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New method of calculating the amount of heat input to the weld

Abstract: New method of calculating the amount of heat introduced into the welded joint is presented. Instead of the previously used measure of heat input per unit length, heat input per unit volume was proposed. The proposed method and general formula are based on the basic technological parameters of the welding process (i.e. energy generated by the electric arc and welding speed) and the cross-sectional area of the fusion zone in the welded joint. A simplified method of calculating heat input per unit volume is presented by using simple formulas to calculate the surface area of the fusion zone in cross-section of the weld for the most common shapes in classic welding methods. The proposed general formula allows for a more accurate way of calculating the heat input per unit of volume depending on the the energy generated by the electric arc (e.g. for pulse current) and the surface area of the reinforcement and fusion zone using other direct measurement methods.

Keywords: heat input per unit length, heat input per unit volume, weld geometry, fusion zone, actual electric arc power.

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Introduction

The heat input per unit length is a commonly used measure of the amount of heat delivered to a welded joint. The classical definition describes the heat input per unit length of electric arc welding as the amount of energy generated in an electric arc needed to make a unit of weld length [1]. The following formula is commonly used to calculate the linear energy El of arc welding [2]:

$$E_l = \eta \frac{UI}{v}$$

where: I - mean value of welding current for unidirectional current or effective value of welding current for alternating current, U - mean value of arc voltage for unidirectional current or effective value of arc voltage for alternating current, v – welding speed, η – arc efficiency.

For many years, the literature indicates that the above formula is not adequate in relation to the actual amount of heat introduced into the welded joint. The biggest doubts are in the case of using innovative welding techniques and modern welding sources. Already in 1993, Loos [3] noticed that the values of the heat input per unit length in relation to impulse current are subject to an error. In connection with the introduction of the notion of 'useful energy' in mechanized welding processes, Kensik

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[4] proposed a method for estimating this energy, among others in the case of an impulse arc. The problem of incompatibility between power per unit length of the weld and the actual amount of heat introduced into the weld was pointed out by Goldak et al. [5]. Kudła and Wojsyk [6] determined factors with influence on heat delivery in joint not taking under consideration in the based formula of welding energy. The American Society of Mechanical Engineers section IX has approved (in addition to the existing) new heat input equations [7] in standard QW-409.1:

$$Heat\ Input = \frac{Energy}{Travel\ speed}$$

or

$$Heat\ Input = \frac{Power\ x\ Arc\ Time}{Weld\ Bead\ Length}$$

The paper [2] presents a formula that could theoretically be used to determine the actual heat input per unit length:

$$E_l = k_1 \cdot k_2 \cdot .... k_n \frac{P_r}{v}$$

where: k_1 .... k_n – material and technological factors as well as those related to the heat source used, Pr – actual power of the heat source, v – linear welding speed.

Wojsyk and Macherzyński [2] indicate, however, that determining so many k_1 .... k_n coefficients in practice is very difficult. Therefore, further work is being carried out by scientists on the adequacy of the formula for estimating the amount of heat introduced into the welded joint [8 - 12]. Wojsyk et al. in [13] they presented an original approach indicating that it seems perspective to estimate the heat introduced into the welded joint based on transverse fields of remelting welds and padded welds.

Heat input per volume unit

As postulated in [13], an indicator of the amount of heat introduced into the welded joint may be the cross-sectional area of the weld (padded weld), i.e. the remelted (fusion) zone and reinforcement. Therefore, as a measure of the amount of heat introduced into the welded joint per unit of time, the volumetric energy of the weld (heat input per unit volume) can be proposed according to the formula:

$$E_{vw} = \eta \frac{E_a}{vA_w} \quad \left[\frac{J}{mm^3}\right]$$

where: E_{vw} – heat input per unit volume, E_a – actual electric arc energy, A_w – cross-sectional area of the weld (padded weld). In equation (6), the values E_a and A_w have been introduced, taking into account the postulates contained in, among others in [4, 6, 11, 13].

The concept of heat input per unit volume should be interpreted here as the amount of energy needed to perform the weld at a unit length with a given cross-sectional area (defined volume).

While the heat input per unit length can be determined before starting the process, the heat input per unit volume can be determined after the control weld (padded weld), which will allow to determine the dimensions of the cross-section of the fusion zone (penetration and reinforcement).

