УДК 621.791.725
UDC 621.791.725

Bernatskyi A. V., Siora O. V., Yurchenko Yu. V., Lukashenko V. A., Harder D. A.
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine

DEVELOPMENT OF THE TECHNOLOGY OF LASER WELDING OF A THIN-WALLED GIRTH JOINT FOR THE MANUFACTURE OF THE HOUSING STRUCTURE OF THE SENSOR

Thin-walled products with girth welded joints are widely used in modern machine building and instrumentation, where the quality of welded joints is subject to particularly high requirements. Welding of such products is accompanied by a number of technological challenges, especially when laser welding is used. The main problems are the instability of the metal remelting process due to the small diameters of the focused laser radiation, the risk of burns, lack of penetration, pore formation, and localized weakening of the joint due to overheating. In this work, laser welding of girth welded joints of sensor housings made of AISI 304 stainless steel was studied using a fiber laser YLR-400-WC. Welding was performed in a pulsed mode with a frequency of 1000 Hz using high-purity argon as a shielding gas. To ensure high quality of welded joints, special technological solutions were used: smooth increase and decrease of laser power at the beginning and end of the welded joint to avoid cratering, use of a precision rotator with high positioning accuracy, and modernization of the design of the welded edges. During the experiments, it was found that the original scheme with flanging only on the cover of the sensor part led to depressurization due to overheating in the area where the sensor contacts are attached. To eliminate this problem, a new design scheme was developed with remote flanges on the sensor cover and flange, and a heat dissipation system with an aluminum spacer and thermal paste applied to it was introduced. Additionally, a metal ball was used to stabilize the rotation, which reduced friction. The results of the study confirmed the effectiveness of the proposed solutions: stable formation of a tight welded joint without defects and local overheating was achieved. The data obtained demonstrate the prospects of using laser welding for girth joints of thin-walled products, provided that the design of the welded elements is optimized and the thermal regime is controlled.

Keywords: laser welding, thin-walled products, development of welded joint design, flanging, parts with a rotation axis, stainless steels, AISI 304.

INTRODUCTION

Thin-walled products with girth welded joints play an important role in modern mechanical engineering and instrumentation. They are used in a variety of industries, including aviation and space technology, power engineering, food processing, chemical production, medical equipment, etc. [1-3]. These industries have increased requirements for the quality of welded joints, as even minor defects can lead to a decrease in tightness, loss of strength, or failure of the assembly during use. One of the most common materials for the manufacture of thin-walled welded structures is stainless steel, in particular AISI 304 [4]. This material combines high corrosion resistance in a wide range of aggressive environments, good mechanical properties, structural stability at low and high temperatures, and weldability without a tendency to hot crack formation. Due to these properties, AISI 304 is a universal material for structures operating under dynamic loads, temperature changes, and aggressive environments [4]. The Ukrainian industry traditionally uses such welding methods as plasma, electron beam, and argon arc (TIG) welding to join thin-walled parts with girth welds [5]. These methods can achieve a sufficient level of quality, but have a number of limitations. Electron beam welding requires the use of vacuum chambers that limit the dimensions of the parts to be welded; complex electron beam control systems, which significantly increases the cost and complexity of the equipment. Although TIG welding is more flexible in application, it forms a larger heat affected zone, which causes higher levels of residual stresses and deformations compared to other welding methods [6-7]. In this regard, laser welding, a technology that allows for the formation of high-quality welded joints with a minimum heat affected zone, is becoming increasingly widespread. One of the key advantages of laser welding is the ability to weld without the use of vacuum chambers and complex positioning systems, which significantly reduces time and resources spent on preparing the welding process. In addition, laser welding ensures the stability of the product geometry due to minimal residual deformations and stresses [8].

LITERATURE ANALYSIS AND PROBLEM STATEMENT

In the process of implementing both laser and electron beam welding for girth welded joints of thin-walled products, there are problems associated with the design of the joint, since these welding methods have small diameters of focus spots. In particular, with small wall thicknesses and concentric surfaces of the welded parts, there is a problem of insufficient volume of melted metal in the welded joint zone [9]. This reduces the stability of the penetration process and can lead to the formation of defects such as burn-throughs, lack of fusion, pores, and cause a decrease in joint strength due to its local weakening [10].

The article on electron beam welding of Mo-Ti-Zr alloy gas valve elements discusses measures to improve the structure and tightness of welded joints [9]. It is noted that traditional methods, such as preheating, careful edge preparation, and remelting, although reducing the risk of pore formation, were not effective enough to ensure high ductility and reliability of welded joints. They did not solve the problem completely, but were retained in the technological process due to their possible positive impact on structural transformations during crystallization.

The research focused on constructive improvement of the shape of the welded edges. It was found that one of the most effective ways to reduce the possibility of pores and crystallization cracks is to change the geometry of the joint. The use of flanging of the welded edges made it possible to implement a more favorable melt solidification scheme, where the primary crystallites in the process of melt solidification do not contact the vertices but the side faces, which significantly increases the crack resistance of the weld. As a result of the gradual improvement of the component design and assembly scheme, the manufacturability of the welding process was improved (Fig. 1).

