The amount of heat input to the weld per unit length and per unit volume

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Abstract. This paper presents a comparative analysis of heat input per unit length and per unit volume for selected methods of welding. The purpose of the analysis is to assess the usability of calculating heat input per volume unit. The interpretation of heat input per unit length according to the standards: QW-409.1 of ASME IX, EN ISO 1011-1 is discussed. The concept of calculating heat input per unit volume is described. For exemplary padded welds and spot welded joints, the heat input values were calculated in accordance with the above-mentioned standards and based on the concept of heat input per unit volume. The study showed a lack of consistency between the individual standards in the interpretation of the heat input. In addition, the practical application of the heat input per unit volume method in calculating the actual amount of heat introduced into the weld was justified.

1. Introduction

The essence of welding processes is the use of heat generated by a concentrated source of heat (e.g. an electric arc, laser, gas flame) or frictional heat in order to make a connection, regenerate, improve the surface properties of the workpiece or cut.

The scope of application of welding heat sources is wide: joining, rebuilding, hardfacing, cutting (laser, plasma), heat treatment (laser, electric arc). A separate issue is the use of the phenomenon of friction (Friction Stir Welding, Friction Stir Processing).

In all the above-mentioned processes, the amount of heat needed to achieve the intended technological effect is the determining factor. In arc and laser welding processes, the amount of this heat is estimated by the heat input to the weld per unit length [1]:

\[ E_u = \frac{E}{l} \]  \hspace{1cm} (1)

where: \( E_u \) – heat input per unit length (welding linear energy), \( E \) – thermal energy introduced into the element, \( l \) – length of the weld,

or the power of the heat source divided by the speed of its movement:

\[ E_u = \frac{P}{v} \]  \hspace{1cm} (2)

where: \( P \) – thermal power generated during welding, \( v \) – linear velocity of the heat source.
The authors of many publications [2–6] state that the heat input per unit length does not correspond to the actual amount of heat introduced into the welded joint. It is conditioned by many other technological parameters (e.g., gas shield, CTTWD - contact-tip-to-work-distance) or material parameters (e.g., thermal conductivity). Therefore, this issue is a constant area of research by scientists [7–12].

Wojsyk and Macherzyński [13] proposed the equation for linear welding energy \( E_l \) (heat input per unit length) in the form:

\[
E_l = k_1 \cdot k_2 \cdot \ldots \cdot k_n \frac{P_r}{v}
\]  
(3)

where: \( k_1, k_2, \ldots, k_n \) – factors of introducing heat method, welding conditions and technique, materials, \( P_r \) – the actual power of the heat source, \( v \) – linear welding velocity.

As the authors of the work [13] state themselves, it is very difficult to experimentally determine so many coefficients. It should also be noted that the dynamic development of welding methods does not allow for the development of too detailed formulas and standards that take into account more and more modern varieties of welding methods and materials. Since an easy to measure comparative value is the cross-sectional area of the weld (the area of the reinforcement and the fusion zone), Wojsyk et al [14] proposed estimating the heat introduced into the welded joint on the basis of the transverse fusion areas of welds, arguing such an approach with numerous test results and graphs presented in the article.

The papers [15, 16] present the concept of the heat input per volume unit allowing to take into account the cross-sectional area of the weld.

In this study, a comparative analysis of heat input per unit length and per unit volume was performed for selected examples of welding. Heat input was also calculated for the example of spot welding (stationary heat source), which is not possible using the equations for calculating heat input per length unit.

2. **Input heat to the weld per unit length in arc welding**

According to the American Society of Mechanical Engineers standard ASME IX QW-409.1 [17, 18]:

\[
\text{Heat Input} = \frac{\text{Voltage} \times \text{Amperage} \times 60}{\text{Travel Speed} \ (\text{in/min or mm/min})}
\]  
(4)

or

\[
\text{Heat Input} = \frac{\text{Energy (Joules)}}{\text{Weld Bead Length (in or mm)}}
\]  
(5)

or

\[
\text{Heat Input} = \frac{\text{Power} \times \text{Arc Time}}{\text{Weld Bead Length (in or mm)}}
\]  
(6)

As the measuring instruments in modern welding devices measure and the displays show different quantities (energy or power), equations (5) and (6) have been introduced into the standard. It is easy to notice that equations (4) - (6) do not contain the thermal efficiency coefficient. The value of heat input according to formulas (4) - (6) should be understood as the amount of energy needed to make a weld of a unit length. This allows you to estimate the energy consumption and costs during the execution of a specific joint or the whole construction.