Hrabe et al. [15] stated that in the event that the weld (padded weld) has a regular shape, the weld face and fusion line can be described with a parabola. Then the functions describing the weld face and the fusion line will have the form (Fig. 1) [16]:

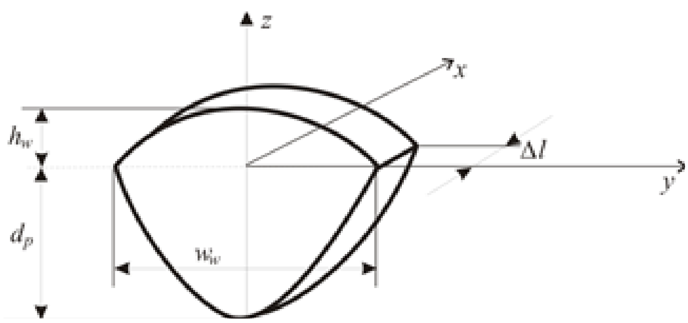

Fig. 1. Scheme of the weld geometry: h_w – height of the reinforcement, w_w – width of the weld, d_p – depth of the penetration, Δl – unit length

– face of the weld:

$$z = -\frac{4h_w}{(w_w)^2} y^2 + h_w$$

– fusion line:

$$z = \frac{4d_p}{(w_w)^2} y^2 - d_p$$

where: h_w – height of the weld reinforcement, w_w – width of the surfaced weld, d_p – depth of the fusion in the central of the weld, Δl – the unit length.

Integrating the fields bounded by these curves, the cross-sectional area of the reinforcement and remelted zones will be determined by the following formulas:

– reinforcement:

$$A_r = \frac{2}{3} h_w w_w$$

– remelted zone:

$$A_f = \frac{2}{3} d_p w_w$$

that is, the total cross-sectional area of the weld equals:

$$A_w = A_r + A_f = \frac{2}{3}(h_w + d_p) w_w$$

Then formula (5) will take the form:

$$E_{vw} = \frac{3\eta E_a}{2v(h_w + d_p) w_w}$$

For weld surfacing without filling the cavities (flat surface or with minimal depth of penetration $d_p = 0$) the following formula can be adopted:

$$E_{vw} = \frac{3\eta E_a}{2v h_w w_w}$$

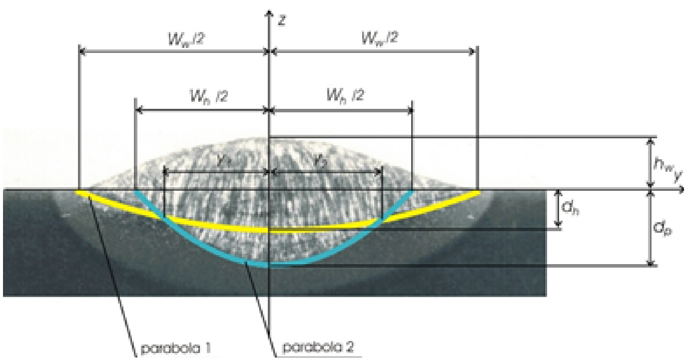

Fig. 3. Scheme for calculating the cross-sectional area of the weld with an irregular fusion zone shape

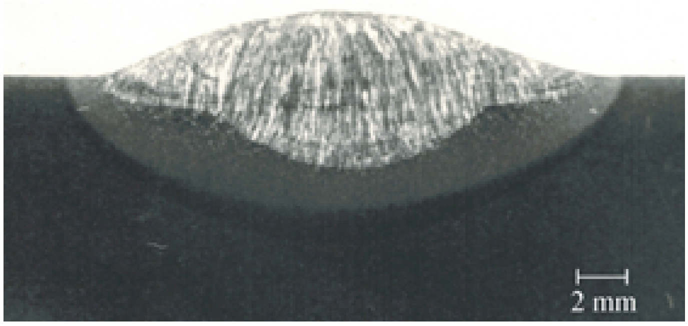

Fig. 2. Metalographic macro-section of the padded weld

In the case of an irregular shape of the fusion line shown in Fig. 2, hypothetical parabolas can be determined (Fig. 3):

– parabola 1:

$$z = \frac{4d_h}{(w_w)^2} y^2 - d_h$$

– parabola 2:

$$z = \frac{4d_p}{(w_h)^2} y^2 - d_p$$

The parabola intersection coordinates are as follows:

$$y_{1,2} = \pm \sqrt{\frac{d_p - d_h}{\frac{4d_p}{(w_h)^2} - \frac{4d_h}{(w_w)^2}}}$$

Then the surface area of the fusion zone will be equal:

