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ESTIMATION OF HEAT ENERGY IN REGENERATION OF AGRICULTURAL MACHINE PARTS BY WELDING METHODS

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ABSTRACT

In the paper, the method of calculating the welding energy needed to regenerate parts of agricultural machines by welding (joining) or surfacing (rebuilding, hardfacing) is presented. Problems with the lack of adequacy of the commonly used formula for linear welding energy to the actual amount of heat introduced into the welded joint are discussed. A volumetric approach based on the effective amount of heat generated by the electric arc introduced per unit volume of the weld was proposed. The simplified formulas for volumetric energy are presented. The considerations are illustrated with examples of calculations. The analyzed examples include the use of a computerized stand for geometric measurements of metallographic specimens. The proposed volumetric method of calculating the amount of heat introduced into the welded joint is a more realistic indicator of heat demand than linear energy. On the other hand, based on the volume of the weld (padding weld), it allows to determine the amount of energy needed to regenerate machine parts, including agricultural ones.

Introduction

Welding methods are commonly used in the regeneration of agricultural machinery parts (Romek et al., 2020). They are used in the repair of, among others, working parts of cultivation machines (mainly by surfacing, i.e. applying a layer of weld metal on the worn surface with properties equal to or better (hardfacing) than the native material (e.g. plow blades). Regeneration of parts by surfacing extends the life of the working elements of machines working in soil. Welding most often concerns structural elements of devices such as frames, covers, supports, beams, etc. Then it becomes necessary to determine the parameters of welding processes, including the amount of heat needed to make the welding joint or apply the hardened layer.

For decades in welding, the concept of linear welding energy has been widely used as a measure of the amount of heat supplied to the welded joint. In the welding technological instructions it is required to define the linear welding energy for a given process, in which the formula for calculating the linear energy E_l of the arc welding is used (Wojsyk and Macherzyński, 2016):

$$E_l = \eta \frac{UI}{v} \left[\frac{J}{mm}\right] \quad (1)$$

where:

- I – average value of the welding current intensity for unidirectional current or effective value of the welding current for alternating current,
- U – average value of the arc voltage for unidirectional current or effective value of the arc voltage for alternating current,
- v – welding velocity,
- η – welding efficiency.

As we became acquainted with the nature of the phenomena occurring in welding processes and the results of research analyzing the influence of various factors on the course of these processes, including the transport of heat to the welded joint, doubts began to arise as to the adequacy of the commonly used formula (1) in relation to − the actual amount of heat introduced into the weld joint. At the end of the last century, Loos (1993) found that the values of the linear energy of welding (the actual amount of heat introduced into the weld) do not take into account the actual influence of the current intensity. In turn, Kensik (2006) referred to the estimation of the real energy of the welding arc. He pointed out that, especially in the case of a pulsed arc, determining its real power is difficult. He showed that not taking into account the power factory λ_s etermined by the ratio of the actual power to the apparent power in the formula for the welding line energy, may lead to errors of 20-25%. Goldak et al. (2010) also found that the linear energy of welding does not characterize the actual amount of heat introduced into the weld. Kudła and Wojsyk (2010) specified factors influencing the amount of heat introduced into the welded joint, dividing them into three groups:

1) a method of introducing heat,
2) welding conditions and technique,
3) materials.

Lack of adequacy of formula (1) to the actual heat input to the welded joint, this problem arouses more and more interest among researchers (Liskevych et.al., 2015, Matkowski et al., 2016; Nasir et al., 2017; Ostromęcka, 2017; Górka et al., 2017; Sajek and Nowacki, 2018).

In the work by Wojsyk and Macherzyński (2016), the formula for linear welding energy was proposed, taking into account the above factors:

$$E_l = k_1 \cdot k_2 \cdot \ldots.\; k_n \frac{P_r}{v} \quad (2)$$

where:

- $k_1 \ldots. k_n$ – material and technological factors as well as factors related to the heat source used,
- P_r – the actual power of the heat source,
- v – linear welding velocity.