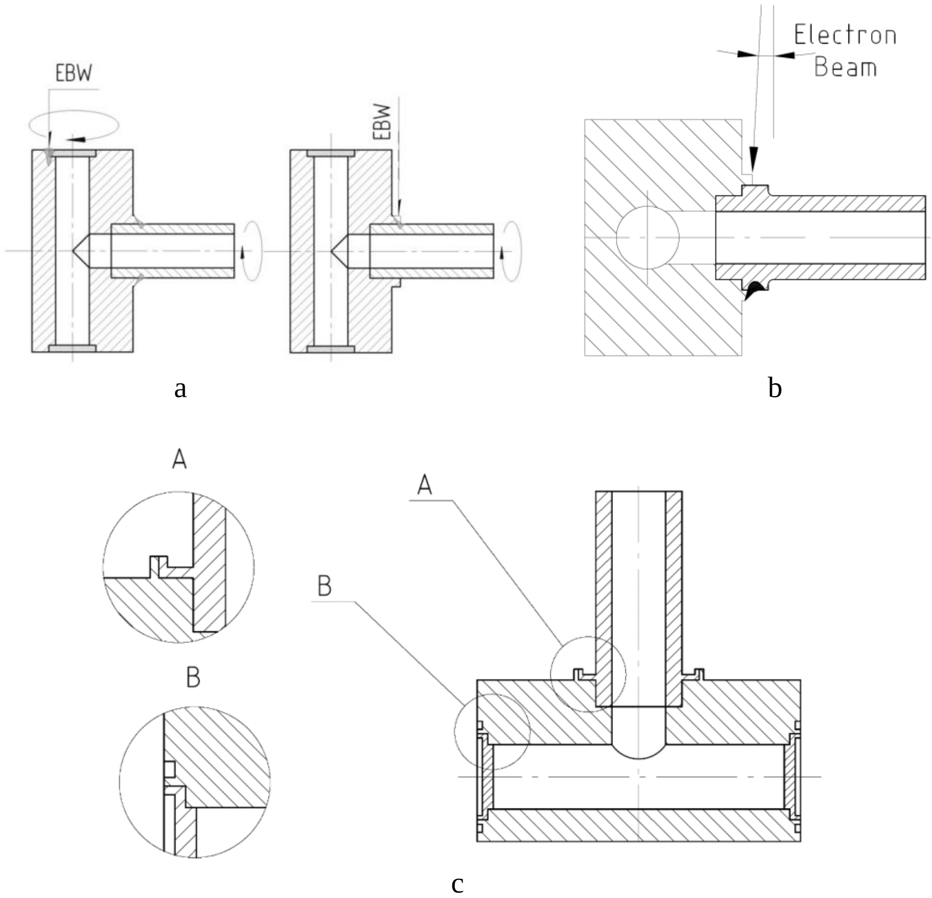


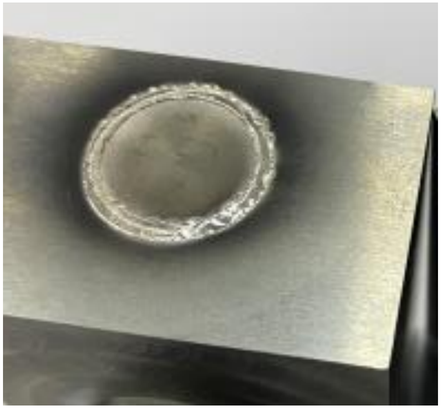
Fig. 1. Three stages of modernization of the design of welded joints of the assembly: (a) welding of the nipple with the housing “in the lock” was replaced by a scheme with a ‘collar’ fused to the nipple wall, the housing with plugs - “in the lock”, (b) the nipple was modified for welding with an inclined electron beam, (c) modernization of the joints of fittings in the form of flanging the edges of the joint [9].

As part of the modernization of the welded joint design, the study considered several configuration options that affect the quality of weld formation during electron beam welding of gas valve elements.

In one of these variants (Fig. 1, b), the deflection angle and focus position of the electron beam were adjusted, which made it possible to weld three joints in one vacuum of the welding chamber. This significantly increased the productivity of the process. However, during the welding process, it turned out that the existing gaps in the joints of the parts - the housing, fittings and plugs - made it impossible to achieve the required tightness of the joints, which was confirmed during hydraulic tests. In order to eliminate this problem, it was proposed to use the H7/p6 type fit, which provides guaranteed tension in the joint, eliminating the gap in the joint. To implement this solution, high-precision grinding of the contact surfaces of the parts before welding was performed. This technological addition made it possible to achieve high assembly accuracy and ensure the tightness of the entire assembly.

