Research on welding processes of multi-node aircraft frames and methods for their control

Badania procesów spawania wielowęzłowych kratownic lotniczych oraz sposoby ich kontroli

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The designed aircraft frame structure uses a connection of tubular rods by welding. To apply automatic welding of trusses, the authors designed and assembled the welding station adapted to the dimensions and truss shape. You should also choose the appropriate welding power source and an interface for communication with a robot or automaton. Automatic welding of trusses also requires programming of the robot's movement trajectory, especially the welding head, and a particularly accurate selection of welding process parameters. The most important issue of automation of the welding process is the nodes of the aircraft engine frame, whose limited access requires manual welding. Therefore, the future of welding lattice aircraft structures requires a hybrid approach to the process, i.e. some of the node connections can be easily automated, and some will remain in classical manufacturing methods. In addition, the topic of checking such connections using NDT methods was discussed. In addition, the issue of checking this type of connection using methods approved for aviation, i.e. NDT, was discussed.

KEYWORDS: welding, frame welding, aircraft welded structures, automatic welding, NDT testing

W projektowanej konstrukcji ramy samolotu zastosowano połączenie prętów rurowych poprzez spawanie. Aby zastosować spawanie automatyczne kratownic, autorzy zaprojektowali i zmontowali stanowisko spawalnicze dostosowane do wymiarów i kształtu kratownicy. Należy również dobrać odpowiednie źródło zasilania spawania i interfejs do komunikacji z robotem lub automatem. Spawanie automatyczne kratownic wymaga programowania trajektorii ruchu robota, zwłaszcza głowicy spawającej, oraz bardzo dokładnego doboru parametrów procesu. Najistotniejszą kwestią automatyzacji procesu jest spawanie węzłów ramy silnika samolotu, które ze względu na ograniczony dostęp wymagają spawania ręcznego. Zatem przyszłość spawania kratowych konstrukcji lotniczych wymaga hybrydowego podejścia do procesu – czyli częściowo proces łączenia węzłów można będzie prosto zautomatyzować, a częściowo trzeba będzie pozostać przy klasycznych metodach wytwarzania. Ponadto podjęto tematykę kontroli tego typu połączeń metodami dopuszczonymi dla lotnictwa, tj. NDT.

SŁOWA KLUCZOWE: spawanie, spawanie ram, konstrukcje spawane samolotów, spawanie automatyczne, badania NDT

Introduction

Welding processes are among the most frequently used in the production of aircraft frame structures. The efficiency of this process, as well as sufficient quality assurance for such connections, requires the introduction of robotization at the highest technical level, which is justified by the necessary reliability of the structure. The welding methods used in the processes mentioned can be classified according to their heat generation methods. The most frequently used solution is the use of electricity. Gas welding, due to its low power density and relatively low flame temperature, has limited applications, while high-energy methods with high power density (i.e. laser, plasma and electron welding) are constantly being developed and utilized.

Making a weld of suitable quality in aircraft structures requires experience, skill, and repeatability, which is why the introduction of robotic welding stations is justified by the shortage of qualified welders on the labor market. For this reason, there is great interest in industry 4.0 in the automation of this type of process. The introduction of automation in welding process for aircraft structures requires the preliminary preparation of semi-finished products and attaching them to welded components.

Research on automatic welding processes

The designed aircraft frame structure uses a connection a series of tubular rods connected by welds. Welding of such structures is performed manually or automatically, depending on the equipment available

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to the contractor and the complexity of the connected nodes. While manual welding is widely known and used, automatic welding is still developing dynamically. Automatic welding of a frame is a process carried out using a welding robot or automatic welding machine. This is a method that ensures high quality and repeatability of welds, as well as increases work efficiency and safety. Automatic frame welding can be performed by various welding techniques, such as TIG, MIG, electric arc welding, and laser welding. The most commonly used method is TIG. To use automatic welding of trusses, an appropriate welding station must be designed and assembled, which will be adapted to the dimensions and shape of the truss. You should also select an appropriate welding power source and interface for communication with the robot or automatic machine. Automatic welding of a frame for a given movement trajectory requires programming of the robot or automatic working unit, especially the welding head, and the accurate selection of the welding process parameters are particularly important. Automatic truss welding holds many advantages when compared to manual welding. Some of these include:

- saving time and costs thanks to reduced material and energy consumption and elimination of human errors,
- increasing the quality of welds thanks to precise control of welding process parameters and eliminating the influence of external factors,
- improving occupational safety by reducing employee exposure to harmful gases, radiation, and high temperatures,
- increased production flexibility thanks to the ability to easily change the welding program and adapt it to various truss types.