Experimental determination of so many coefficients $k_1 \ldots. k_n$ (as the authors of the concept rightly point out) in practice is very difficult, and perhaps even impossible due to the emergence of new materials and welding methods. Therefore, the same paper presents a proposal to estimate the line energy of welding on the basis of the transverse surface area of the welds, but without proposing any formula. The work (Wojsyk et al., 2017) presents numerous examples for which a comparative analysis of the transverse fields of welds and padding welds made with various welding methods and the corresponding linear welding energies was performed. In conclusion, there was no correlation between the linear welding energy calculated according to formula (1) and the areas of the remelted weld area (padding weld).

The size of the cross-sectional area of the weld does not only depend on the amount of heat introduced into the joint (factors mentioned above). It also depends on the thermal properties (including the heat conduction coefficient, specific heat) and the dimensions of the welded object (material), which affects the heat transfer. Nevertheless, the transverse surface area can be an indicator useful in estimating the actual heat input to the weld.

Material and Methods - Objętościowe ujęcie ilości ciepła wprowadzanego do spoiny

As suggested by Wojsyk et al. (2016, 2017) regarding the recognition of the cross-sectional area of the weld (weld) as a value adequate to the amount of heat introduced into the welded joint, after dividing the linear welding energy by the weld cross-sectional area, we obtain:

$$E_{vw} = \frac{E_l}{A_w} \left[\frac{J}{mm^3}\right] \quad (3)$$

where:
E_{vw} – volumetric welding energy,
A_w – cross-sectional area of the weld.

The volumetric welding energy is therefore the amount of heat introduced into the welded joint per unit volume (heat input per unit volume). After inserting into the formula (3) the expression determining the linear welding energy according to the eqation (1) we have:

$$E_{vw} = \eta \frac{UI}{vA_w} \left[\frac{J}{mm^3}\right] \quad (4)$$

In turn, taking into account the postulates formulated by Kensik (2006) and in the PN-NE 1011-1 standard (2001), after introducing the actual electric arc energy, equation (4) will take the form:

$$E_{vw} = \eta \frac{E_a}{vA_w} \left[\frac{J}{mm^3}\right] \quad (5)$$

where:
E_a – the actual energy of the electric arc.

While the linear welding energy can be determined prior to the commencement of the process, the determination of volumetric welding energy requires the preparation of the weld and metallographic inspection and macro analysis in order to dimension the cross-section of the remelting zone (fusion and reinfocement).

Measurement of the remelting area can be done using a microscope and specialized software (e.g. the Olympus GX51 metallographic microscope with Stream software). In the case of typical shapes of the remelting zone, you can use the analytical method based on the characteristic dimensions of the weld (padding weld), such as the height and width of the reinforcement and the fusion depth.

For a regular shaped weld, the weld face and the fusion line can be described by a parabola (Hrabe et al., 2009). Then the functions describing the weld surface and the fusion line will have the form (Fig. 1) (Winczek, 2011):

$$E_{vw} = \eta \frac{E_a}{vA_w} \quad \left[\frac{J}{mm^3}\right] \tag{6}$$

– weld face:

$$z = -\frac{4h_w}{(w_w)^2} y^2 + h_w \tag{7}$$

– fusion line:

$$z = \frac{4d_p}{(w_w)^2} y^2 - d_p \tag{8}$$

where:
h_w – height of the reinforcement,
w_w – width of the weld,
d_p – depth of the penetration,
Δl – weld length made within 1 s.

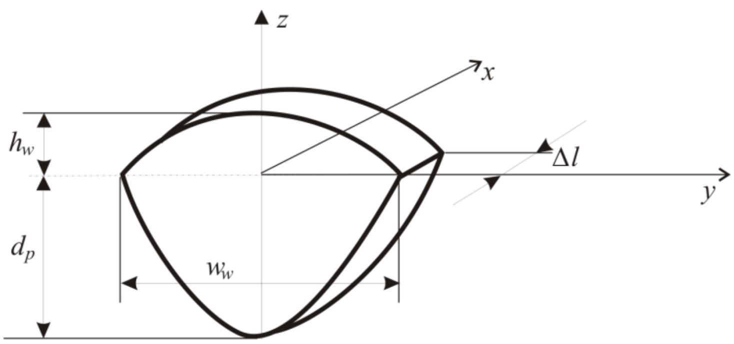

Figure 1. Characteristic dimensions of the weld: h_w – height of the reinforcement, w_w – width of the weld, d_p – depth of the penetration, Δl – weld length made within 1 s

