Determination of the heat source parameters for the case of simultaneous two-sided laser-arc welding of extended T-joints

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Abstract. Effective application of hybrid laser technologies can help to decide the problem of creating high-performance welding technologies that allow to optimize the process of producing critical structures, as well as to reduce labor intensiveness material consumption. Today the development of industrial technologies for the manufacture of extended body parts under minimum tolerance condition requires the numerical simulation of thermal deformation processes occurring in the material during welding and affecting the final operating characteristics of products. The article is devoted to the search for the optimal solution of the problem of determining the T-joint geometrics, taking into account the possibility varying the positional relationship of the laser and arc heat sources on both sides. The thermal field that is created by two simultaneously operating combined heat sources is one of the key parameters of the process.

1. Introduction
Quality of critical structures directly depends on welding technologies. Today in the welding industry laser and hybrid welding methods are used more often. Those methods can increase quality and performance of the welding process. The main problem of welding is to determine the thermal field. Thermal field influences the quality, deformation, structure, defects of the weld.

Since T-joint is very common, this article will consider the problems of laser and arc heat sources’ distribution in T-joints based on the knowledge of well-researched processes of heating in elementary volumes. Usually the heating of complex geometry volumes is calculated numerically, but there are some cases where analytical methods can be faster.

2. Heat-sources method
The problem of the temperature field determination can be solved by different methods. There are numerical methods, like finite element method, and analytical methods, such as Fourier and operational methods. Heat-sources method is analytical too.

The main idea of the heat sources method is to present a heat transfer process as a sum of heat fluxes from several elementary heat sources. Heat-sources method can be used if thermophysical properties of material are independent of temperature.

Consider moving heat source in an infinite flat layer. Let borders of the layer \((z = 0 \text{ and } z = \delta)\) be adiabatic. Total thermal field from the full source is defined as [1]:

\[ U_{total} = \frac{Q}{2\pi}\left[\ln\left(\frac{\delta}{r}\right) - 1\right] \]
Where, \( q_0 \) is power density of the heat source, \( a \) is thermal diffusivity of material, \( \lambda \) is thermal conductivity of material, \( v \) is the welding speed, \( R_{i,j} = \sqrt{(x-i\xi)^2 + (y-j\eta)^2 + (z-j\zeta - 2\text{i}h)^2} \) is the distance between the heat source and a point, where temperature is determined. In the article we will use source with index \( i = 0, -1 \) and \( j = \pm 1 \) because other heat sources have no effect on the total heat field.

3. Laser heat source model
Deep penetration case is typical for laser welding of the thick plates. Power density keyhole depth distribution can be taken from the research [3]. This model is based on numerical calculation of reflections from walls inside the keyhole. Target thickness is layered. Absorbed and reflected powers are calculated in every layer. Calculation is finished when the input energy is fully consumed. Value of the absorbed power on every layer is the power density of the point heat source, which can be used to calculate the thermal field.

Mostly the keyhole has depth much greater than its width; therefore total heat field can be represented as a sum of heat sources located along the keyhole. So temperature from laser heat source will be defined as:

\[
T(R,z) = \int_0^\delta \left( \frac{q(z)}{4\pi\lambda R(xa,ya,za,z)} \exp \left(-\frac{v(xa + R(xa,ya,za,z))}{2a} \right) \right) dz
\]

Where, \( q(z) \) is a power density depth distribution, \( \delta \) is a keyhole depth.

4. Arc heat source model
Arc heat source has a flat distribution. Distribution of power density is adequately described by the Gauss curve and expressed by formula:

\[
q(x,y) = \frac{Qd}{2\pi R_a^2} \exp \left(-\frac{x^2 + y^2}{2R_a^2} \right)
\]

Where \( R_a \) is a radius of the heating spot, \( Qd \) is a standardized arc power. \( Qd \) is defined as:

\[
Qd = \frac{Qarc}{\int_{-R_a}^{R_a} \int_{-R_a}^{R_a} \left( \frac{1}{2\pi R_a^2} \exp \left(-\frac{x^2 + y^2}{2R_a^2} \right) \right) dx dy}
\]

Where \( Qarc \) is arc power.