The TIG method was used in the work carried out. TIG welding parameters on a welding robot (fig. 1) depend on many factors, such as the type and thickness of the material, the geometry and position of the weld, quality and normative requirements, the type and diameter of the non-consumable electrode, the type and intensity of the welding current, and the type and flow of gas. There is no single, universal recipe for selecting the ideal TIG welding parameters, because each case requires individual adaptation, especially due to the different thicknesses of the welded materials. However, there are some general rules and tips that can help you choose the right parameters. Direct current is used to weld steel, titanium, copper, and other non-ferromagnetic metals. The welding current affects the depth of penetration and the width of the weld. Too low a current may result in lack of fusion or arc instability, and too high a current may cause the material to melt or burn through. The welding current should be selected depending on the material thickness, electrode diameter, welding position and type of shielding gas. Taking into account the results of the tests carried out, as well as the company's own experience using the TIG method, the most generally favorable welding parameters were determined and used to produce a model truss node:

- welding speed: 5 cm/min,
- welding arc voltage 8.4 V,
- DC current, current source intensity 50 A,

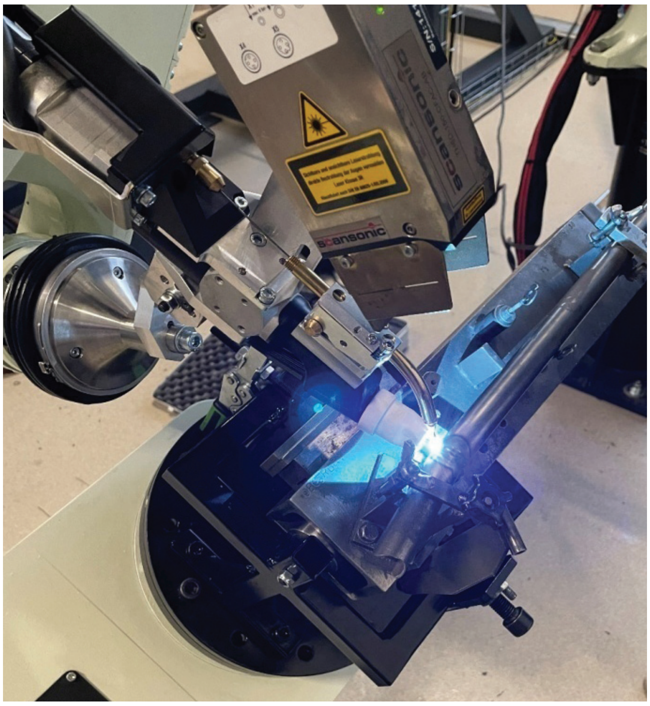

Fig. 1. Robot during the welding process of pipes constituting parts of the truss and the TIG welding process at a robotic station

- wire feed speed 0.7 m/min,
- wire glow delay 1 s,
- shortening the wire feeding in the final phase by 1 s,
- type and flow rate of shielding gas: Ar = 7 dm^3/min with a purity of 99.995%,
- diameter and type of material of the non-consumable tungsten electrode: WL15 with 1.5% lanthanum and $d = 1.6$ mm,
- diameter and type of additional material (binder) 15CDV6 $d = 1.2$ mm.

An example of a sample prepared for welding and welded automatically is shown in figures 2 and 3 [1, 2, 10].