Further improvement led to the development of a variant with flanging of the joint edges (Fig. 1, c), which was adopted as the basic one. This version changed the geometry of the joint, which simplified the positioning of the elements before welding. There is no longer a need to use a tilted beam, as was envisaged in the previous versions. This design not only improves the manufacturability of the process, but also reduces the likelihood of defects associated with inaccurate beam guidance. All welds made according to the updated scheme with a “tight” connection (without a gap in the joint) demonstrated stable formation of the outer bead (Fig. 2), which indicates the effectiveness of the design changes.

a



b

Fig. 2. Formation of girth seams with edge flanging imitating nipple- housing (a) and plug- housing (b) connections [9].

Given that in modern work on welding thin-walled products with an axis of rotation, little attention is paid to modernizing the design of welded joints, this area of research is relevant. The scientific development of new approaches in this area will not only reduce the likelihood of defects, but also increase the efficiency of the welding process, ensure reproducibility of results and expand the scope of laser technologies in precision welding of thin-walled structures.

AIM AND OBJECTIVES OF THE RESEARCH

The aim of the work is to develop the technology of laser welding of girth welded joints made of AISI 304 stainless steel, which is used in the manufacture of the sensor housing.

To achieve this goal, it was necessary to solve the following tasks:

1. Develop an optimal design of the welded joint.

2. To develop a laser welding process that would not cause thermal effects on the sensor part contacts and ensure the tightness of the structure.

RESULTS OF RESEARCH

A 400 W fiber laser YLR-400-WC manufactured by IPG (Germany) was used for laser welding of the girth welded joints of the sensor housing.

The laser radiation was focused using an optical head for laser welding with a focal length of 200 mm (Fig. 3).

Fig. 3. 3D model of the optical head for laser welding

For laser welding of girth welded joints of thin-walled products, an auxiliary precision process tooling was used, which is a precision rotator (Fig. 4).

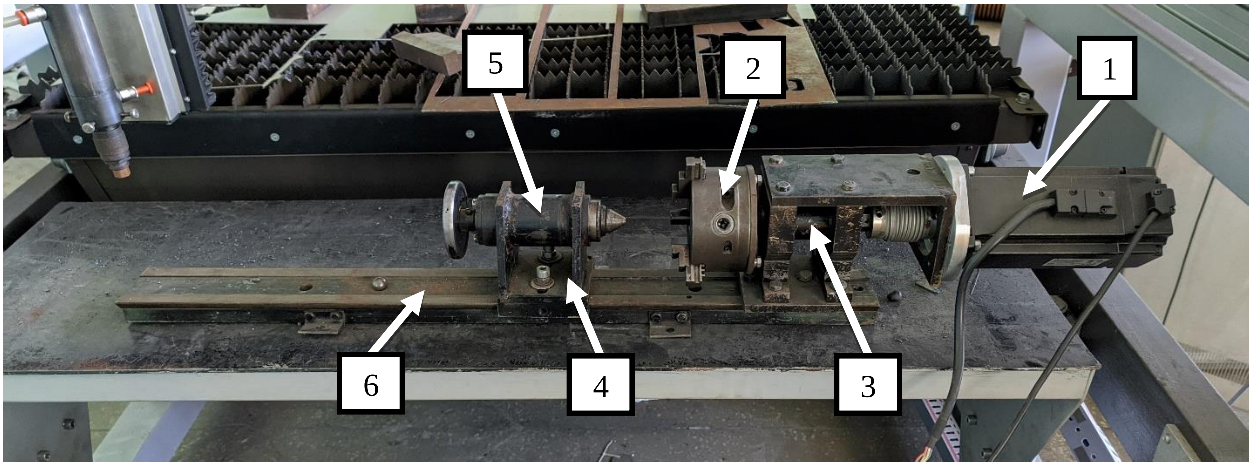


Fig. 4. Precision rotator, where 1 – servo motor, 2 – chuck for clamping the parts of rotation, 3 – front headstock, 4 – rear headstock, 5 – rear headstock pinnacle for supporting the parts of rotation, 6 – bed

Due to the presence of a bed, the precision rotator allows welding parts up to 450 mm long, and parts with a diameter of 6...80 mm can be fixed in the chuck for clamping the parts of the rotation. The servo motor is synchronized with the laser welding machine, which ensures a positioning accuracy of 0.1 mm and repeatability of at least ± 0.08 mm.

The precision rotator allows performing laser welding according to the scheme shown in Fig. 5.

