phase $Ni_3(Al,Ti)$, which is accompanied by volume changes and a reduction in the material’s ductility during the relaxation of welding stresses [8].

Additive technologies, in particular microplasma powder cladding (MPC), represent a promising approach to addressing this task [9–12]. This method combines the precision of energy delivery characteristic of laser processes with the metallurgical ‘mildness’ and cost-effectiveness of arc processes. The aim of this work is a comprehensive study of the feasibility of using MPC for the repair of turbine blades made of the heat-resistant alloy ЖС32-ВИ, including the optimisation of cladding parameters and post-weld heat treatment regimes.

Analysis of research and publications

The problem of welding and cladding heat-resistant nickel alloys (superalloys) has remained a key focus for materials scientists over the past five decades. Scientific fundamental works laid the foundations for understanding the physical metallurgy of these materials. However, the main difficulty of the process lies in the fact that alloying aimed at improving high-temperature strength (increasing the volume fraction of the γ´- phase) has a diametrically opposite effect on weldability.

Alloy ЖС32-ВИ (analog to western alloys such as René and CMSX) belong to the class of dispersion-hardened materials. When heated above the solidus temperature (during welding), partial melting occurs along the grain boundaries in the heat-affected zone, caused by the presence of low-melting eutectics and the segregation of impurities (S, P etc.). During cooling, under the action of tensile thermal stresses, these liquid films open up, forming hot cracks [5, 13–15].

An even more insidious phenomenon is stress-induced ageing cracking. These cracks occur during post-weld heat treatment in the temperature range of 700…900°C. In this range, there is an intense precipitation of the secondary γ'-phase within the grains, which significantly strengthens their interior. If the grain boundaries remain relatively weak or have low ductility, the relaxation of residual stresses occurs not through plastic deformation, but through the formation of cracks along the grain boundaries.

A number of repair techniques are currently available for damaged components, each with its own advantages and disadvantages. The traditional method – argon arc welding – is widely used for repairing less alloyed alloys (e.g. Inconel 625, Inconel 718). However, for alloys with a γ'-phase content exceeding 40…50 % (which includes ЖС32), TIG welding is characterised by excessively high heat input. This leads to a wide heat-affected zone, grain growth and catastrophic cracking. Numerous studies confirm that the use of TIG welding to restore the aerodynamic profile of blades made from ЖС32 is impractical due to the low yield of serviceable parts [5, 14].

Laser technologies (laser metal deposition) ensure minimal heat input and high precision. However, high cooling rates ($10^3…10^4$ K/s) lead to the formation of non-equilibrium, hardened structures with high levels of internal stresses [2, 3, 14]. Furthermore, laser cladding is prone to porosity and lack of fusion if parameters are selected incorrectly, and is characterised by high equipment

DOI 10.15588/1607-6885-2026-2-9

and operating costs. Another issue is the anisotropy of properties and the need for strict control of particle size.

Electron beam welding ensures the highest metal purity, but requires a vacuum chamber, which limits productivity and part dimensions and makes it a challenging method for the layer-by-layer fabrication of complex geometries.

Microplasma powder cladding occupies a unique place. The use of a low-power compressed arc (currents of 2…50 A) allows for precise control of heat input, ensuring “gentle” mixing of the filler material with the base metal.

The works of the Ukrainian school of welding (E.O. Paton Electric Welding Institute), in particular those by K.A. Yushchenko, O.V. Yarovitsyn and others, have examined the physics of the MPC process in detail [9–12]. It has been shown that laminar plasma flow provides reliable protection of the molten pool against oxidation, which is critical for alloys containing active elements (Al, Ti, Hf).

Previous studies have demonstrated the successful use of MPC for repairing blade tip sections (build-up of up to 3…5 mm) [10, 11, 16, 17]. However, when repairing integral wheels, there is often a need to restore significantly larger volumes - for example, when cutting out a defect near the root of the blade, up to 45…50 mm of the profile to be restored. This shifts the task from the realm of «cosmetic repair» to that of «additive manufacturing on an existing substrate».

The issues of structural stability and properties during multi-layer cladding of such large volumes of the ЖС32-ВИ, as well as the selection of heat treatment regimes that would mitigate the effects of repeated thermal cycling, remain insufficiently studied. This work is specifically aimed at addressing these «gaps» in the technology.

