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Analysis of Actual Problems of Laser Welding of Stainless Steel Thin Sheets and Search for Solutions

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Abstract- Over the past decade, there has been a rapid development of laser technologies, in particular laser welding, which has become more cost-effective due to a nearly 10-fold reduction in the cost per kilowatt of laser power. The global market for laser welding equipment is estimated at USD 2.5-2.9 billion in 2022-2023, with a projected growth to USD 4 billion by 2032. At the same time, laser welding is only gaining popularity in Ukraine. Therefore, the authors reviewed modern scientific works on laser welding of thin-walled products made of high-alloy corrosion-resistant steels to identify the main problems of welding such products. The review identified the main problems of laser welding of thin-walled products, such as: joining the edges of welded parts, clamping of welded parts, ensuring constant uniform heat removal, providing gas protection of the weld pool and cooling metal of the welded joint from interaction with the surrounding atmosphere, and forming a weld "on the hinge" and on the substrate. Based on the known problems, technological equipment in the form of a clamp and a gas protection system was developed to prepare test welded joints made of thin-walled corrosion-resistant steels in accordance with EN ISO 15614-11:2015. This will improve the quality and level of operational and functional properties of the resulting welded joints and develop technological recommendations for the manufacture of thin-walled products for various industries, taking into account the relevant operational requirements.

Keywords- laser welding, thin sheet materials, technological equipment, problems of laser welding.

I. INTRODUCTION

Over the past 10 years, there has been a rapid development of laser technologies, which has reduced the cost of a used kilowatt of fiber laser radiation power by several dozen times (from about 100 thousand USD to 3-5 thousand USD), making laser welding even more competitive with respect to traditional types. This is evidenced by the estimates of various consulting agencies. They report that the global market for laser welding equipment was estimated at USD 2.5-2.9 billion in 2022-2023 [1-3]. It was predicted [3] that the market will grow to approximately USD 4 billion by 2032, showing a compound annual growth rate (CAGR) of 5.5% over the forecast period. At the same time, the adoption of fiber laser-based welding equipment is expected to grow significantly. According to [3], the main consumers of laser welding equipment are the electronics industry, automotive and aircraft industries (Fig. 1). As for the distribution by region, the trend of dominance of the Asia-Pacific market (about 40% in 2024) continues. The Asia-Pacific laser welding machine market is expected to grow significantly from 2024 to 2032. This is due to rapid industrialization and the presence of large manufacturing centers. In addition, the rapid development of the region's electronics industry, including the production of smartphones, consumer electronics, and semiconductors, is driving the demand for laser welding machines. In addition, China's laser welding machine market held the largest market share, and India's laser welding machine market was the fastest growing market in Asia Pacific [3].

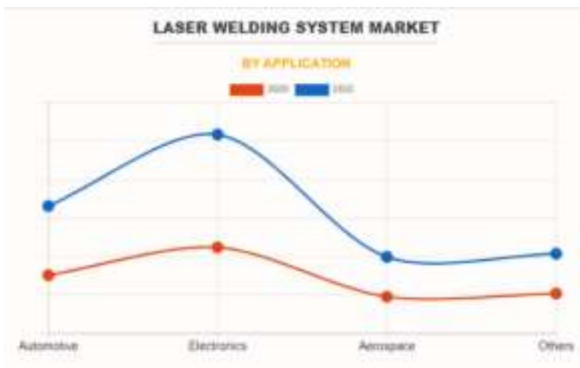


Fig. 1: Distribution of the laser welding equipment market by application [3]

The rapid development of laser technologies is also indicated by a sharp increase in scientific papers related to laser processing, including welding. To estimate the spread of lasers in welding technologies, a bibliometric analysis of the Scopus and Google Scholar databases was conducted. The analysis is a process of determining the number of articles that dealt with laser welding processes and were published over the past decade (2014-2024). The search was conducted using keywords in two categories: "Laser welding processes" and 'Prevalence of laser use'.