In turn, according to the European standard EN-1011-1: 2009 [19], heat input is defined as:

\[
Q = k \frac{UJ}{v} \cdot 10^{-3} \left[ \frac{kJ}{mm} \right]
\]  
(7)

where: \( Q \) – the heat input, \( k \) – the thermal efficiency, \( U \) – the arc voltage, measured as near as possible to the arc [V], \( I \) – welding current [A], \( v \) – the travel speed [mm/s].
According to the interpretation of the standard [19], \( Q \) is the amount of heat introduced to the welded joint.

### 3. Input heat to the weld per unit volume

It is reasonable to consider the cross-sectional area of the weld as an indirect measure of the amount of heat introduced into the material. The amount of heat introduced, taking into account the boundary conditions, determines the distribution of the temperature field, and thus also the solidus temperature isoline (fusion line). Then, dividing the input heat to the weld per unit length \( Q \) (7) by the area of the weld cross-section \( A_w \) [15, 16] is:

\[
\frac{Q}{A_w} = k \frac{UI}{vA_w} \left[ \frac{J}{mm^2} \right]
\]  
(8)

By introducing

\[
Q_{vw} = \frac{Q}{A_w}
\]  
(9)

Eq. (8) takes form:

\[
Q_{vw} = k \frac{UI}{vA_w} \left[ \frac{J}{mm^2} \right]
\]  
(10)

where: \( Q_v \) – the input heat per unit volume.

By introducing into the equation (10):

\[
P = UI \quad [W]
\]  
(11)

and

\[
v = \frac{l}{t} \quad [mm / s]
\]  
(12)

where: \( P \) – power, \( l \) – length of the weld, \( t \) – heat source operating time,

equation (12) takes the form:

\[
Q_{vw} = k \frac{Pt}{lA_w} \left[ \frac{J}{mm^3} \right]
\]  
(13)

or

\[
Q_{vw} = k \frac{Energy}{lA_w} \left[ \frac{J}{mm^3} \right]
\]  
(14)

Sinc \( lA_w \) is the volume of the weld \( V_w \) the equations (13) i (14) are:

\[
Q_{vw} = k \frac{Pt}{V_w} \left[ \frac{J}{mm^3} \right]
\]  
(15)

and

\[
Q_{vw} = k \frac{Energy}{V_w} \left[ \frac{J}{mm^3} \right]
\]  
(16)

Omitting the thermal efficiency in the equations (15) and (16) they take the form:

\[
Q_{vw} = \frac{Pt}{V_w} \left[ \frac{J}{mm^3} \right]
\]  
(17)

and

\[
Q_{vw} = \frac{Energy}{V_w} \left[ \frac{J}{mm^3} \right]
\]  
(18)

Then the equation (17) and (18) correspond with the equations (5) and (6).
Equations (15) - (18) can be used to calculate heat input in spot welding processes (with stationary heat source). Then, commonly known formulas for the volume of solids can be used to calculate the volume of the weld.

In the case of the paraboloidal shape of the weld (Figure 1), its volume equals [15]:

\[
V_w = \frac{\pi (w_w)^2 H}{8}
\]  

(19)

For the cylindrical shape of the weld, its volume is equal [16]:

\[
V_w = \frac{\pi (w_w)^2 H}{4}
\]  

(20)

\[
V_w = \frac{\pi}{12} H (w_{w1}^2 + w_{w1} w_{w2} + w_{w2}^2)
\]  

(21)

where: \(H\) – cone height (thickness of joined sheets), and \(w_{w1}\) i \(w_{w2}\) the penetration diameters on both sides of the weld, respectively.