Purpose of the study

The aim of this work is to provide a theoretical justification and experimental development of a technology for the repair of turbine blades in aircraft engines, manufactured using the «blisk» process from heat-resistant nickel alloys, by means of additive micro-plasma powder cladding.

To achieve the set objective, the following tasks must be addressed:

- to develop a methodology for the additive manufacturing of test specimens made from the ЖС32-ВИ alloy, which replicate the thermophysical conditions involved in restoring the blade profile;
- conduct a comparative analysis of the microstructure of the deposited metal in the original state and after various homogenisation annealing regimes;
- determine the effect of homogenisation temperature on the dissolution of non-equilibrium eutectic phases and prevent the formation of defects;
- to determine the mechanical properties (tensile strength, elongation) of the remanufactured metal and verify their compliance with the requirements of industry standards for cast materials;
- to investigate the failure mechanism of the remanufactured samples using fractography to confirm the absence of hidden defects of metallurgical origin.

Materials and methods

The high-temperature nickel alloy ЖС32-ВИ was selected as the subject of the study. It is one of the most advanced casting alloys for aircraft turbine blades, capable of operating at temperatures of up to 1050…1100°C.

The filler material used was spherical-shaped metal powder of the ЖС32-ВИ alloy, produced by vacuum induction gas atomisation in argon. The particle size distribution of the powder was 63…163 μm [9, 11, 12]. Choice of particle size was dictated by the requirements for a stable feed into the plasmatron: finer particles (<50 μm) are prone to agglomeration and “clogging”, whilst larger ones (>160 μm) may not have time to melt completely in a low-power plasma arc.

The experimental work was carried out on a specialised robotic system the STARWELD 190H. The process MPC was performed using direct current of positive polarity (negative electrode). High-purity argon was used as the plasma-forming and shielding gas. To simulate blade repair, a strategy of layer-by-layer cladding on the end face of a plate made of the ЖС32-ВИ alloy was chosen. The plates measured 115×15×2 mm (Figure 2). The thickness of 2 mm corresponded to the average thickness of the turbine blade and vane in the repair zone. The cladding was carried out using a reciprocating motion.

Figure 2. Sample cutting plan

The mechanical properties of the specimens following heat treatment (T=1255±10°C for 1…1.5 hours), produced by additive manufacturing using microplasma powder cladding, were determined on standard flat specimens.

Results and discussion

The first stage of the study involved assessing the quality of the metal’s formation immediately following the additive manufacturing process (original condition). A visual inspection of the surface of the deposited layers revealed satisfactory formation: consistent width, and no coarse burrs, undercuts or macro-cracks. The surface had

DOI 10.15588/1607-6885-2026-2-9

a characteristic structure resulting from the crystallisation of individual molten pools.

Analysis of cross-sectional micro-sections in the unetched state revealed the presence of scattered microporosity. The pores were predominantly spherical in shape, with a size not exceeding 20 µm (Figure 3). The spherical shape of the pores indicated that they were of gaseous origin. The most likely causes are either argon entrapped by powder particles during their production (gas atomisation) or microbubbles of shielding gas that entered the turbulent flows of the weld pool. It should be noted that, from the point of view of fracture mechanics, small spherical pores (up to 20…30 µm) are significantly less dangerous stress concentrators than flat oxide films or sharp hot cracks [2, 10].

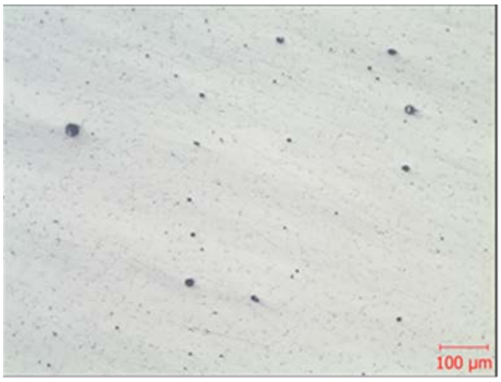

Figure 3. Microstructure of the deposited metal prior to etching

Etching revealed a dendritic structure resulting from directional crystallisation. The axes of the dendrites are predominantly oriented along the heat dissipation path (from bottom to top, away from the substrate). The microstructure of the samples prior to heat treatment consisted of a γ-solid solution containing an intermetallic γ´- phase, carbides and carbonitrides [3, 5, 6]. Particular attention was drawn to the presence of a eutectic (γ-γ´)- phase, ~5µm in size, in the inter-axial spaces of the dendrites, which is characteristic of the as-cast state of the ЖС32-ВИ alloy (Figure 4). This is a consequence of dendritic solidification, where elements with a partition coefficient k <1 (Al, Ti, Ta) are displaced by the crystallisation front into the liquid phase, enriching the final portions of the melt to the eutectic composition. It is precisely these zones that are potential weak points.