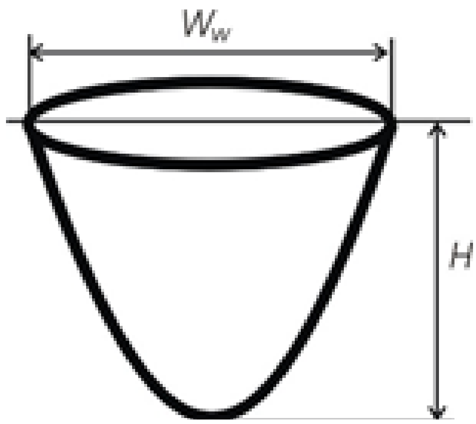

Fig. 4. Scheme of a paraboloid weld

$$A_f = 2\left[\int_{\frac{w_w}{2}}^{y_1}\left(\frac{4d_h}{(w_w)^2}y^2 - d_h\right)dy + \int_{y_1}^{0}\left(\frac{4d_p}{(w_h)^2}y^2 - d_p\right)dy\right] =$$

$$= \frac{2}{3}d_h w_w + \frac{2}{3}(d_p - d_h)\sqrt{\frac{(d_p - d_h)(w_h)^2(w_w)^2}{d_p(w_w)^2 - d_h(w_h)^2}}$$

and the total area of the weld cross-section is equal to:

$$A_w = A_r + A_f = \frac{2}{3}h_w w_w + \frac{2}{3}d_h w_w + \frac{2}{3}(d_p - d_h)\sqrt{\frac{(d_p - d_h)(w_h)^2(w_w)^2}{d_p(w_w)^2 - d_h(w_h)^2}}$$

Then formula (5) will take the form:

$$E_{vw} = \frac{3\eta E_a}{2v\left(h_w w_w + d_h w_w + (d_p - d_h)\sqrt{\frac{(d_p - d_h)(w_h)^2(w_w)^2}{d_p(w_w)^2 - d_h(w_h)^2}}\right)}$$

For spot welding, the welding speed (v = 0) should be omitted in the formula, while the volume of the weld should be used directly according to the formula:

$$E_{vw} = \eta\frac{E_a\tau}{V_w}$$

where: Vw – the volume of remelted material, τ – welding time.

Then two remelting shapes should be considered: paraboloid and cylindrical. For paraboloid shape of the weld (Fig. 4), the formula for heat input per unit volume will take the form:

$$E_{vw} = \eta\frac{4E_a H\tau}{\pi(w_w)^2}$$

where: H – means the height of the joint (e.g. the sum of the thickness of the welded sheets), and dp diameter of the joint measured on the surface of the welded elements.

Whereas for a cylindrical joint:

$$E_{vw} = \eta\frac{E_a H\tau}{\pi(w_w)^2}$$

Of course, the proposed formulas for calculating heat input per unit volume do not exhaust the expectations and possibilities of their application. Wojsyk et al. [13] presented numerous examples of weld shapes depending on the welding methods used. These examples constitute a wide area for further considerations and defining further formulas for calculating the heat input per unit volume of the weld. In the absence of a formula for calculating the cross-sectional area of the weld, it can be done, e.g. using a microscope and software calculating the surface area of the fusion zone or mapping the melting area in the AutoCAD program. e.t.c.

Sample of calculation

The padded weld, whose metalographic macro-section is shown in Fig. 2, was made using the hidden arc welding method, with the following technological parameters: v = 0.0084 m/s (8.4 mm/s), U = 30 V and I = 400 A. Measured dimensions of the weld: hw = 2,5 mm, hp = 13,66 mm, ww = 19 mm, dp = 3,8 mm, dh = 1,9 mm. Assuming η = 1 for the hidden arc welding method and taking into account:

$$E_a = UI$$

The heat input per unit volume according (18) equals:

$$E_{vw} = \frac{36000}{16.8\left(47.5 + 25.954 + 1.9\sqrt{\frac{1.9\cdot 186.5956\cdot 361}{3.8\cdot 361 - 1.9\cdot 186.5956}}\right)} =$$

$$= 20.59\,[J/mm^3]$$

Summary and conclusion

The advantage of the current method of heat input per unit length determination is the simplicity of the formula and the ability to calculate its value before making the first bead. The disadvantage, emphasized in many publications, is the growing discrepancy between the calculated heat input per unit length and the actual energy introduced into the welded joint. The proposals presented in the paper to determine the amount of heat introduced into the welded joint require at least one attempt to make a welded joint (padded weld). However, it should be noted that the qualification of welding technology requires such a test. The heat input per unit volume can be calculated based on the measured cross-section area of the welded joint.

In the case of a more complex formula for heat input per unit length, including correction factors, the number of experimental tests needed increases with the number of these factors. Considering the number of welding methods, possible combinations of technological and material parameters, the number of experimental tests necessary to perform can be difficult to implement.

The proposed method of calculating the amount of heat introduced into the welded joint can be a more real indicator than heat input per unit lengt, especially taking into account factors influencing the estimation of the actual power of the electric arc [6, 13].

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