Application of system of geometrical and technological adaptation of process laser-arc hybrid welding for production in the minimum tolerances of hull designs of means of marine engineering

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Abstract. The shipbuilding industry requires high-performance production technologies for the heavy gauges. One of the key tasks in advancing of hull production technology is minimization of welding deformations and simultaneous provision of high production performance. An arc augmented laser-arc welding technology which provides higher productivity, improvement of production effectiveness and reliable quality of welded joints is the most promising technology for this task. There are several limitations of industrial application of laser and hybrid laser arc welding concerned with sensitivity of laser technologies to the assembling quality of details before welding. Presented work describes designed algorithm and system of geometrical and technological adaptation increasing efficiency of laser-arc hybrid welding for production in the minimum tolerances of hull designs of means of marine engineering.

1. Introduction
Wide application of hybrid laser-arc welding is limited due to the sensitivity of technology to the presence of random deviation of the blanks joining line, as well as fluctuations of the gap values between welded edges and the quality of edge preparation. The most effective way to ensure high quality and reliability of welded structures is the management of technological process. Due to the fact that the hybrid welding process as a control object is a complex multifactor object, the most promising is the adaptive process management.

Algorithm of the designed system of geometrical and technological adaptation establishes a relationship between the parameters of the hybrid laser-arc welding, welded structures elements (cutting edges), formed seam geometry and position of the welding tool.

The work of the algorithm of technological adaptation is based on the probability estimation of the quality indicators overrun (for example, depth of penetration, height and width of the seam). This task is common to all technological operations. The difference of used procedure for assessing quality consists in the object of analysis. The object of analysis is a computer model of a joint forming for this welding method. For such analysis, the process model should reproduce the influence of all significant
technological factors on basic indicators of the welded joint quality. Models based on the numerical solution of mathematical physics equations, which strictly describe physical phenomena at welding in a wide range of process parameters fulfill described requirement. The procedure for predicting quality includes the formation of computational experiment on a process model, processing results of modeling and estimation of probability of defects.

2. Geometrical and technological adaptation (GTA) system design

Adaptation features of automated welding equipment can be divided into two types of tasks: geometric and technological.

Geometric adaptation includes methods and means of determining the current values of the welded joint parameters, which determine the required characteristics of the welding mode (for example, the size of the gap in the joint, the cutting area, etc.). Technological adaptation corrects the values of the current welding mode parameters (current, voltage, welding speed, laser power) directly during the welding process.

One of the main problems of quality assurance during T-joints welding is the presence of a changing gap between the welded parts. In case the gap between the workpieces changes, there is a danger of unfilled metal zones occurrence and, consequently, defects formation (such as pores and lack of penetration). In this connection, it is necessary to compensate the lack of the metal volume due to the additional metal of the filler wire. The changing of the gap between the workpieces can be determined using a triangulation sensor (optical scanner), presented on figure 1.

![Figure 1. Optical scanner for hybrid laser-arc welding system.](image)

The scanner software allows performing the following operations, which are used in solving GTA tasks:

- scanning of visible surface;
- imposition of a geometric filter on the scan space;
- selection of geometric shapes (lines) from the scanned surface in the filter area;
- calculation of the intersection point of the lines.

Functional scheme of the scanner describing recognition of the points on T-joint parts conjugation line is shown on figure 2.
Figure 2. Search for T-joint edge preparation using an optical scanner.

A geometric region is superimposed on the scanner's capture zone (figure 2, the region shaded by squares). The region is assigned when setting up the scanner software, taking into account the required distance from the scanner to the parts to be welded and the angle of capture of the scanner. In the working position of the tool there are two segments located on the surface of the welded parts - A1-B1 and A2-B2. These segments are extended to the point of their intersection. The point of intersection (P) is the point of junction of the parts surfaces to be welded. At the moment of relative position of the welded parts monitoring by the sensor the set of points of contact forms the axis of the welding tool movement.

The use of such a region allows to determine junction point of surfaces despite the presence of a gap between the parts or the presence of technological tacks (tack welds).

To detect and measure the gap between the welded parts (Figure 3), the following operations are performed:

– additional geometric region is superimposed on the measurement area - a circle with the center at the point P and passing through the point B1 (or B2);

– two segments of the object line of the parts surface, belonging to a circular region constructed on previous step are built (B1-D1 and B2-D2)

– definition of a point with the largest Z coordinate for each segment (in figure 3 these are points D1 and D2)

– a point with a lower Z coordinate is selected from the obtained two points, this point defines the gap between the parts to be welded;

– the distance between points P and D1 (the point founded on previous step) is the size of the gap (Delta).
If points P and D1 coincide, i.e., the length of the P-D1 segment is close to zero, the parts are arranged without a gap. If the gap is not zero, the gap value for the drive Z of the guidance system is added to the coordinate of the mating point (P).