The cross-sectional areas of the weld limited by these curves (reinforcement and fusion) are determined by the following equations:
– reinforcement:

$$A_r = \frac{2}{3} h_w w_w \tag{9}$$

– fusion area:

$$A_f = \frac{2}{3} d_p w_w \tag{10}$$

Then the surface area of the entire remelting area is:

$$A_w = A_r + A_f = \frac{2}{3}\left(h_w + d_p\right) w_w \tag{11}$$

and equation (5) takes the form:

$$E_{vw} = \frac{3\eta E_a}{2v\left(h_w + d_p\right) w_w} \tag{12}$$

For surfacing with the minimum penetration depth ($d_p = 0$), the equation takes a simplified form:

$$E_{vw} = \frac{3\eta E_a}{2v h_w w_w} \tag{13}$$

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

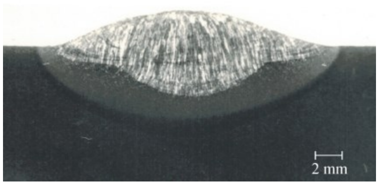

Figure 2. Metallographic examination of the padding weld

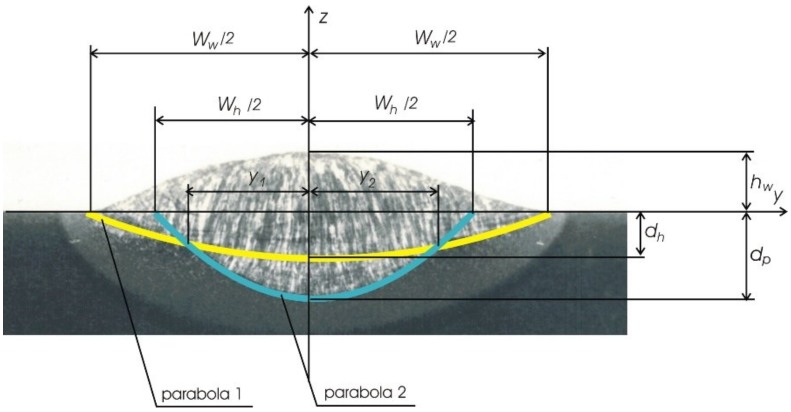

Figure 3. Scheme for calculating the cross-sectional area of a weld with an irregular shape of the remelting zone

– parabola 1:

$$z_1 = \frac{4d_h}{(w_w)^2} y^2 - d_h \tag{14}$$

– parabola 1:

$$z_2 = \frac{4d_p}{(w_h)^2} y^2 - d_p \tag{15}$$

The coordinates of the intersection of the parabolas z_1 i z_2 are as follows:

$$y_{1,2} = \pm \sqrt{\frac{d_p - d_h}{\frac{4d_p}{(w_h)^2} - \frac{4d_h}{(w_w)^2}}} \tag{16}$$

The area of the fusion zone will be equal:

$$A_f = \frac{2}{3} d_h w_w + \frac{2}{3}\left(d_p - d_h\right)\sqrt{\frac{\left(d_p - d_h\right)\left(w_h\right)^2\left(w_w\right)^2}{d_p\left(w_w\right)^2 - d_h\left(w_h\right)^2}} \tag{17}$$

The equation (5) will then take the form:

$$E_{vw} = \frac{3\eta E_a}{2v\left(h_w w_w + d_h w_w + \left(d_p - d_h\right)\sqrt{\frac{\left(d_p - d_h\right)\left(w_h\right)^2\left(w_w\right)^2}{d_p\left(w_w\right)^2 - d_h\left(w_h\right)^2}}\right)} \tag{18}$$

Results and Discussion

The cross-sections of two padding welds (Fig. 4) (Łabanowski, 2019), made with the same linear welding energy of 1.2 $kJ \cdot mm^{-1}$, but performed under different conditions: in air (Fig. 4a) and in water using a dry chamber (Fig. 4b), were analyzed.