The samples were then subjected to heat treatment – homogenisation at T=1270±10°C for 1…1.5 hours. Homogenisation is necessary to equalise the chemical composition, dissolve non-equilibrium eutectics and form the optimal morphology of the strengthening γ´- phase.

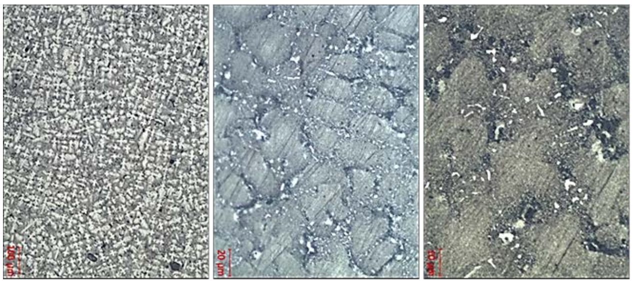

Figure 4. Microstructure of the deposited metal prior to heat treatment following etching

Metallographic analysis of samples after ageing at 1270°C revealed the presence of structural defects classified as “overheating” or “incipient melting” [3, 5, 7]. The microstructure photographs clearly show thickened grain boundaries and «islands» with traces of melting around former eutectic zones (Figure 5).

Figure 5. Microstructure of the deposited metal after heat treatment (homogenisation at T=1270±10°C)

Although the nominal solidus temperature of the ЖС32-ВИ alloy is higher than 1270°C, the deposited metal contains zones enriched with boron, carbon and liquidus elements as a result of non-equilibrium crystallisation. These localised zones have a significantly lower melting point. When heated to 1270 °C they turn to a liquid state. Upon subsequent cooling, the liquid crystallises in the form of brittle films or coarse eutectics, which drastically reduces the mechanical properties. Thus, this particular heating temperature is unacceptable for the deposited material without prior stepwise preparation.

To prevent the metal samples from overheating, the homogenisation temperature was reduced by 15 °C. Another series of samples underwent heat treatment – homogenisation at T=1255±10 °C for 1…1.5 hours. Decreasing the temperature by 15 °C allowed entry into the safe heat treatment interval. The structure after heating at 1255 °C was characterised by the absence of melting traces, a significant degree of solid solution homogenisation, a reduction in the number and size of non-equilibrium eutectics due to diffusion dissolution, and the formation of a regular γ-γ´ phase structure with a cuboid morphology, which is optimal for creep resistance and corresponds to the normal state of the ЖС32-ВИ alloy (Figure 6).

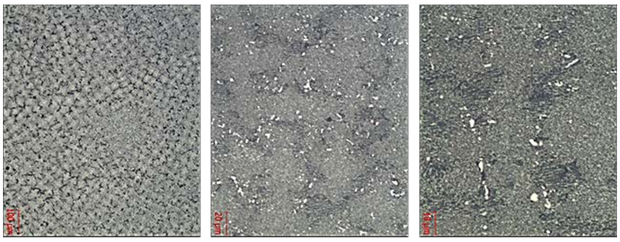

Figure 6. The microstructure of the deposited metal after heat treatment (homogenisation at T = 1255±10°C)

The results of the tensile strength tests on samples treated under optimal conditions are presented in the comparative table (Table 1).

The obtained results demonstrate that the properties of the deposited metal significantly exceed the minimum requirements. This is because rapid crystallisation during MPC resulted in a more dispersed structure compared to conventional casting, where slow cooling led to the formation of large dendrites and significant microporosity.