The conducted research concerned welding with a weld in an inert gas shield (Argon) using the TIG method in a local manner for the location of a tack weld and a continuous weld. Work was carried out using manual and automated welding (on a robotic test stand) to check the efficiency of the method. Various

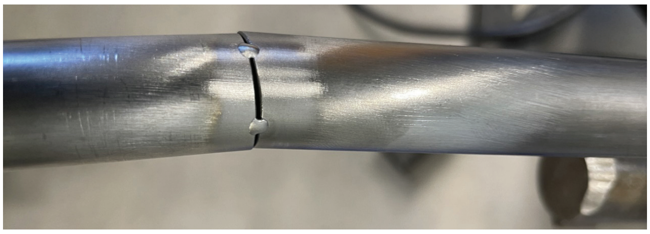

Fig. 2. Sample prepared in advance for automatic welding (three fixing points)

Fig. 3. Sample welded automatically with a welding robot

institutions and companies are developing technologies for the automated welding process of spatial lattice structures, and looking for optimal solutions for this. Robotic welding is one of the most advanced and effective ways of welding three-dimensional structural elements such as trusses. Welding robots (fig. 1) can make welds precisely and quickly in various positions and shapes, which allows for high-quality and durable joints. Robotic welding, however, requires appropriate programming of the robot, adaptation of the welding equipment to the shape of the structure, and the use of process sensors and geometry, as well as integration of the control system [6, 8, 9].

Tests of welded joints

Visual research

Visual inspections were treated as a priority for each welded product. The scope of these tests included all welded joints due to the adopted quality levels. Visual Tests included visual inspection and measurements of elements prepared for welding, checking the correctness of their assembly and checking the joints after welding. The research was conducted in a laboratory with room lighting intensity of 550 Lx. The research was carried out based on naked eye observations and the use of a magnifying glass with 16× magnification, as well as measuring instruments like calipers and linear instruments. The following external nonconformities were taken into account in the conducted tests: joint shape, joint dimensions, cracks, porosity, and unevenness of the surface undercutting of the weld edges, and material spatter. The truss structure allowed this research to be conducted. As a result of the metric and observational tests, it was found that the dimensions of the structure are consistent with the construction documentation, maintaining the tolerances imposed by the designer for class A structures according to PN-EN ISO 13920. No observable, external defects in the form of transverse or longitudinal cracks were found in the tested joints. There were no discrepancies regarding the shape or dimensions of the joints, including the occurrence of sticking or incorrect height and width of the joint. The tests did not take into account the ridges of the joints due to their absence on the workpieces. An example of the appearance of welds is shown in fig. 4. In order to better assess the faces of the welds, they were inspected using a magnifying glass with a magnification of 20× (fig. 5). Based on the observations, it can be concluded that there are no visible external cracks on the face of the joints. Clear, characteristic transverse lines resulting from the direction of the joint are visible. It should be stated that there are no unacceptable surface imperfections in the welds [10, 11].

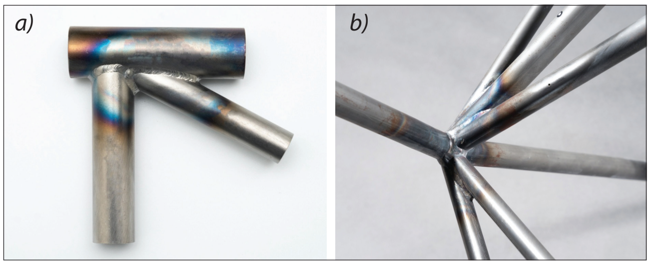

Fig. 4. Observed examples of truss nodes: *a*) simple automatic welded node, *b*) complex knot welded by hand

The quality of the external surfaces of automatically made welds (joint face) is definitely higher than that of manually made welds, although welds made in the aerospace industry always meet the required noncompliance conditions.

Quality control of aircraft truss welds using the magnetic-particle MT method

Testing and inspection of spatial properties, including welds and engine truss frames, is very difficult. An effective control method is the magnetic-particle method. Tests of complete, welded joints were carried out using the HD 1500 alternating current flaw detector and the YOKE 6 alternating current glow flaw detector, both of which have the following parameters:

- the tests were conducted in white light with an intensity of 1990 Lx,
- magnetic field strength > 2.7 kA/m,
- test agent: fluorescent suspension MAGNAGLO 14HF 2003152 with a concentration of 0.2 ml/100 ml with fluorescent properties, petroleum-based agent,