a) b)

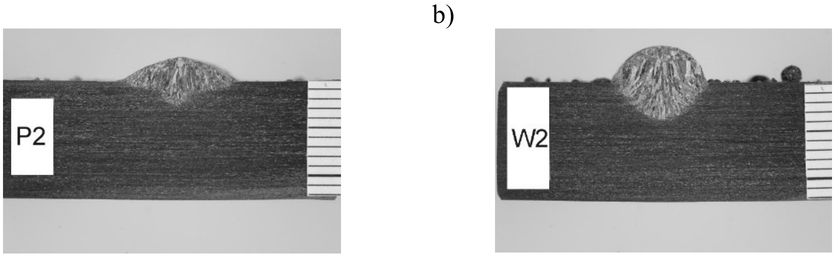

Figure 4. Cross-sections of welds made: a) in air, b) under water (Łabanowski, 2019)

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. The following technological parameters were adopted for surfacing (Table 1) (Łabanowski et al., 2011).

Table 1.
Parameters of weld surfacing of duplex steel sheet UR45N

Sample	Environment	Volatge (V)	Current (A)	Welding velocity ($mm \cdot s^{-1}$)
P2	air	30,5	240	6,1
W2	water	32,5	224	6,1

As it results from the value of linear energy, the authors of the work (Labanowski et al., 2011) calculated it using the formula recommended by the ASME IX QW-409.1 standard (2010):

$$HeatInput = UI/v \tag{19}$$

where:

Heat Input Heat should be understood as welding linear energy. The calculated values of this energy of the welds are respectively 1200 $J \cdot mm^{-1}$ (in air) and 1193 $J \cdot mm^{-1}$ (in water). The choice of formula (19) was probably dictated by the lack of value of the efficiency factor for the underwater welding process.

Geometric measurements of padding welds were performed using an Olympus GX51 metallographic microscope with the Stream program. Photos of the measurements of the padding weld made in the air are shown in Fig. 5. Characteristic dimensions of padding welds (in accordance with Figures 1 and 3) are summarized in Table 2. The results of measurements and calculations of surface areas and volumetric energy are summarized in Table 3.

a) b)

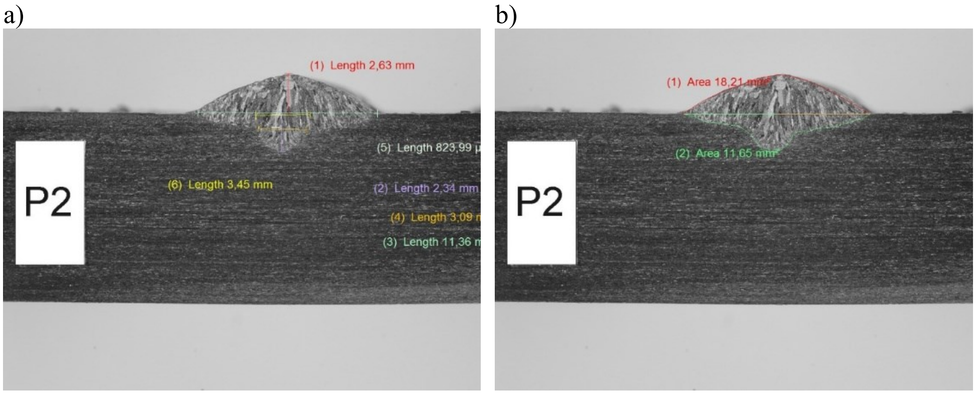

Figure 5. Dimensions of padding weld and calculated cross-sectional areas

Table 2.
Dimensions of padding welds

Sample	Heigth of the reinforcement h_w (mm)	Depth of the fusion d_p (mm)	Width of the weld w_w (mm)	$y_{1,2}$	d_h	w_h
P2	2,63	2,34	11,36	3,09	0,82	3,45
W2	3,8	3,9	9,5	-	-	-

The results of measurements and calculations of surface areas and volumetric energy are presented in Table 3. The calculation of the cross-sectional area of the samples was made using the equations: (17) for the sample surfaced in air P2 and (11) for the sample surfaced in water W2. Volumetric energy values were determined by the formulas (18) for P2 and (12) for W2, respectively.