Table 1 – A comparative analysis of the mechanical properties of the remanufactured ЖС32-ВИ alloy and the relevant standards

Characte-ristics	Mean value (experi-ment, MPC)	Require-ments (casting, technical specifica-tions)	Deviation	Rating
Strength limit σ, MPa	1147	≥ 882	+ 30 %	excellent
Relative elongation δ, %	9.5	≥ 6.0	+ 58.3 %	excellent
Yield point $\sigma_{0.2}$, MPa *	931	-	-	-

* *The yield point value is an estimate, based on the typical ratio for this class of alloys*

Examination of the fracture surfaces following rupture confirmed that metal was of a sufficiently high quality. The fracture had a matt grey hue, characteristic of ductile fracture. No defects such as lack of fusion between the cladding layers were detected (Figure 7), confirming the correct selection of the process's energy parameters (current, cladding rate).

Figure 7. Fracture patterns in specimens following tensile testing

Discussion

The obtained data made it possible to formulate a concept for the «blisk» blade remanufacturing process. The main point is to demonstrate that the MPC method can produce dense metal with properties not worse than those of cast metal, even at high build-up heights. It is important to note the role of heat treatment. In industrial conditions, higher heating temperatures (1280…1290 °C) are often used for cast blades to ensure complete dissolution of γ- phase. However, for metal formed by the MPC method, which has its own specific crystallisation characteristics, these temperatures are unacceptable [3, 5, 7]. It has been established that reducing the temperature to 1255°C is a necessary compromise that ensures a sufficient level of mechanical properties.

The economic benefits of implementing this technology are clear. The cost of a new turbine monowheel can run into tens of thousands of dollars. The cost of repair using the MPC method (powder + labour + heat treatment) amounts to 10…15% of the cost of a new part. Furthermore, this also resolves the issue of logistics and spare parts delivery times.

Conclusions

Based on the comprehensive research carried out, the following conclusions can be drawn:

1. The feasibility of using the additive MPC method to repair deep damage and fully restore the profile of the working blades of "blisk"-type turbine wheels made from the ЖС32-ВИ alloy has been confirmed.
2. The developed technology ensures the production of dense deposited metal. The residual microporosity does not exceed 20 µm, is spherical in shape and does not compromise the static strength. There are no cracks or lack of fusion..
3. The critical sensitivity of the deposited metal to the homogenisation temperature has been established. A temperature of 1270 °C is excessive and causes the eutectic phases to melt. The optimum condition has been determined to be T = 1255±10 °C (1…1.5 hours), which ensures the formation of the required microstructure.
4. The clad metal exhibits high mechanical strength (σ = 1147 MPa) and plasticity (δ = 9.5%), which significantly exceeds the specifications for the base material.
5. The results of this work form the basis for the development of standard operating procedures for the aircraft engine repair process, which will significantly extend the service life of the aircraft fleet.

References

1. Балушок К. (2024). Ремонт деталей авіаційних двигунів із жароміцних нікелевих сплавів із застосуванням адитивних технологій. Авіаційно-космічна техніка і технологія, № 5. DOI: https://doi.org/10.32620/aktt.2024.5.04

DOI 10.15588/1607-6885-2026-2-9

2. Sarkar R. et al. (2022). Additive manufacturing-based repair of IN718 superalloy and high-cycle fatigue assessment of the joint. *Additive Manufacturing*, 60, Part A, 103276. DOI: DOI: https://doi.org/10.1016/j.addma.2022.103276

3. Chen J. et al. (2025). Laser-based powder bed fusion of nickel-based superalloy designed specifically for turbine blades using high-power flat-top laser: Towards high-speed manufacturing and directional solidification. *Journal of Alloys and Compounds*, 1022(11), 179902. DOI: https://doi.org/10.1016/j.jallcom.2025.179902

4. Yarovytsyn O. V., Khuschchov H. D., Chyhileychik S.L. (2019). Estimation to optimize energy spent on a single welding pool creation in micro-plasma powder deposition process of JS32 nickel superalloy HPT blade`s bandage shelve. *International Journal of Mechanical and Production Engineering*, 7, 1, 5 IJMPE-IRAJ-DOI-14928.

5. Schulz F. et al. (2024). Gamma prime formation in nickel-based superalloy weld metal fabricated by laser beam welding. *Materials today Communications*, 38, 107905. DOI: https://doi.org/10.1016/j.mtcomm.2023.107905

6. Zhang G. et al. (2024). Research progress in repair and remanufacture of compressor blisk. *Journal of Aeronautical Materials*, 44(3). DOI: https://doi.org/10.11868/j.issn.1005-5053.2019.000153

7. China. (2023). *Integral heat treatment method for nickel-based high-temperature alloy leaf disc after laser additive repair* (Patent No. CN116944521A/B). China National Intellectual Property Administration.