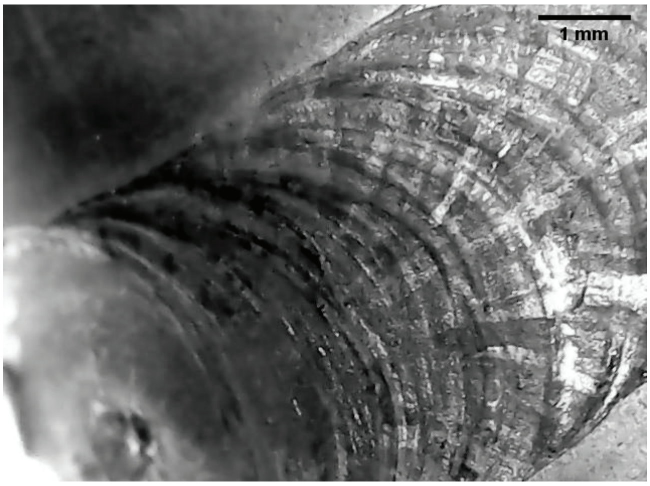

Fig. 5. Appearance of the weld face when viewed at 20× magnification; weld made automatically

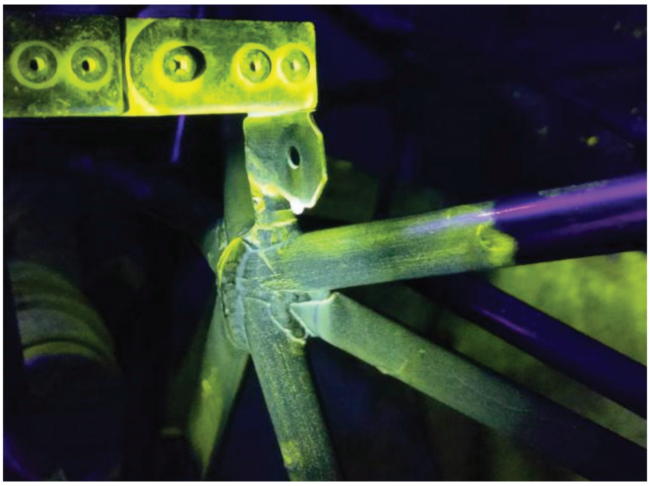

Fig. 6. Testing of the welded truss node using the magnetic-particle MT method

- observation conditions: tests in UV light with intensity $Ee = 2690\ W/cm^2$, white light $E = 4.9$ Lx, LEVY HILL MK VI 7656 white light meter.

The tests were carried out on the truss nodes. Example images obtained during the tests are shown in fig. 6. The test results enable a comprehensive assessment of the connection quality. This method is quick and allows you to assess the quality of the object at the welding station. The tests confirmed that the welds were of high quality.

Examination of engine trusses using the RT radiographic method

Due to their very complex geometry, the welds connecting the welded spatial nodes of frame are difficult to perform and it is also difficult to check their properties, which is necessary in order to confirm compliance with the non-compliance conditions. This applies especially to the internal cross-sections of the joints, due to the very complex geometric structure of the frame, and especially connecting nodes, where up to ten bars converge in one node. An effective method of weld quality control is the radiographic method applied directly to a simple joint or samples imitating a joint. Since there were very complex nodes in the tested structure, a comparative method was used, making butt and circumferential welds on pipes on structural elements of identical dimensions. Pipe dimensions were $D \times t = 32 \times 2$ and 28×2. The tests were carried out on the CERAM 235 device with an X-ray tube equipped with a DT-2 thermometer; Kowolux 4/4S negatoscope; NF 06-308 densitometer; densitometric standard 17330. Examples of samples made using automatic welding and radiographs of the tested butt welds are shown in figures 7 and 8.

Fig. 7. Photos of samples of welded pipe joints on which radiographic examination of the welds was performed

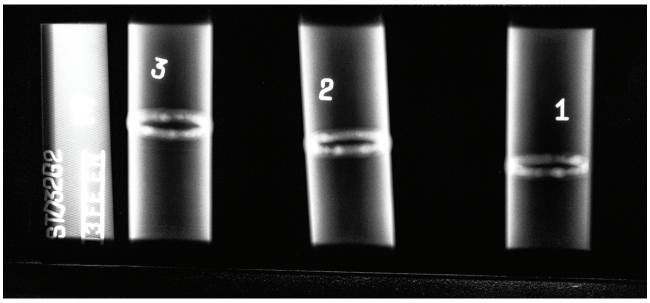

Fig. 8. Sample radiograph of radiographic examination of end-to-end joints of welded pipes joined by a butt weld