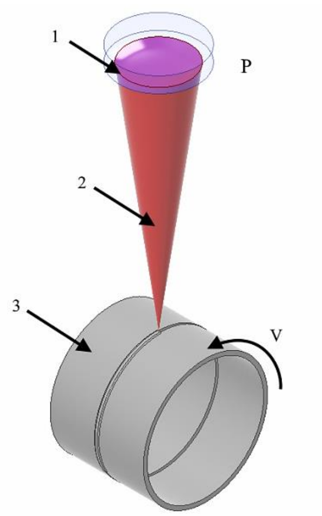


Fig. 5. Schematic of laser welding on a precision rotator, where 1 – lens, 2 – laser beam, 3 – workpiece to be welded

Laser welding was performed in pulse mode with a pulse frequency of 1000 Hz. As a shielding gas for the welding zone from the ambient atmosphere, we used extra-pure argon at a flow rate of 12 l/min. To prevent the formation of craters at the beginning and end of the welded joint, a technique of gradual ramp-up and ramp-down of laser power at the start and end of the welding process, respectively, was employed. The entire welding process was performed continuously, without stopping between program commands. The housing of the sensor part is made of AISI 304 stainless steel, the chemical composition of which is shown in Table 1. The parameters of the laser welding mode are shown in Table 2.

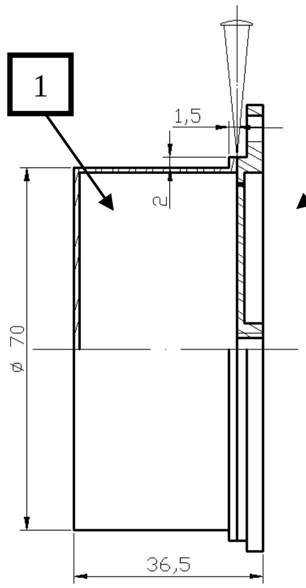
Table 1. Chemical composition of AISI 304 stainless steel, % wt.

C	Si	Mn	Ni	S	P	Cr	Cu	Ti	Fe
≤0,08	≤0,8	≤2,00	9,00 – 11,00	≤0,02	≤0,035	17,00 – 19,00	≤0,3	≤0,5	Balance

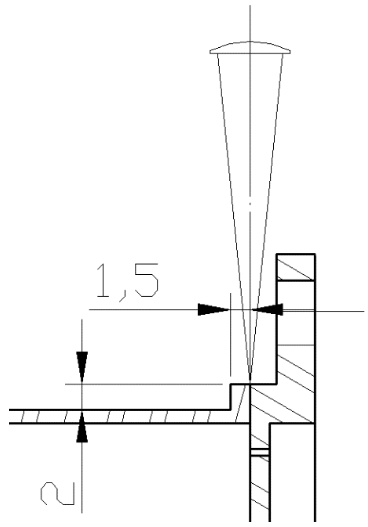
Table 2. Laser welding parameters

Welding stages	Welding speed, V m/min	Welding power, $P_{average}$ W	Rotation relative to the workpiece axis, °
Increasing power	0,3	20	3
	0,3	40	3
	0,3	70	3
	0,3	100	3
Main seam	0,3	200	365
Decreasing power	0,3	100	3
	0,3	70	3

The first scheme of the welded joint design was the "cover with flanging" scheme (Fig. 6). In this scheme, the flanging was made on the cover of the sensor detail.



a



б

Fig. 6. Welding scheme "cover with flanging": (a) general view, (b) welding location, where 1 – cover, 2 – flange

In Fig. 7 the process of laser welding and mounting of the sensor detail in the rotator is shown.