8. Ющенко К. А. та ін. (2022). Дослідження і оптимізація процесу серійного ремонту робочих лопаток авіаційного газотурбінного двигуна Д-18Т микроплазмовим порошковим наплавленням. *Космічні матеріали та технології*, 28, 3, 3–16.

9. Cherviakov M., Yarovytsyn O., Khrushchov H. (2023). Expanding the Technological Possibilities of Multilayer Micro-Plasma Powder Deposition Process by Optimizing the Quality and Composition of Process Gases. *Science and Innovation*, 19(5), 89–99. DOI: https://doi.org/10.15407/scine19.05.089

10. Balushok K. et al. (2024). Developing technology of directed energy deposition of workpieces of parts of aircraft engines from heat-resistant nickel alloys by means of using layer-by-layer microplasma surfacing method. *Mechanics and Advanced Technologies*, 8, 2(101), 121–129. DOI: https://doi.org/10.20535/2521-1943.2024.8.2(101).296932

11. Yarovytsyn A. V. (2015). Energy approach in analysis of microplasma powder surfacing process parameters in restoration of blades of aircraft GTE. *The Paton Welding Journal*, 6, 28–34.

12. Yarovytsyn O.V. et al. (2024). Development and approval of the procedure of high-temperature uniaxial creep strength tests of difficult-to-weld high-temperature nickel alloys specimens with microplasma powder deposition. The Paton Welding Journal, 9, 29–37. DOI: https://doi.org/10.37434/tpwj2024.05.04

13. 10. Tan Q. et al. (2024). A review on cracking mechanism and suppression strategy in nickel-based superalloys during laser cladding. *Journal of Alloys and Compounds*, 1001. DOI: https://doi.org/10.1016/j.jallcom.2024.175164

14. Dmitrieva A. et al. (2023). Effect of the Laser Cladding Parameters on the Crack Formation and Microstructure during Nickel Superalloy. *Gas Turbine Engines Repair*. *Metals*, 13(2), 393.

15. Wang D. et al. (2024). A laser powder bed fusion-based methodology for repairing damaged nickel-based turbine blades. *Materials Characterization*, 212, 113948. DOI: https://doi.org/10.1016/j.matchar.2024.113948

16. Яровицін О. В., Чигилейчик С. Л. (2024). Формування критеріїв оцінки придатності застосування присадних матеріалів з нікелевих стопів у адитивних технологіях 3D-натоплення. *Металофізика та новітні технології*, 4, 129–149.

17. Yuschenko K.A. et al. (2017). Understanding the impact of oxygen and nitrogen content in metal powder on microplasma multilayers deposition of aircraft GTE blade edges. Proceedings of 9th International conference of young scientist on welding and related technologies, PWI NAS of Ukraine, 23–26 May, 257–261.

Received 09.04.2026
Accepted 22.04.2026
Published 07.05.2026

DOI 10.15588/1607-6885-2026-2-9

УДК 338:658.5

МІКРОПЛАЗМОВЕ ПОРОШКОВЕ НАПЛАВЛЕННЯ ДЛЯ РЕМОНТУ МОНОКОЛІС ТУРБІН ІЗ НІКЕЛЕВИХ ЖАРОМІЦНИХ СПЛАВІВ

Олександр Чечет	заступник начальника цеху, ОАО «Мотор Січ», Запоріжжя, Україна, *e-mail: Chechetalex1979@gmil.com*, ORCID: 0009-0003-2070-9885
Руслан Куликовський	канд. техн. наук, доцент, проректор з науково-педагогічної роботи та питань перспектив розвитку Національного університету «Запорізька політехніка», Запоріжжя, Україна, *e-mail: kulikovski@zp.edu.ua*, ORCID: 0000-0001-8781-2113
Сергій Чигілейчик	провідний науковий співробітник ДП ЗМКБ «Івченко-Прогрес», Запоріжжя, Україна, *e-mail: ChigileychikSL@ivchenkoprogress.com*, ORCID: 0000-0002-2372-9078
Юрій Торба	канд. техн. наук, заступник директора ДП ЗМКБ «Івченко-Прогрес», Запоріжжя, Україна, *e-mail: Torba.Yuriy@gmail.com*, ORCID: 0000-0001-8470-9049
Андрій Добровольський	провідний інженер ДП ЗМКБ «Івченко-Прогрес», Запоріжжя, Україна, *e-mail: dobrovolskiyj5@gmail.com*, ORCID: 0009-0007-8015-821X
Наталія Широкобокова	канд. техн. наук, доцент, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: nsonik11@gmail.com*, ORCID: 0000-0002-7009-6218