The tested samples were x-rayed in two mutually perpendicular cross-sections, while the pipe was angularly displaced in relation to the direction of radiation by an angle of approximately 30°. This original method of testing allows one to obtain an image of the weld in the form of an ellipse, where it is possible to observe both the face and the root of the weld. The image of the sample and its quality is the basis for assessing the quality of the weld of the completed structure from identical material and identical conditions. The welds did not show any internal damage and could be classified as class *B* according to relevant standards.

Results of microstructural tests

The tested welded truss elements were made of 14CrMoV6-9 in heat-treated condition. Examination of the welds using light microscopy indicates the banding of the microstructure of the steel mentioned, resulting from the pipe manufacturing process (cold drawing) (fig. 9*a*). The microstructure of the steel, taking into account its heat-treated condition, does not have features typical of highly tempered martensite. Taking into account the chemical composition of the tested steel, as well as the results of other tests [3, 4], it cannot be ruled out that the main component of its microstructure is tempered bainite (fig. 9*b*).

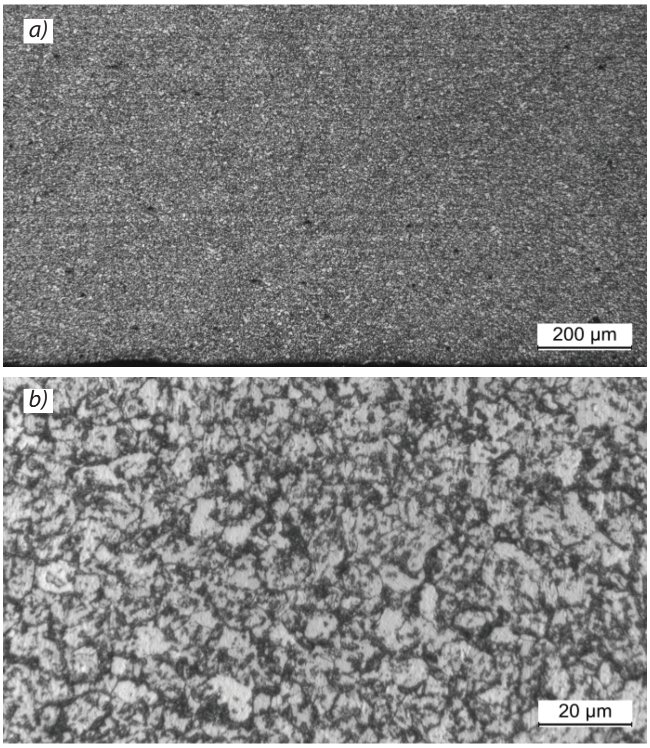

Fig. 9. Microstructure of steel 1.7734.5 (14CrMoV6-9) – longitudinal section – sample cut from a pipe