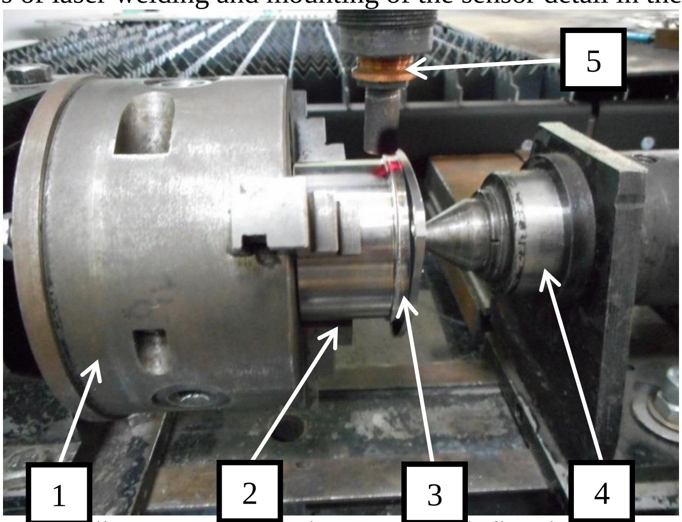


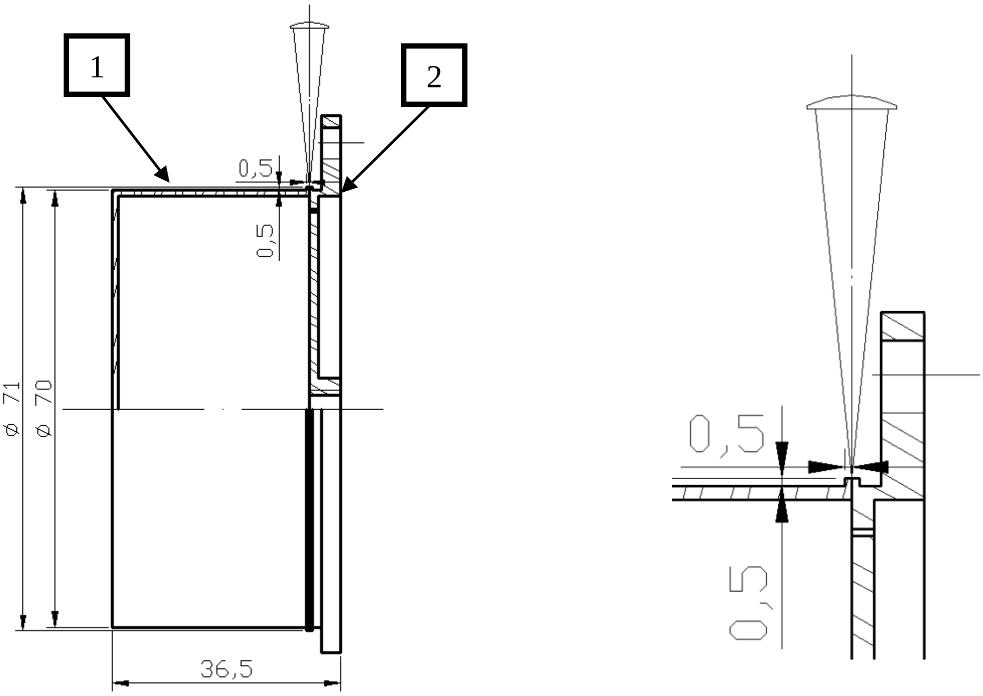
Fig. 7. The process of laser welding according to the "cover with flanging" scheme, and fixing the welded part in the rotator, where 1 – clamping chuck, 2 – sensor part housing, 3 – welded joint, 4 – tailstock, 5 – laser welding head

Fig. 8 shows a welded sensor part using the “cover with flanging” scheme.

Fig. 8. Welded sensor part using the “cover with flanging” scheme

After welding the part, it was discovered that the sensor contact mounting point in the flange was depressurized, as the melting of a relatively large volume of metal caused the welding area and the surrounding metal to overheat. Therefore, it was decided to modernize the geometry of the welded edges and to additionally cool the housing on the side of the sensor contacts.

In the following welding scheme, it was proposed to make a flanging not only on the cover but also on the flange (Fig. 9). To reduce the thermal effect on the sensors mounted in the flange, the welded edges were made in the form of remote flanges measuring 0.5×0.5 mm, and an aluminum spacer with applied thermal paste was used, which is pressed from the side of the sensor mounting point. To reduce the friction during rotation, a metal ball was used, which fits into a special recess in the aluminum spacer and the rotator headstock.



a **б**

Fig. 9. Welding scheme “cover and flange with flanging”: (a) general view, (b) welding location, where 1 – cover, 2 – flange

Fig. 10 shows the process of laser welding and mounting the part in the rotator.

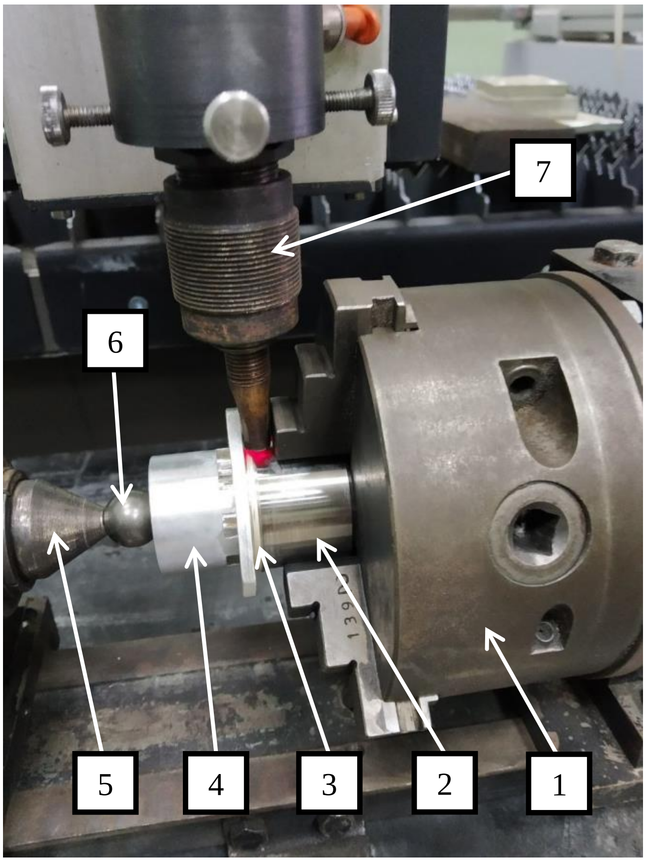


Fig. 10. The process of laser welding according to the scheme “cover and flange with flanging”, where 1– clamping chuck, 2 – sensor part housing, 3 – welded joint, 4 – aluminum spacer, 5 – tailstock, 7 – metal ball, 6 – laser welding head

As a result of laser welding, a high-quality sealed welded joint was obtained without overheating of the surrounding metal and the sensor mounting point in the flange. Therefore, it can be concluded that the technological decisions made were reasonable.