Мета роботи. *Теоретичне обґрунтування та експериментальна розробка технології відновлення робочих лопаток колеса турбіни авіаційного двигуна, виконаного за технологією «бліск» із жароміцних нікелевих сплавів, методом адитивного мікроплазмового порошкового наплавлення (МПН).*

Методи дослідження. *В ході дослідження було застосовано метод пошарового порошкового наплавлення з використанням мікроплазми на торцеві поверхні пластин зі сплаву ЖС32-ВИ за допомогою спеціалізованої роботизованої системи STARWELD 190H. Процес МПН здійснювався з використанням постійного струму позитивної полярності (силою струму 2…50 А). В якості плазмоутворюючого та захисного газу використовували аргон високої чистоти. Розміри експериментальних пластин становили 115×15×2 мм. Наплавлення здійснювали з використанням зворотно-поступального руху. Після наплавлення зразки піддавали термічній обробці. Механічні властивості зразків, отриманих методом адитивного нарощування, визначали на стандартних плоских зразках.*

Отримані результати. *Після механічних випробувань зразки мали наступні властивості: середні значення міцності* $\sigma_в=1147$ *МПа, пластичності* $\delta= 9{,}5$ *%, при вимогах нормативної документації* $\sigma_в \geq 882$ *МПа,* $\delta= 6{,}0$ *%. Злами мали середньо-кристалічну структуру. Дефекти у зламах не виявлено. Мікроструктура матеріалу зразків до термообробки являє собою* γ*- твердий розчин з наявністю інтерметалідної* γ'*-фази, карбідів, карбонітридів, а також евтектичної (*γ*-*γ'*) - фази розміром 5мкм, яка характерна для литого стану сплаву ЖС32-ВИ. Мікроструктура матеріалу зразків після термообробки відповідає нормальному стану сплаву ЖС32-ВИ.*

Наукова новизна. *При виготовленні коліс турбін методом лиття одна з найсерйозніших проблем – це ливарні дефекти, такі як тріщини, пористість, раковини. Використання існуючих методів ремонту, які основані на зварюванні або наплавленні методом аргонодугового зварювання, наприклад для лопаток, обмежені високою схильністю жароміцних нікелевих сплавів (ЖС3ДК, ВЖЛ12) до появи термовтомних тріщин через високий вміст* γ'*-фази. Запропонована технологія ремонту полягає у зрізанні лопатки до місця розташування дефекту і подальшому пошаровому відновленню профіля лопатки методом адитивного мікроплазмового наплавлення.*

Практична цінність. *Встановлено, що відновлення колеса турбіни авіаційних двигунів методом адитивного мікроплазмого порошкового наплавлення забезпечує високі механічні властивості по всій висоті вирощеної лопатки без виникнення дефектів лиття.*

Ключові слова: *колесо турбіни, адитивне мікроплазмове наплавлення, порошок,* γ'*-фаза, механічні властивості, мікроструктура.*

DOI 10.15588/1607-6885-2026-2-9

Список літератури

1. Балушок К., Чигілейчик С. Ремонт деталей авіаційних двигунів із жароміцних нікелевих сплавів із застосуванням адитивних технологій. *Авіаційно-космічна техніка і технологія*. 2024. № 5. DOI: https://doi.org/10.32620/aktt.2024.5.04

2. Additive manufacturing-based repair of IN718 superalloy and high-cycle fatigue assessment of the joint / R. Sarkar et al. *Additive Manufacturing*. 2022. Vol. 60. Part A. 103276. DOI: https://doi.org/10.1016/j.addma.2022.103276