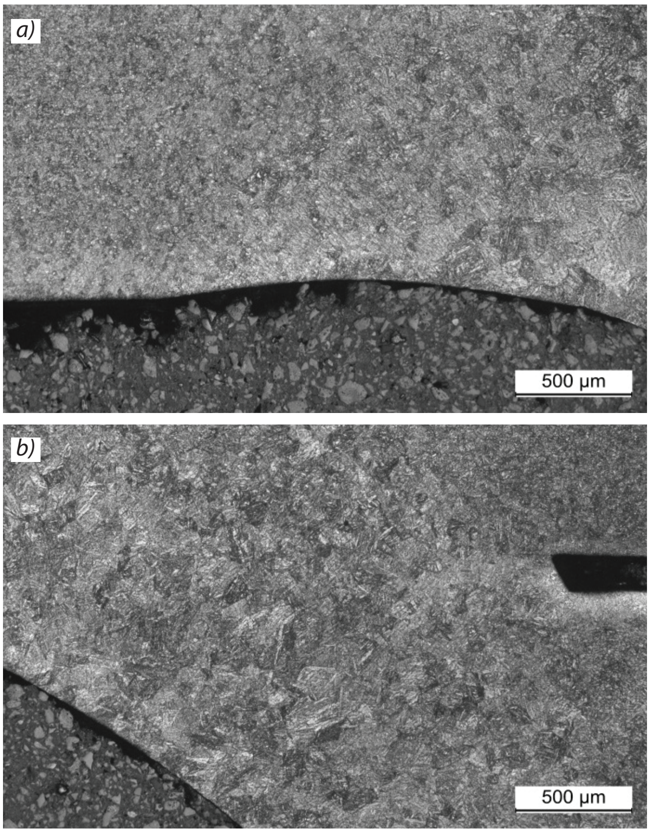

Fig. 10. Microstructure of weld 1: *a*) transition area between the base material and melting zone, *b*) melting zone

The microstructure of welded joints is characterized by a resulting gradient from the existence of the heat affected zone (HAZ) between the parent material and the remelting zone (fig. 10).

In the fusion zone of all tested welds, a similar morphology of the phase components of the microstructure was identified. As a result of the re-crystallization of steel 14CrMoV6-9 martensitic transformation is possible during welding [5, 7]. The acicular nature of the microstructure seems to confirm this.

Tests of the hardness of the weld material

The weld hardness was measured using the micro-indentation method using a Nexus 4303 micro hardness tester from Innovatest. The Vickers method and a load of 0.5 kG were used.

Measurements at a distance of approx. 0.3÷0.5 mm were made on the cross-sectional surface of weld 2 (fig. 11) – along a straight line, from the base material, through the heat affected zone, to the fusion zone (fig. 12).

The analysis of the hardness measurement results indicates that the hardness of the native material (points 1÷4 – table and fig. 13) is approximately 360 HV0.5 (37 HRC according to the hardness conversion table). It can be assumed that the hardness of the HAZ (point 5 – table and fig. 13) is approximately 400 HV0.5, while the hardness of the fusion zones (points 6÷15 – table) is greater than 420 HV0.5. The large variability of results in the fusion zone results from the heterogeneity of the microstructure, which significantly determines the results of hardness measurements. The obtained results of the hardness of the base material and HAZ are similar to those presented in publication [4] – the hardness of the fusion zones were not compared due to a different welding method used (TIG method).

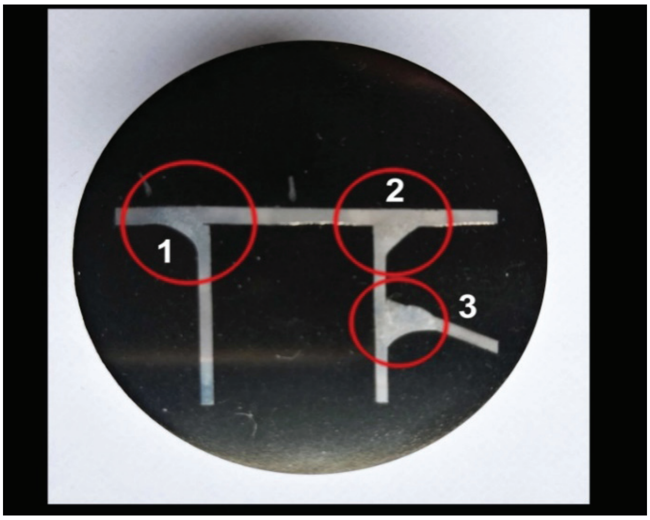

Fig. 11. Marking of the welds of the tested joint

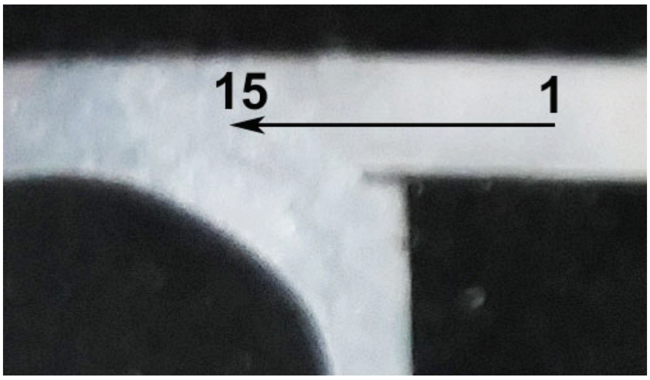

Fig. 12. Line of hardness measurements on the weld cross-section 3 (1 and 15 – markings of the extreme measurement points – table)