According to the results of the analysis, it can be noted that papers on the study of laser welding technologies and processes account for approximately 12% of papers from Google Scholar (90000) and 17% of papers from the Scopus database (88850) related to welding materials. Of the papers published in peer-reviewed journals in the Scopus database, it was determined that the majority of papers (340600 or 51%) are devoted to work on materials processing in industry (Materials Science and Engineering). 160190 papers, or 24% of all cited works, are devoted to the use of laser technologies in medicine and biotechnology. The main "top three" are chemical sciences with 108970 (16%) scientific papers. In general, the development of laser technologies has made laser welding more accessible and attractive to a wide range of industries, contributing to its spread and market growth. The highest demand for laser equipment is observed in regions with active industrialization. Along with the economic benefits, there is also growing scientific interest in laser welding, as evidenced by numerous scientific studies. These factors point to a steady trend towards the introduction of laser technologies in key industrial sectors in the long term.

II. LITERATURE REVIEW

The use of laser technologies in welding plays a key role in increasing labor efficiency and competitiveness in various industries [4-6]. The use of laser welding technologies for thin-sheet high-alloy corrosion-resistant steels is widespread in the nuclear, automotive, space, aviation, shipbuilding, and other industries. Currently in Ukraine, about 80% of welded joints of thin-sheet materials are made using plasma, microplasma, electron beam, and TIG welding [7]. Recently, laser welding has been introduced, which has significant advantages: it does not require complex vacuum chambers, provides the most localized thermal effect, has a small thermal impact zone and minimal residual deformation [8-9].

We have analyzed scientific papers on laser welding of thin-sheet high-alloy corrosion-resistant steels and identified a number of features of their welding.

The study of internal stresses arising during welding of thin-walled products is relevant. Thin-walled welded structures are often subject to deformation because they have extremely low stiffness. Therefore, it is necessary to understand the process of formation of internal stresses that create deformations during welding. Welding deformations were studied in [10]. The authors concluded that with an increase in heat input, significant tensile forces are created, which are responsible for the development of longitudinal and transverse deflection in the welded structure (Fig. 2).

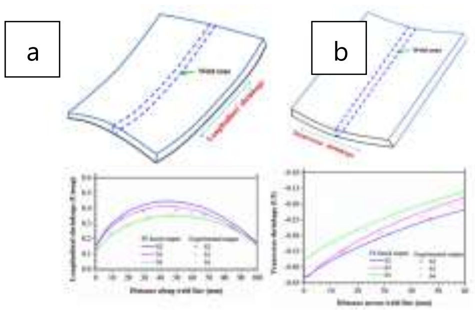


Fig. 2: Schematic representation of deformation in:
a - longitudinal direction; b - transverse direction;
c - longitudinal shrinkage along the weld line;
d - transverse shrinkage across the weld line [10]

The next problem is the formation of the required microstructure of the welded joint. Crystallization of the molten metal of a welded joint depends on the kinetics of the liquid-solid interface. Paper [11] describes this phenomenon by using the value of the thermal gradient and the velocity of the liquid-solid interface (Fig. 3). Four possible modes of crystallization of the welded metal were identified: planar, cellular, columnar dendritic, and equilibrium dendritic. It is also noted that the crystallization of the weld pool can occur in one of two ways, namely, in an ordered and disordered manner, depending on the chemical composition of the welded joint metal [11].

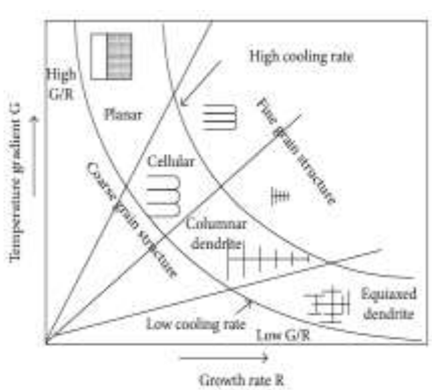


Fig. 3: Dependence of grain growth rate on temperature gradient [11]

In turn, microstructure is closely related to the corrosion resistance of a welded joint. The authors of [12] studied how chromium content affects the effectiveness of localized corrosion. It was found that the effect of chromium on the corrosion process is not static but dynamic, influenced by both environmental factors and electrochemical or chemical reactions in the corrosion layer. The chromium content generally reduces the susceptibility to corrosion of welded joints, but with its increase, localized corrosion increases. The deposition of nitrides in the heat-affected zone and the reduction of nitrogen in the melting zone can significantly affect the mechanical and corrosion properties of welded parts [13]. In [14], the theory is confirmed that it is the HAZ that is susceptible to corrosion. It is the most susceptible to corrosion and affects the overall corrosion resistance of the welded joint (Fig. 4).