DISCUSSION OF THE RESEARCH RESULTS

The obtained results of laser welding of sensor parts using a pulsed mode with a frequency of 1000 Hz and the use of high-purity argon as a shielding gas indicate the effectiveness of the proposed technological solutions in ensuring the tightness of the welded joint without overheating of critical parts of the structure. The implementation of gradual ramp-up and ramp-down of laser power at the beginning and end of the welding process made it possible to avoid defects such as crater formation, which could reduce the tightness and strength of the welded joint.

Compared with the results of a study on electron beam welding of gas valve elements made of Mo-Ti-Zr alloy [9], we can note the commonality in approaches to improving the geometry of the welded joint as one of the main factors in ensuring a high-quality welded joint. In contrast to electron beam welding, where the improvement of the joint configuration made it possible to avoid crystallization cracks, the main challenge in this study was to localize the thermal impact in order to prevent overheating of the sensors installed in the flange. The use of remote flanges (0.5×0.5 mm) in combination with a heat-removing aluminum spacer with thermal paste allowed us to effectively implement the concept of a controlled thermal regime. Such solutions were not available in the mentioned article on electron beam welding, where the problem of heat dissipation or impact on neighboring components was not critical. Additionally, the proposed design – a ball that reduces friction during rotation – provided increased positioning stability, which is important for the laser welding process when the workpiece rotates. Another difference is the approach to ensuring tightness. In the aforementioned study, achieving tightness required the use of H7/p6 type fit and high-precision surface grinding, while in the presented work it is ensured primarily due to local control of the thermal regime, the geometry of the welded joint, and a well-thought-out choice of cooling elements. The proposed approaches have demonstrated high efficiency, especially in conditions where even a local temperature excess in sensitive areas of the structure is unacceptable.

CONCLUSIONS

In the course of the research, it was found that laser welding of the sensor component details in the pulsed mode with a frequency of 1000 Hz and the use of high-purity argon as a shielding gas ensures the formation of a high-quality tight welded joint, provided that a number of technological measures are followed. One of the important problems in welding thin-walled products with a axis of rotation was the formation of craters at the beginning and end of the weld. To eliminate them, a technique of gradual ramp-up and ramp-down of laser power at the beginning and end of the welding process, respectively, was applied, which ensured uniform formation of the weld pool and prevented defects in the edge zones of the joint. In addition, structural modernization of the welded edges, including the use of flanging on the cover and the flange, as well as the use of a heat-removing aluminum spacer with thermal paste, prevented localized overheating of the metal in the area of sensor mounting. An additional solution, such as the use of a metal ball in the rotation system, helped reduce friction and stabilize the welding process. Thus, the results of the research confirm the validity of the selected technological solutions. Improvements in the geometry of the welded edges and a well-thought-out organization of heat removal made it possible to eliminate the primary problems, in particular overheating and depressurization, and to achieve stable formation of a high-quality welded joint.

ПЕРЕЛІК ДЖЕРЕЛ ПОСИЛАННЯ

1.McNair S. A. M., Chaharsooghi A. S., Carnevale M., Rhead A., Onnela A., Daguin J., et al. Manufacturing technologies and joining methods of metallic thin-walled pipes for use in high pressure cooling systems. *The International Journal of Advanced Manufacturing Technology*. 2021. Vol. 118, No 3–4. P. 667–681. https://doi.org/10.1007/s00170-021-07982-8

2.Korzhyk V., Khaskin V., Peleshenko S., Grynyuk A., Chunlin D., Illyashenko E., & Yao Y. Selection of parameters of laser welding of thin-walled items from light alloys with nonthrough thickness penetration. *The Paton Welding Journal*. 2022. No 5. P. 16–25. https://doi.org/10.37434/tpwj2022.05.03

3.Wang D., Wang Y., Yang Y., Lu J., Xu Z., Li S., et al. Research on design optimization and manufacturing of coating pipes for automobile seal based on selective laser melting. *Journal of Materials Processing Technology*. 2019. Vol. 273. 116227. https://doi.org/10.1016/j.jmatprotec.2019.05.008

4.Dutta S. Different types and new applications of stainless steel. *Stainless steel*. 2018. Vol. 62, No 5. P. 86–91. URL: https://www.researchgate.net/profile/S-Dutta/publication/330383386_Different_Types_and_New_Applications_of_Stainless_Steel/links/5c3d6a31a6fdccd6b5ad9ee0/Different-Types-and-New-Applications-of-Stainless-Steel.pdf (дата звернення 28.04.2025)

5.Zasiadko I. Z., Korinets I. P. Zvariuvannia tonkolystovykh konstruktsii [Welding of thin sheet constructions]. *Naukovi visti NTUU "KPI"*. 2010. Vol. 5. P. 81-87.