TABLE. Results of HV0.5 hardness measurements of the joint fillet weld

Measurement no.	1	2	3	4	5	6	7	8
HV0,5	367	329	381	363	400	441	451	424
Measurement no.	9	10	11	12	13	14	15	
HV0,5	412	409	398	385	445	431	441	

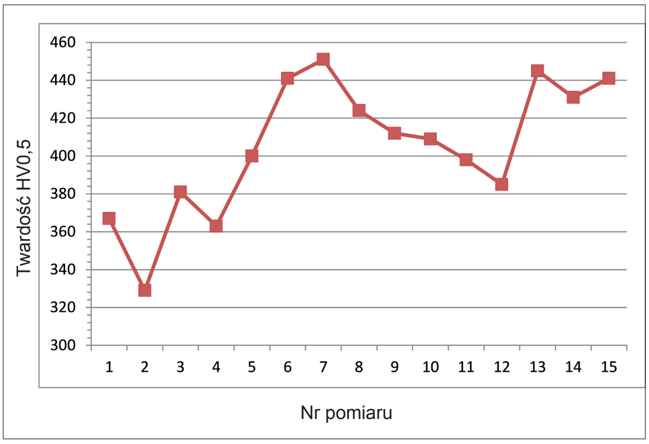

Fig. 13. Hardness distribution on the weld cross-section 3

Conclusion

Welding parameters have a significant impact on the quality of joints and the efficiency of the welding process, especially automated welding. The welding current has the greatest impact on the depth of penetration, the width of the weld, and the welding speed. However, it is necessary to limit it due to the possibility of overheating the electrode and melting it. The voltage of the welding arc results from the arc length (and the shielding gas used) and affects the shape of the weld. Its value depends on the welding current and shielding gas used. The higher the arc voltage, the less stability in the process, and if then the width of the weld face increases and the penetration depth decreases. Welding speed is a parameter that affects the linear energy of welding and, therefore, the amount of heat supplied to the place where the welded joint is made. Research carried out on the automation of the welding process of structural steel 14CrMoV6-9, which is characterized by good weldability, confirmed its suitability for making structures such as aircraft trusses in a heat-treated condition. As tests have shown, manual welding is more efficient for individual production of lattice structures, but even with several dozen pieces, e.g. of aircraft engine frames, the efficiency of automatic welding is 100% higher.

This especially applies to circumferential welding, e.g. of the RPS mounting sleeve to the pipe node using a rotator. The quality of automatic welding is also better and more repeatable. Nevertheless, the average time for setting and selecting the parameters of the first welding cycle of one node of a lattice structure for automatic welding is approximately 8÷12 hours, which significantly extends the implementation of the operation. The process of retooling the equipment itself with a previously written program takes up to approximately 2 hours, including test runs.

The most important issue of automation for the welding process is the nodes of the aircraft engine frame, whose limited access requires manual welding. Therefore, the future of welding lattice aircraft structures will require a hybrid approach to the process, i.e., some of the node connections can be easily automated, while some will need to remain performed using classic manufacturing methods.

Metallographic examination of welds allowed for the assessment of welding inconsistencies described by the relevant standards for microscopic examination with etching:

- no cracks in the joints in any form were noticed,
- the joints were free of bubbles and inclusions,
- no edge gluing type 4011,
- the morphology of the structure of phase components is regular, maintaining differences between melted zones and native material,
- the fusion line is clear and without any gaps.

Steel 14CrMoV6-9 is a material that can be welded well. During the welding process, the structure of steel changes, taking on a martensitic or bainitic form.

For the steel used, the index of steel's tendency to crack UCS and the index of steel's tendency to decrease ductility CEV have values indicating the risk of weld cracks. Our own tests, including TIG welding tests, showed that the microhardness of the weld material is in the range HV0.5 = 340÷450, which indicates the possibility of cracks occurring.

Tests were carried out on welding and cooling the welds at various speeds. These tests showed that there were no cracks in the entire volume of the weld, and the welds were of very good quality, qualifying them for group *B* according to the relevant standards and could be used in the production of important components.

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