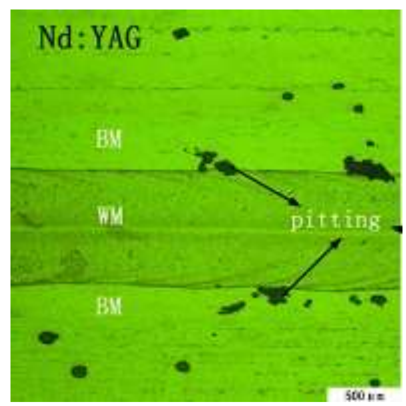


Fig. 4: Polarization test of pitting corrosion distribution [14]

When welding high-alloyed corrosion-resistant steels, one of the characteristic defects is the formation of hot cracks. There are several theories of hot cracks [15]. The first theory is “shrinkage embrittlement” [16]; the second theory is “strain theory”, which considers solid-liquid interface rather than solid-solid interface [17]; and the third is “generalized theory” [18]. According to these theories, several strategies have been developed to control grain structure and prevent cracking during crystallization:

1) Significant grinding of metal grains in the weld zone is achieved by stimulating their nucleation during crystallization. The addition of elements such as titanium and boron helps to change large columnar grains, which cause low critical strain and the formation of crystallization cracks, into more equilibrium and smaller ones [19].

2) Additional scanning of laser radiation during welding. The device (the so-called scanner) provides additional movement, namely, oscillation of focused laser radiation in the direction transverse to the welding line. When using this method, grain grinding is ensured compared to welding without scanning laser radiation [20]. Work [21] shows that laser scanning allows changing the distribution of heat input by changing the shape of the weld pool on the metal surface, which in turn changes the crystallization process (Fig. 5). Namely, the formation of grains during the solidification of liquid metal, which in turn affects the occurrence of temporary local stresses and the formation of residual stresses and deformations after welding [22].

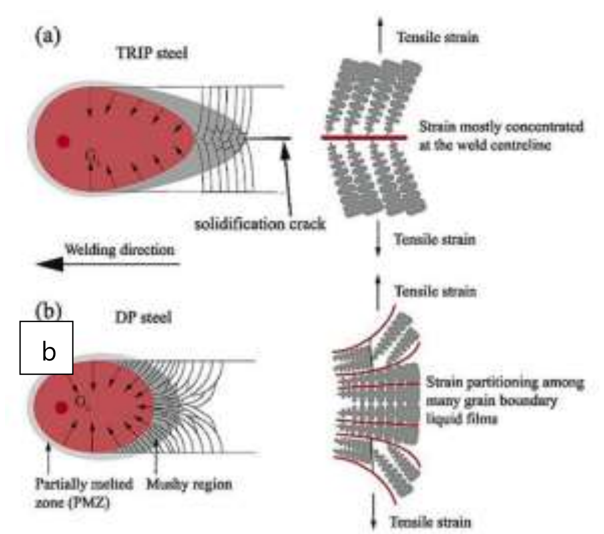


Fig. 5: Weld pool shape on the surface of the metal being welded: a - teardrop-shaped;
b - elliptical [21]

Study [23] analyzed the effect of a scanning frequency of 100-300 Hz on hot crack formation. The authors concluded that, compared to linear welding, oscillating beam laser welding results in the formation of a larger molten pool, and therefore a reduced tendency to cracking, as the temperature gradient in the crystallization region decreases, expanding the equilibrium zone in the center of the melting zone. At an oscillation frequency of 100 Hz, laser radiation led to the formation of a morphology with repeated oscillations of the weld pool (Fig. 6, b). As a result, crack propagation was hampered by this crystallization morphology. With an increase in the oscillation frequency to 200-300 Hz, the resulting fusion line straightens, resembling a linear welded joint (Fig. 6, a, c, d).