6.Khoshnaw F., Krivtsun I., & Korzhyk V. Arc welding methods. *Elsevier eBooks*. 2023. P. 37–71. https://doi.org/10.1016/b978-0-323-90552-7.00004-3

7.Ahmad A. Y. Al-Qenaei. Fusion welding techniques. *International Jornal of Engineering Research and Applications.* 2016. Vol. 6, No 3. P. 78–83. https://www.academia.edu/download/47559936/M6302078083.pdf

8.Deepak J., Anirudh R.P., & Sundar S. S. Applications of lasers in industries and laser welding: A review. *Materials Today Proceedings*. 2023. https://doi.org/10.1016/j.matpr.2023.02.102

9.Zagornikov V., Nesterenkov V., Khripko K., & Ignatusha O. Electron beam welding of gas valve elements from Mo-Ti-Zr alloy. *Automatic Welding*. 2025. Vol. 1. P. 30–39. https://doi.org/10.37434/as2025.01.05

10.Madhvacharyula A. S., Pavan A. V. S., Gorthi S., Chitral S., Venkaiah N., & Kiran D. V. In situ detection of welding defects: a review. *Welding in the World*, 2022. Vol. 66, No 4. P. 611–628. https://doi.org/10.1007/s40194-021-01229-6

REFERENCES

1.McNair, S. A. M., Chaharsooghi, A. S., Carnevale, M., Rhead, A., Onnela, A., Daguin, J., et al. (2021). Manufacturing technologies and joining methods of metallic thin-walled pipes for use in high pressure cooling systems. *The International Journal of Advanced Manufacturing Technology*, *118*(3–4), 667–681. https://doi.org/10.1007/s00170-021-07982-8

2.Korzhyk, V., Khaskin, V., Peleshenko, S., Grynyuk, A., Chunlin, D., Illyashenko, E., & Yao, Y. (2022). Selection of parameters of laser welding of thin-walled items from light alloys with nonthrough thickness penetration. *The Paton Welding Journal*, *2022*(5), 16–25. https://doi.org/10.37434/tpwj2022.05.03

3.Wang, D., Wang, Y., Yang, Y., Lu, J., Xu, Z., Li, S., et al. (2019). Research on design optimization and manufacturing of coating pipes for automobile seal based on selective laser melting. *Journal of Materials Processing Technology*, *273*, 116227. https://doi.org/10.1016/j.jmatprotec.2019.05.008

4.Dutta, S. (2018). Different types and new applications of stainless steel. *Stainless steel*, *62*(5), 86–91. Retrieved from https://www.researchgate.net/profile/S-Dutta/publication/330383386_Different_Types_and_New_Applications_of_Stainless_Steel/links/5c3d6a31a6fdccd6b5ad9ee0/Different-Types-and-New-Applications-of-Stainless-Steel.pdf

5.Zasiadko, I. Z., Korinets, I. P. (2010). Zvariuvannia tonkolystovykh konstruktsii [Welding of thin sheet constructions]. *Naukovi visti NTUU "KPI"*, 5, 81-87.

6.Khoshnaw, F., Krivtsun, I., & Korzhyk, V. (2023). Arc welding methods. *Elsevier eBooks*, 37–71. https://doi.org/10.1016/b978-0-323-90552-7.00004-3

7.Ahmad A. Y. Al-Qenaei. (2016). Fusion welding techniques. *International Jornal of Engineering Research and Applications*, *6*(3), 78–83. https://www.academia.edu/download/47559936/M6302078083.pdf

8.Deepak, J., Anirudh, R.P., & Sundar, S. S. (2023b). Applications of lasers in industries and laser welding: A review. *Materials Today Proceedings*. https://doi.org/10.1016/j.matpr.2023.02.102

9.Zagornikov, V., Nesterenkov, V., Khripko, K., & Ignatusha, O. (2025). Electron beam welding of gas valve elements from Mo-Ti-Zr alloy. *Automatic Welding*, *1*, 30–39. https://doi.org/10.37434/as2025.01.05

10.Madhvacharyula, A. S., Pavan, A. V. S., Gorthi, S., Chitral, S., Venkaiah, N., & Kiran, D. V. (2022). In situ detection of welding defects: a review. *Welding in the World*, *66*(4), 611–628. https://doi.org/10.1007/s40194-021-01229-6

Бернацький А. В., Сіора О. В., Юрченко Ю. В., Лукашенко В. А., Гардер Д. А. **Відпрацювання технології лазерного зварювання тонкостінного кільцевого з'єднання для виготовлення корпусної конструкції датчика**