3. Laser-based powder bed fusion of nickel-based superalloy designed specifically for turbine blades using high-power flat-top laser: Towards high-speed manufacturing and directional solidification / J. Chen et al. *Journal of Alloys and Compounds*. 2025. Vol. 1022(11). 179902. DOI: https://doi.org/10.1016/j.jallcom.2025.179902

4. Yarovytsyn O. V., Khuschchov H. D., Chyhileychik S. L. Estimation to optimize energy spent on a single welding pool creation in micro-plasma powder deposition process of JS32 nickel superalloy HPT blade`s bandage shelve. *International Journal of Mechanical and Production Engineering*. Vol. 7. Issue 1. Jan. 2019. 5 p. IJMPE-IRAJ-DOI-14928.

5. Gamma prime formation in nickel-based superalloy weld metal fabricated by laser beam welding Schulz F. et al. *Materialstoday Communications*. 2024. Vol. 38. 107905. DOI: https://doi.org/10.1016/j.mtcomm.2023.107905

6. Research progress in repair and remanufacture of compressor blisk / G. Zhang, et al. *Journal of Aeronautical Materials*. 2024. Vol. 44(3). DOI: https://doi.org/10.11868/j.issn.1005-5053.2019.000153

7. Integral heat treatment method for nickel-based high-temperature alloy leaf disc after laser additive repair: пат. CN116944521A/B China. № CN202310971641.0A; заявл. 03.08.2023; опубл. 27.10.2023.

8. Дослідження і оптимізація процесу серійного ремонту робочих лопаток авіаційного газотурбінного двигуна Д-18Т микроплазмовим порошковим наплавленням / Ющенко К. А. та ін. *Космічні матеріали та технології*. 2022. Т. 28. № 3. С. 3–16.

9. Cherviakov M., Yarovytsyn O., Khrushchov H. Expanding the Technological Possibilities of Multilayer Micro-Plasma Powder Deposition Process by Optimizing the Quality and Composition of Process Gases. *Science and Innovation*. 2023. 19(5). P. 89–99. DOI: https://doi.org/10.15407/scine19.05.089

10. Developing technology of directed energy deposition of workpieces of parts of aircraft engines from heat-resistant nickel alloys by means of using layer-by-layer microplasma surfacing / Balushok K. et al. *Mechanics and Advanced Technologies*. 2024. Vol. 8. № 2(101). P. 121–129. DOI: https://doi.org/10.20535/2521-1943.2024.8.2(101).296932

11. Yarovytsyn A.V. Energy approach in analysis of microplasma powder surfacing process parameters in restoration of blades of aircraft GTE. *The Paton Welding Journal*. 2015. № 6. C. 28–34.

12. Development and approval of the procedure of high-temperature uniaxial creep strength tests of difficult-to-weld high-temperature nickel alloys specimens with microplasma powder deposition Yarovytsyn O.V. et al. *The Paton Welding Journal*. 2024. № 9. C. 29–37. DOI: https://doi.org/10.37434/tpwj2024.05.04

13. A review on cracking mechanism and suppression strategy in nickel-based superalloys during laser cladding / Tan Q. et al. *Journal of Alloys and Compounds*. 2024, Vol. 1001 . DOI: https://doi.org/10.1016/j.jallcom.2024.175164

14. Effect of the Laser Cladding Parameters on the Crack Formation and Microstructure during Nickel Superalloy / Dmitrieva A. et al. *Gas Turbine Engines Repair. Metals*. 2023. 13(2). 393 p.

15. Wang D. et al. A laser powder bed fusion–based methodology for repairing damaged nickel-based turbine blades. *Materials Characterization*. 2024. Vol. 212. 113948. DOI: https://doi.org/10.1016/j.matchar.2024.113948

16. Яровицін О. В., Чигилейчик С. Л. Формування критеріїв оцінки придатності застосування присадних матеріалів з нікелевих стопів у адитивних технологіях 3D-натоплення. *Металофізика та новітні технології*. 2024. № 4. С. 129–149.

17. Understanding the impact of oxygen and nitrogen content in metal powder on microplasma multilayers deposition of aircraft GTE blade edges. Proceedings of 9th International conference of young scientist on welding and related technologies / Yuschenko K. A. et al. PWI NAS of Ukraine, 23–26 May 2017. P. 257–261.

DOI 10.15588/1607-6885-2026-2-9