4. Experimental work

As part of the experimental research, tests were carried out using the GMA (Gas Metal Arc) method with the classic short-circuit arc (CV) and four modern and advanced variants of this process:

- STT (Surface Tension Transfer) – in this welding method, the instantaneous current value depends on the physical condition of the inter-electrode space. At the moment of contact of the drop with the liquid pool and the creation of a narrowing between the electrode wire and the liquid drop, the microprocessor controller reduces the value of the current flowing in the welding circuit to a value of approx. 10 A. The droplet detachment occurs with the use of forces derived from the surface tension [20], and not as in the classic short-circuit arc due to electrodynamic forces;

- Power Mode – in the welding device for welding with this process, an appropriately shaped output characteristic is used, the high slope of which in the range of low welding currents lowers the short-circuit current value, while in the area of the spray arc it protects against excessive current reduction and global transport;

- Puls – welding process with a programmed course of the dynamic characteristics of the arc, in which the corresponding pulses of current and voltage of the arc cause the filler material to melt, form a drop and its short-circuit detachment from the end of the electrode wire;
- Rapid-X – is a variation of high-performance and deep-fusion welding. In this process, a modified short pulse arc is used, in which two drops of liquid metal are torn off in one pulse cycle as a result of reducing the arc length. Shorter arc length than in the classic pulse process, increases the arc temperature in the area of the cathode and anode spot [21], increasing the heating efficiency of the base and additional material.

An analysis of the results of weld surfacing tests in air and under water with use local dry cavity method carried out by a team of scientists from the Gdańsk University of Technology under the supervision of prof. Łabanowski [22, 23] was also performed.

Tests of spot welding with the GMA method and resistance spot welding were performed.

For the above-mentioned tests, calculations of the cross-sectional areas of the welds were carried out using a Olympus GX51 metallographic microscope with Olympus Stream Essentials software. Then, the heat input per volume unit values were calculated for the above-mentioned experimental studies.

5. Research result

5.1. Weld surfacing with modern varieties of the GMA method (MAG – Metal Activ Gas)

The surfacing tests were carried out at Lincoln Electric (Bielawa, Poland) using a Power Wave S350CE welding device with Power Wave Manager software recording current-voltage waveforms and a display that allows reading the welding current, arc voltage and True Energy™ value. Padding welds were made on plates 330 mm long, 100 mm wide and 80 mm thick made of S275J2G3 steel, the cross-sections of which are presented in Figure 3. Ultra MAG SG3 solid wire from Lincoln Electric, grade G4Si1 according to EN 440 with a diameter of 1.2 mm, was used for the tests. The gas shield was M21 mixture according to EN 439 (Ar 80%, CO2 20%). Technological parameters of the processes, calculated and measured energy values are summarized in Table 1.

![Figure 3. Cross-sections of padding welds: a) CV, b) STT, c) Power Mode, d) Pulse, e) RapidX.](image)

| Parameter          | CV   | STT  | Power Mode | Puls  | Rapid-X |
|--------------------|------|------|------------|-------|---------|
| Average arc voltage [V] | 15,9 | 14,5 | 15,5       | 20,8  | 23,6    |
| Average amperage [A]       | 159  | 140  | 170        | 106   | 120     |
Welding speed [cm/min]  
36  
28  
37  
30  
39  

Heat input per unit length according to the equation [kJ/cm]  
4,214  
4,350  
4,273  
4,279  
4,357  

Heat input per unit length - True Energy™ [kJ/cm]  
3,990  
5,360  
3,937  
5,760  
6,383  

Cross-sectional area of the padding weld [mm²]  
15,41  
19,96  
16,85  
18,22  
19,06  

Volumetric heat input based on linear energy calculated according to the equation [J/mm³]  
27,982  
21,794  
25,350  
23,485  
22,859  

Volumetric heat input based on True Energy™ [J/mm³]  
25,892  
26,854  
23,365  
31,614  
33,489  

5.2. Surfacing in air and underwater local dry cavity method

Very interesting are the experimental results presented in [22]. The padding welds, the cross-sections of which are shown in Figure 4, were made with the same material conditions and the same value of the linear welding energy: in air and underwater local dry cavity method [24].