Value of the heat spot radius can be obtained as \( R_a = 1.74/\sqrt{k} \), where \( k \) is a concentration coefficient (for arc processes \( k \) varies from 1.1 to 6) [2].

If the total heat source is presented as a sum of elementary heat sources, then temperature from the arc heat source can be obtained as:

\[
T(x,R) = \int_{-R_a}^{R_a} \int_{-R_a}^{R_a} \left( \frac{q(x,y)}{4\pi\lambda R(xa,ya,za,x,y)} \exp \left(-\frac{v(xa + R(xa,ya,za,x,y))}{2a} \right) \right) dx dy
\]
5. Laser source in T-joint

Let point \( A \) be the focus of the laser beam (figure 1). We divide a T-joint into the geometric primitives, presented as red, blue and green rectangles on the figure 1.

![Figure 1. Division of T-joint.](image)

At first we consider the blue rectangle (figure 2(a)). Since we suppose that the borders are adiabatic we introduce three fictive sources according to the “reflected sources method”. Thus heat field is a sum of one “real” heat source, two heat sources above and below the real heat source and one on the left side. Right border is not taken into account because addition from the right side is not significant for the total temperature field.
In the red rectangle the fictive heat sources are located on the left side, on the right side and below the target. A source above the red part is not considered because its addition to the sum is not significant. The green rectangle is symmetrical to the blue one.

Let’s sum up the temperature fields of the red, blue, and green rectangles in pairs and take into account their signs. So there are places (curves) where difference between temperature fields is equal to zero (black curves on the figure 3). The right curve (number 1) is a line, it is a border between the
temperature fields of the red and blue primitives. The left curve (number 2) separates the temperature fields of the red and green primitives as well as the blue and green ones. This curve can be described by a cubic expression. Tolerance for the expression doesn’t exceed ±2°C. So the total temperature field will depend on the angle α, that is a laser beam inclination angle. It will be determined differently for every part and be joined along the curves where temperature difference is zero. It is easy to obtain the total temperature field for the two-side case of the welding: the field for the opposite side is symmetrical and they can be summed up.

Figure 3. Borders where difference of the temperature field is zero.

6. Arc source in T-joint
Let the electrode axis be directed through the cross point of the red and blue rectangles, the angle between the electrode and the blue part is equal to β. Point with coordinates (y₀,z₀) is the end of the electrode (figure 4).

Figure 4. Scheme of the arc source location.
The arc source moves along the welding direction (x-direction) and heats the area with width of $2R$. Although the arc power distribution is symmetrical relative to its axis, power density in y and z directions is different. Along y-axis the area of effect is between $y_{\text{min}}$ and the origin point (figure 4) and along z-axis it is between $z_{\text{min}}$ and the origin point.

7. Comparison with the experiment

The calculation results compared with the experimental data are shown on figures 5-7 for laser welding and on fig.8 for laser-arc welding. We see satisfactory fit of the data even for aluminum alloy. Maximum deviation is on the top of the weld. Perhaps it is necessary to correct the initial position of the origin of coordinates to coincide with laser beam focus.

![Figure 5. Steel AH36, 8mm, laser angle 10°, laser power 4.56 kW, welding speed 1 m/min][4].

![Figure 6. Steel AH36, 8mm, laser angle 15°, laser power 6 kW, welding speed 1.25 m/min][5].

![Figure 7. Al6013, 1.6mm, laser angle 17°, laser power 1.5 kW, welding speed 2 m/min][6].

![Figure 8. Steel K36D, 14mm, laser angle 10°, arc angle 60°, laser power 8 kW, arc power 8 kW, welding speed 1 m/min][7].

Since the comparison results are rather successful we can calculate examples of the two-side welding of T-joint (figure 9).
Figure 9. Calculation examples for the two-side hybrid arc-laser welding of T-joint for (a) $\alpha = 6^\circ$, (b) $\alpha = 15^\circ$ and (c) $\alpha = 45^\circ$.

8. Conclusion
In this article we used the heat source method to obtain the temperature field in a T-joint for laser-arc welding. The calculation results were compared with the experimental data. This method can be used for quick evaluation of the melting zone.

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