Тонкостінні вироби з кільцевими зварними з'єднаннями широко застосовуються в сучасному машинобудуванні та приладобудуванні, де до якості зварних з’єднань висуваються особливо високі вимоги. Зварювання таких виробів супроводжується низкою технологічних викликів, особливо при використанні лазерного зварювання. Основними проблемами є нестабільність процесу переплавлення металу через малі діаметри сфокусованого лазерного випромінювання, ризик прожогів, непроварів, пороутворення, а також локальне ослаблення з’єднання через перегрів. У роботі проведено дослідження лазерного зварювання кільцевих зварних з’єднань корпусів датчиків із нержавіючої сталі AISI 304 за допомогою волоконного лазера YLR-400-WC. Зварювання здійснювалося в імпульсному режимі з частотою 1000 Гц із застосуванням високочистого аргону як захисного газу. Для забезпечення високої якості зварних з’єднань були використані спеціальні технологічні рішення: плавне наростання та зменшення потужності лазерного випромінювання на початку і в кінці зварного з’єднання для уникнення утворення кратерів, застосування прецизійного обертача з високою точністю позиціювання, а також модернізація конструкції зварюваних крайок. Під час експериментів виявлено, що первісна схема з відбортовкою тільки на кришці **деталі датчика** призводила до розгерметизації через перегрів у зоні кріплення контактів датчика. Для усунення цієї проблеми було розроблено нову конструктивну схему з виносними відбортовками на кришці **деталі датчика** та фланці, а також впроваджено систему тепловідведення з алюмінієвою проставкою і нанесеною на неї термопастою. Додатково для стабілізації обертання використано металеву кульку, що зменшувала тертя. За результатами дослідження підтверджено ефективність запропонованих рішень: досягнуто стабільне формування герметичного зварного з’єднання без дефектів і локального перегріву. Отримані дані демонструють перспективність застосування лазерного зварювання для кільцевих з'єднань тонкостінних виробів за умови оптимізації конструкції зварюваних елементів і контролю теплового режиму.

Ключові слова: лазерне зварювання, тонкостінні вироби, розробка конструкції зварного з’єднання, відбортовка, деталі з віссю обертання, нержавіючі сталі, AISI 304.

БЕРНАЦЬКИЙ Артемій Володимирович, кандидат технічних наук, старший дослідник, завідувач відділу «Спеціалізована високовольтна техніка та лазерне зварювання», Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, e-mail: Bernatskyi@paton.kiev.ua. https://orcid.org/0000-0002-8050-5580

СІОРА Олександр Васильович, науковий співробітник відділу «Спеціалізована високовольтна техніка та лазерне зварювання», Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, e-mail: siora@ua.fm. https://orcid.org/0000-0003-1927-790X

ЮРЧЕНКО Юрій Вікторович, аспірант, провідний інженер відділу «Спеціалізована високовольтна техніка та лазерне зварювання», Інститут електрозварювання ім. Є.О.Патона Національної академії наук України, e-mail: yuriyyurchenko14@gmail.com. https://orcid.org/0000-0001-9253-009X.

ЛУКАШЕНКО Володимир Андрійович, кандидат технічних наук, науковий співробітник відділу «Спеціалізована високовольтна техніка та лазерне зварювання», Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, e-mail: z_lyk@ukr.net. https://orcid.org/0000-0002-9685-4654.

ГАРДЕР Дмитро Андрійович, кандидат технічних наук, науковий співробітник відділу «Спеціалізована високовольтна техніка та лазерне зварювання», Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, e-mail: lukash_d@ukr.net. https://orcid.org/0000-0002-4066-8182.

Artemii BERNATSKYI, Candidate of Technical Sciences, Senior Researcher, Head of the Department of the Specialized High-Voltage Engineering and Laser Welding, *E. O.* Paton Electric Welding Institute of the National Academy of Sciences of Ukraine, e-mail: Bernatskyi@paton.kiev.ua. https://orcid.org/0000-0002-8050-5580

Oleksandr SIORA, Researcher of the Department of the Specialized High-Voltage Engineering and Laser Welding, E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine, e-mail: siora@ua.fm. https://orcid.org/0000-0003-1927-790X

Yurii YURCHENKO, PhD, Senior Engineer of the Department of the Specialized High-Voltage Engineering and Laser Welding, E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine. e-mail: yuriyyurchenko14@gmail.com. https://orcid.org/0000-0001-9253-009X.

LUKASHENKO Volodymyr, Candidate of Technical Sciences, Researcher of the Department of the Specialized High-Voltage Engineering and Laser Welding, E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine, e-mail: z_lyk@ukr.net. https://orcid.org/0000-0002-9685-4654.

HARDER Dmytro, Candidate of Technical Sciences, Researcher of the Department of the Specialized High-Voltage Engineering and Laser Welding, E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine, e-mail: lukash_d@ukr.net. https://orcid.org/0000-0002-4066-8182.

DOI 10.36910/automash.v1i24.1704