Table 3.
Calculation results

Measured (calculated) quantity	Sample P2	Sample W2
The real power of an electric arc (W)	7320	7280
The actual cross-sectional area of the padding weld - microscopic measurement (mm^2)	29,86	50,3
The cross-sectional area of the padding weld calculated according to analytical equations (mm^2)	28,99	43
Volumetric energy calculated from the surface area measured with the microscope ($J \cdot mm^{-3}$)	40,19	23,72
Volumetric energy calculated from the surface area determined by analytical equations ($J \cdot mm^{-3}$)	41,39	27,71

The difference in the calculated cross-sectional areas of the padding weld for the sample deposited in air by means of a microscope and a computer program and the formula (17) is 3%, a similar difference occurs in the volumetric energy values. In the case of the padding weld in water, the differences between the values based on the actual field measurement and based on formula (11) are much larger, reaching 14%. It is similar with the values of volumetric energy of weld surfacing. The reason is probably the shape of the cross-section of the padding weld made in water, the lines of the face and fusion of which resemble a semicircle rather than a parabola, which should be the subject of further research and analysis. However, the difference between the volumetric energy values calculated (based on the actual cross-sectional area) for the cases of surfacing in air and in water differs by 41% with almost identical linear welding energy.

Conclusions

The advantage of the current method of determining linear welding energy is the simplicity of the equation. The disadvantage of the method, 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. This is confirmed by the differences in the value of the weld surfacing volumetric energy for the computational example analyzed in the paper. The proposal presented in the article to determine the amount of heat introduced into a welded joint requires at least one attempt to make the welded joint. However, it should be noted that the qualification of the welding procedure requires such a test. Volumetric welding energy can be calculated from the measured cross-sectional area of the welded joint.

In the case of remanufacturing parts of agricultural machinery, the dimensions of the cross-sectional area of the damaged weld are often known. By solving the inverse problem, i.e. on the basis of the cross-sectional area of the weld or its volume and the calculated volumetric energy of welding, the amount of energy needed to regenerate these machine parts can be determined.

The proposed formulas for the simplified calculation of the cross-sectional area of the fusion area of the weld (padding weld) do not exhaust the expectations and possibilities of their application. The work of Wojsyk and Macherzyński (2016) presents numerous examples of the shapes of welds and padding welds using various welding methods, which constitute a rich research material for further considerations and formulating equations for calculating the cross-sectional area of the remelting area.

The proposed volumetric method for calculating the amount of heat introduced into the welded joint may be a more realistic indicator than the linear energy of welding.

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SZACOWANIE ENERGII CIEPLNEJ W REGENERACJI CZĘŚCI MASZYN ROLNICZYCH METODAMI SPAWALNICZYMI

Streszczenie. W pracy przedstawiono sposób obliczania energii spawania potrzebnej do regeneracji części maszyn rolniczych poprzez spawanie (łączenie) lub napawanie (uzupełnianie ubytków, utwardzanie powierzchni). Omówiono problemy braku adekwatności powszechnie stosowanego wzoru na energię liniową spawania do rzeczywistej ilości ciepła wprowadzanego do złącza spawanego. Zaproponowano objętościowe ujęcie oparte na efektywnej ilości ciepła wytworzonej przez łuk elektryczny wprowadzanej na jednostkę objętości spoiny. Przedstawiono uproszczone wzory na energię objętościową. W rozważaniach uwzględniono zastosowanie skomputeryzowanego stanowiska do pomiarów geometrycznych zgładów metalograficznych. Rozważania zilustrowano przykładami obliczeń. Zaproponowana objętościowa metoda obliczania ilości ciepła wprowadzanego do złącza spawanego jest bardziej realnym wskaźnikiem zapotrzebowania ciepła niż energia liniowa. Z kolei na podstawie objętości spoiny (napoiny) pozwala na wyznaczenie ilości energii potrzebnej do regeneracji części maszyn, w tym rolniczych.

Słowa kluczowe: maszyny rolnicze, regeneracja, spawanie, napawanie, energia spawania