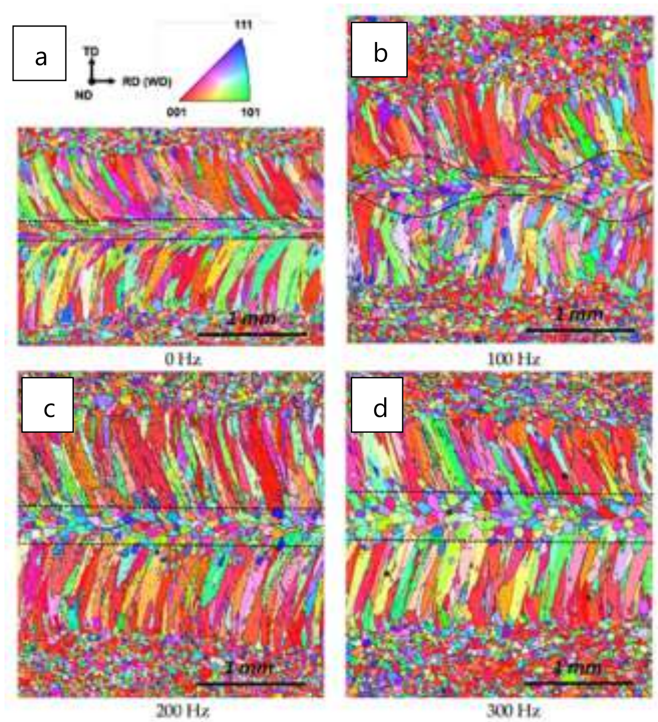


Fig. 6: Analysis by backscattered electron diffraction with changing laser beam oscillation frequency: a -0 Hz; b - 100 Hz; c - 200 Hz and d - 300 Hz [23]

3) Vibration during laser welding. An alternative method for grain refinement and prevention of cracking defects during crystallization is vibration. For example, it is ultrasonic vibration and electromagnetic stirring during crystallization. The results show that crystallization cracks are reduced in size and number when this method is applied [24]. Fig. 7. schematically shows laser welding with the use of ultrasonic vibrations. The melt flow in the

weld pool changes direction due to ultrasonic vibrations, which causes the liquid to flow downward faster. This results in a pressure gradient in the liquid from the weld pool wall to the interior of the weld pool, which subsequently increases the forced convection of the metal. The intense forced convection and disordered flow of liquid metal create a weld pool with a more constant temperature distribution [25].

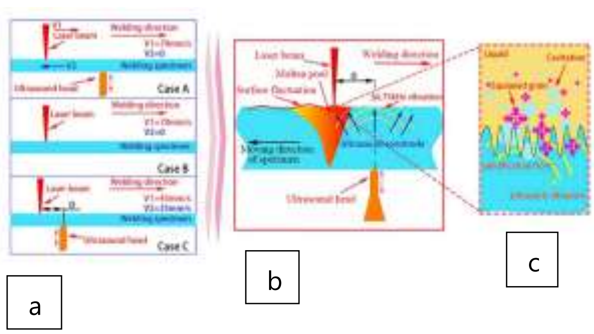


Fig. 7: Laser welding with ultrasonic vibration accompaniment: a - welding modes; b - ultrasonic vibration scheme; c - vibration mechanism in the weld pool [25]

4) Laser welding parameters. The local crystallization rate and temperature gradient during welding are affected by laser power, welding speed, continuous or pulsed mode, preheating, etc. Thus, they can affect the grain structure of welded parts [26]. In [27], the effect of welding speed on crack formation was studied for three types of corrosion-resistant steels AISI 304, AISI 310, and AISI 316 with different grain structures. The results showed that with an increase in welding speed, the tendency to crack during crystallization of AISI 310 steel was much higher than that of AISI 316 and AISI 304 (at a welding speed of 1 m/min). This was due to the fact that a fully austenitic structure was formed in the welded joint of AISI 310 steel, while AISI 316 and AISI 304 had a mixed ferrite-austenitic structure. In addition, with an increase in the welding speed from 1 to 2 m/min, the cracking tendency of AISI 310 slightly decreased, but there was a tendency to increase the cracking tendency of AISI 304 due to a decrease in the amount of ferrite at a higher cooling rate [27].