Depending on the size of the gap, the computer of the control system generates the correcting offset values for the drives (Figure 4):
- \( dZ = Y_3 - Y_{tcp} \) (for vertical drive);
- \( dY = X_z - X_{tcp} \) (for horizontal drive, directed across the seam).

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**Figure 3.** Determination of a T-joint gaps using an optical scanner.

**Figure 4.** Determination of correcting offset values for the drives.
The main task of technological adaptation is guaranteeing that the volume of the filler metal supplied by the welding machine is consistent with the actual values of each fixed section area. The aggregate of these sections comes to the information model of the whole joint.

The actual weld metal area of the i-th seam cross-section is calculated by the formula

$$F_{ai} = F_i + A$$  \hspace{1cm} (1)

where $F_i$ is the actual area of the i-th cross-section of the edge preparation of the welded joint according to the information model, mm$^2$; $A$ is a constant value corresponding to the thickness of the parts to be welded and the type of connection, mm$^2$.

The required volume of the deposited metal is ensured by changing the ratio of the laser power, welding speed, welding current and voltage.

To determine the ratio of laser radiation power and welding speed, which ensured the penetration of metal to a depth of 6 to 20 mm, computer simulation of the hybrid laser-arc welding process was carried out in the LaserCAD [1] engineering and technical analysis program. The simulation results with sufficient accuracy for practical use were approximated by the following equation:

$$h(P, v) = (6.62 + 1.45 \times P) \times e^{(-0.0235 + 1.86 \times 10^{-4}) \times v}$$  \hspace{1cm} (2)

where: $h$ – penetration depth (m);
$P$ – laser power (W);
$V$ – welding speed (m/sec).

On basis of presented formula (2) equations for laser power $P(h, v)$ (3) and welding speed $v(h, P)$ (4) were obtained.

$$P(h, v) = \frac{10^{7}h + 1.48 \times 10^{4} \ln(v) + 2.94 \times 10^{4}}{4.8 \ln(v) + 8.47}$$  \hspace{1cm} (3)

$$v(h, P) = e^{\frac{1 \times 10^{7}h + 8.47 \times P + 2.94 \times 10^{4}}{4.83 \times P + 1.48 \times 10^{4}}}$$  \hspace{1cm} (4)

To fill the required volume of metal, an adequate wire volume is required, calculated on the basis of the equality of volumes:

$$V_{w}S_{wj}t = FV_{fw}t$$  \hspace{1cm} (5)

where: $S_{wj}$ – cross-sectional area of the deposited material; $F$ – cross-sectional area of the wire; $t$ – time of the entire welding process.

The wire feed speed $V_{fw}$ will be calculated using the following formula:

$$V_{fw} = \frac{V_{w}S_{wj}}{2F}$$  \hspace{1cm} (6)

When wire feed speed changes, the welding machine automatically changes the amount of welding current, thereby providing the energy input into the arc, which is necessary to melt the wire.

During the welding process (with a given time step), the gap between the welded parts and the control of the wire feed speed is measured and recalculated by the formula (3). In case it is impossible to change the wire feed speed, the welding speed is refined using the formula (4).

The flowchart of a geometric and technological adaptation (GTA) algorithm is shown on figure 5.
Figure 5. Flowchart of the welding process GTA.

Obtaining data from optical scanners, GTA system generates control signals to the drives, solving the problem of preliminary pointing of the welding tool with respect to the welded joint.

Next, the program performs mathematical data processing in order to generate control signals for drives guidance system and for the calculation module of the process equipment control system.

The program of the GTA computational unit checks the compliance of the configuration of the groove and its dimensions with the permissible limits, determines the position of the groove relative to
the welding tool, and calculates the magnitudes of the signals necessary to correct the position of the welding tool.

The control system, after comparing the actual and specified parameters of the technological mode, transmits information for processing and calculating the mode parameters that provide the welded joint of the required configuration (penetration depth, leg of the seam, and smoothness of the interface).

The developed GTA system can be used on process equipment with two or more working tools, for example, for simultaneously two-sided laser-arc welding of a T-beams or stiffeners of typical hull structures (Figure 6).

![Welded typical hull structure.](image)

Figure 6. Welded typical hull structure.

3. Conclusion
A system for geometrical and technological adaptation is important for stable formation of welding seams because of limitations of hybrid laser-arc welding due to the sensitivity of technology to the presence of random deviation of the blanks joining line, as well as fluctuations of the gap values between welded edges and the quality of edge preparation.

The application of the described method for the manufacture of hull structures of marine equipment, confirmed the effectiveness of the developed system of geometric and technological adaptation of the hybrid laser-arc welding process.

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