![Figure 4. Cross-sections of welds made: a) in air, b) under water][22]

The GMA method was used to weld duplex UR45N steel sheets with a thickness of 12 mm with Avesta AWS A5.9-06 (ER2209) electrode wire with a diameter of 1.2 mm, welding speed 6.1 mm/s, voltage 30.5 V (air) and 32.5 (water), current 240 (air) and 224 (water) [23].

The calculated values of heat input of the welds are respectively 1200 J/mm (in air) and 1193 J/mm (under water). Thermal efficiency was omitted in the calculations, as there is no thermal efficiency value for underwater welding in the literature.

Measurements of macroscopic metallographic specimens made available to the authors by prof. Łabanowski gave the following values: the cross-sectional areas of the padded welds: 29.86 mm² (in air) and 50.3 mm² (under water). The calculated volumetric heat input values were 40.19 J/mm³ and 27.71 J/mm³ respectively.

As can be seen, both the values of the transverse field and the volumetric heat input for the underwater padded sample are significantly higher than for the air padded sample. It can be assumed that the use of a local dry cavity causes an effect similar to submerged arc welding, i.e. it reduces the possibility of direct heat exchange with the water environment. Moreover, on the basis of comparative studies, an attempt can be made to estimate the thermal efficiency for underwater local dry cavity method. Knowing the thermal efficiency for welding in air, the thermal efficiency value for local dry cavity method can be calculated from the proportion of the volumetric heat inputs and the thermal efficiency value for the GMA in air and underwater local dry cavity method.

5.3. Spot welding

5.3.1. Spot welding with arc
Figure 5 shows the spot weld of two steel sheets, each 2 mm thick, made by MAG (Metal Activation Gas) with the following parameters: \( I = 135 \) A, \( U = 25.6 \) V, pulse time \( t = 4 \) s. The height of the reinforcement is \( h_w = 1.34 \) mm, diameter of the reinforcement \( w_{w3} = 12.55 \) mm, depth of penetration \( d_p = 2.59 \) mm, while the diameter of the fusion on the surface of the upper sheet is \( w_{w4} = 7.56 \) mm.

The volume of the weld is calculated as the sum of the volume of the riser and the fusion, where the paraboloid model (17) is assumed for the ridge, and for the fusion - the cone model (19). The volume of the weld is:

\[
V_w = \frac{\pi(w_{w3})^2h_w}{8} + \frac{\pi(w_{w4})^2d_p}{12} = 121.63 \text{ mm}^3
\]

and heat input per volume unit according with (15):

\[
Q_{vw} = \frac{P_t}{V_w} = 111.65 \text{ J/mm}^3
\]

5.3.2. Resistance spot welding

The welding test was performed on a ZPF-16 resistance welding machine (ASPA, Wrocław, Poland) with the following technological parameters: \( I = 10 \) kA, \( t \) (pulse time) = 13 ms, \( U = 2.1 \) V. Figure 6 shows a cylindrical spot weld with the following dimensions: weld diameter \( w_w = 6.58 \) mm, height (thickness) of the weld \( H = 3.28 \) mm.

Based on the formula (18), the volume of the weld is: (18):

\[
V_w = \frac{\pi(w_w)^2H}{4} = 111.54 \text{ mm}^3
\]

and the input heat per volume unit:

\[
Q_{vw} = \frac{P_t}{V_w} = 2.82 \text{ J/mm}^3
\]

6. Conclusions
The advantage of the heat input per unit volume concept is that it can be applied to processes carried out with stationary heat sources (e.g. resistance spot welding, arc spot welding, laser). The difficulty in applying this concept is the necessity to perform a technological trial in order to obtain a metallographic macro of the cross-section of the weld. It should be noted, however, that qualification of the welding procedure requires a test joint. This test allows for the determination of, inter alia, values of the actual welding power or energy, as well as the geometrical dimensions of the connection.

The heat input per volume unit values can be used in comparative studies to estimate the thermal efficiency value. The proposed volumetric method of calculating heat input, and in particular its practical application, requires further analysis. Therefore, the direction of further research will be fillet welds tests, as well as joints made with other welding methods (e.g Laser, Hybrid, Electron Beam) and analysis of the value of heat input per length unit and volume unit in relation to heat source power and the cross-sectional area of the weld.

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