Based on the results of the analysis of the problems of laser welding of thin-sheet stainless steels, the most urgent ones that require the development of technical proposals were identified.

Namely

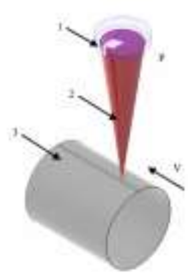
- The problem of joining the edges of welded parts. In case of insufficient joining of the welded surfaces, gaps may form, which can lead to the formation of non-fusion and a decrease in the strength of the welded joint.
- The problem of clamping the parts to be welded. When clamping the parts to be welded, there is a high probability of bending in the center of the flat part. Because of this, there is a high probability of misalignment of the welded edges and the formation of non-fusions.
- The problem of ensuring constant uniform heat dissipation. During laser welding of thin sheet materials, the metal being welded can be severely deformed due to excessive heat, and burns can form.
- The problem of providing gas protection of the weld pool and the cooling metal of the welded joint from interaction with the surrounding atmosphere. In case of insufficient gas protection of the welding zone, porosity and color variability can often occur, indicating a decrease in the strength of the welded joint.
- The problem of forming a weld "on the hinge" and on the substrate. In the case of laser welding, the problem of using substrates is associated with the need to remove part of the radiation from the back of the joint.

As you can see, laser welding of thin-walled products is an urgent task for the industry, and there are problems that must be solved to improve the quality of welded joints. It should be noted that the use of laser technologies in various areas of production requires standardization in the production of test welds. Unfortunately, the results of the studies conducted vary and cannot be generalized. Previously, little attention was paid to the problem of manufacturing specialized technological equipment for creating test welded joints. Therefore, it is necessary to improve technological approaches to laser welding of thin-walled products for the Ukrainian industry.

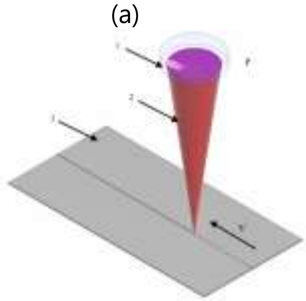
III. DESCRIPTION OF TECHNOLOGICAL EQUIPMENT

To solve the actual problems of laser welding of thin-walled products made of high-alloy corrosion-resistant steels, the authors of the work developed a preliminary design and manufactured technological equipment in the form of a clamp and a gas protection system for the cooling part of the welded joint, which is unified and will be used to prepare control butt welded joints provided for by the standards for the purpose of further certification of laser welding technology in accordance with the requirements of EN ISO 15614-11:2015 on the manufacture of control butt welded joints.

A clamp is used to solve the problems associated with edge joining, clamping of welded parts and ensuring constant uniform heat dissipation. Fig. 8 shows the laser welding schemes that this clamp allows for.



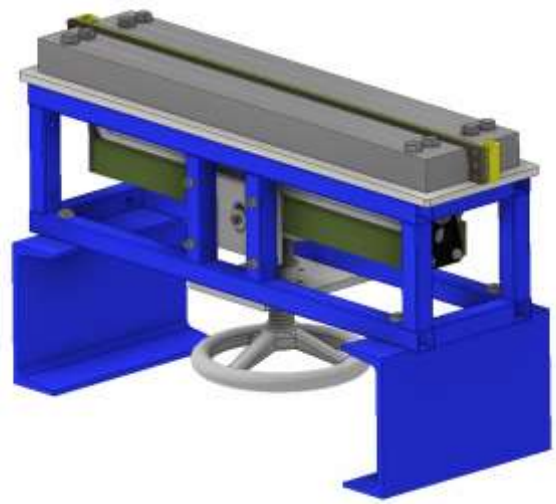
(a)



(b)

Fig. 8: Welding schemes: (a) cylindrical specimens; (b) flat specimens, where 1 - lens, 2 - laser beam, 3 - specimen to be welded

Figure 9(a) shows the 3D model of the clamp designed in Autodesk Inventor 2020, and the already manufactured clamp in Figure 9(b).



(a)

(b)

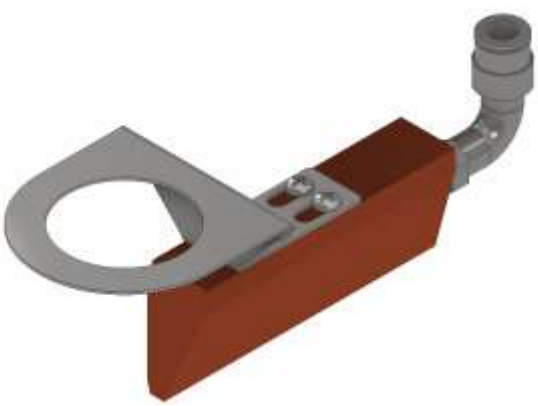
Fig. 9: Clamp for welding flat and cylindrical workpieces made of thin sheet metal

The joining of the welded edges is ensured by the fact that the clamp has a joint orientation device, which consists of two rulers with a thickness of 0.15 mm and 0.35 mm, respectively. They are used to set a guaranteed gap between the joint of the edges of the workpiece (part) before final compression and to orient the joint of the edges along the clamp axis in the manipulator coordinate system.

The welded parts are clamped using two clamping bars attached to the upper part of the clamp, as well as a movable clamp from the lower part, which allows you to securely clamp the welded parts from below along the entire length.

Uniform heat dissipation is ensured by two copper plates with different profiles that are mounted in the clamp body. The bars can be changed depending on the parts being welded (flat or cylindrical).

To solve the problem of gas shielding of the weld root during laser welding, holes for shielding gas supply are made in the copper cooling bars of the clamp. A gas protection system for the cooling part of the welded joint was also designed and manufactured. Fig. 10(a) shows a 3D model of the gas protection system designed in the Autodesk Inventor 2020 program, as well as the already manufactured system in Fig. 10(b).



(a)

(b)

Fig. 10: Gas protection system for the cooling part of the welded joint

The gas shielding system for the cooling part of the welded joint consists of two elements, a shielding gas distributor and a fixture. The presented gas protection system provides reliable protection of the welded joint during laser welding due to the fact that the body of the gas protection distributor has a blind hole with a G1/8 thread for connecting the fitting and perpendicular to it are made holes with a pitch of 2 mm for the shielding gas supply, the diameter and length of which has a ratio of 1:5 or more, which ensures a laminar flow of the shielding gas and eliminates the appearance of turbulence. The gas shielding system distributor is made of copper and has two 75° bevels for unobstructed passage between the clamp clamps and a 15° bevel for docking with the laser welding head nozzle. The gas shielding system is attached to the laser welding head with a corrosion-resistant steel mounting bracket.

IV. CONCLUSION

Over the past ten years, laser technology has developed significantly, reducing the cost of a kilowatt of fiber laser power from 100 thousand to 3-5 thousand US dollars. This has made laser welding more cost-effective and competitive with traditional methods. In 2022-2023, the global market for laser welding equipment was estimated at USD 2.5-2.9 billion, and by 2032 it is projected to grow to USD 4 billion at an annual rate of 5.5%. The main consumers are the electronics, automotive, and aviation industries, with the highest demand in the Asia-Pacific region (about 40% of the market), especially in China and India. At the same time, the relevance of work aimed at improving technologies and developing new equipment for laser welding is growing. This is supported by the growing interest of the scientific community, which is reflected in the number of scientific publications: on Google Scholar, approximately 12% of articles (90,000 papers) and on Scopus, 17% (88,850 papers) related to welding materials are dedicated to laser welding. Such research is aimed at improving process efficiency to meet the growing demands on the quality and speed of welding operations in industry. The use of the created technological equipment (clamps and gas protection systems) will make it possible to determine the regularities of the influence of laser welding parameters on the structure formation, geometry and level of mechanical characteristics of the resulting welded joints made of high-alloy corrosion-resistant steels in the manufacture of thin-walled products. This will improve the quality and level of operational and functional properties of the resulting welded joints and develop technological recommendations for the manufacture of thin-walled products for various industries, taking into account the relevant operational requirements. Implementation of the proven set of technological measures for laser welding of welded joints made of high-alloy corrosion-resistant steels in the manufacture of thin-walled products will allow solving a wide range of tasks set by the rocketry, chemical, medical, defense, and other industries in the manufacture of a wide range of products from thin-sheet materials.

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