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A New Methodology for the Determination of Linear Welding Energy

Abstract: The article presents a new methodology enabling the determination of linear welding energy as well as discusses inaccuracy-related issues accompanying the calculation of the aforesaid energy using a commonly applied formula. In addition, the article describes the correlation between the cross-sectional fusion area and energy used to melt the base material and the filler metal. The article also discusses the determination of a coefficient applied successfully in the new methodology and presents its practical application, including the possibility of identifying the heat input also in highly problematic or entirely unquantifiable cases.

Keywords: linear welding energy, heat input

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Introduction

Linear welding energy E_L is a measure of thermal energy supplied to a welded joint and being an indispensable factor for the welding process to take place [1]. The value of E_L is usually calculated using the following formula:

$$E_L = \frac{\eta UI}{v}, \quad \frac{J}{mm} \tag{1}$$

where
η – coefficient of welding arc thermal efficiency,
U – arc voltage,
V, I – welding/cladding current, A.

The welding process involves two phenomena, i.e. the fast heating and cooling of materials. The fact that both phenomena may adversely affect weld properties necessitates the limitation of changes resulting from significant gradients of temperature in the joint. The development of materials engineering leads to the continuous improvement of structural materials, which env narrowing down of conditions under which dissimilar materials can be joined. In cases of technologically advanced steels, one of the factors affecting the obtainment of proper welded joints is a heat input. The above-named condition imposes increasingly narrow range of welding parameters. An example of narrowing down the range of welding parameters in relation to increasingly advanced steels is presented in Figure 1.

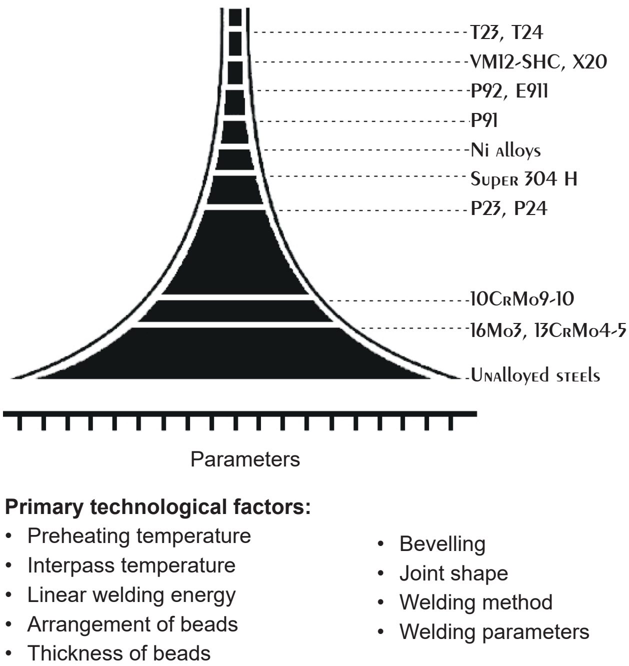

Fig. 1. Narrowing down the range of welding parameters in relation to increasingly advanced steels [2]

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Factors affecting ultimate value E_L

The above-presented information justifies the conclusion that welding processes trigger smaller or larger changes in materials, potentially leading to the formation of welding imperfections. One of the procedures enabling the obtainment of joints without unfavourable changes in the heat affected zone (HAZ) and, consequently, the formation of welding imperfections, involves the maintaining of appropriate linear welding energy. The heat input to the material depends on various factors affecting the ultimate value of E_L, and, as a result, the geometrical shape of the weld and the structure of the material. The aforesaid factors are referred to as principal variables affecting the actual heat input to the joint. It should be noted that none of the variables discussed in the remainder of the article is taken into account when calculating linear welding energy using most popular formula (1), which leads to errors during the determination of the actual heat input to the joint. Widely defined welding specialists are aware of the fact and, because of this, undertake attempts to investigate the effect of individual variables on the value of E_L [3]. Presented below are divisions of the principal variables in relation to materials, welding conditions/techniques and heat input-related methods.

a) Division of variables in relation to the type of material:
   - chemical composition of the base material,
   - chemical composition of the filler metal,
   - type of shielding gas, coating or flux,
   - chemical composition of the activator,
   - diameter, type and shape of the electrode,
   - shape and thickness of the joint,
   - type of the backing strip.

b) Division of variables in relation to welding conditions and technique:
   - ambient temperature,
   - temperature used in preheating the base material and filler metal,
   - type of bevelling,
   - welding position and direction,
   - q-v ratio,
   - hybrid processes,
   - electrode extension,
   - arc length,
   - angle of torch inclination in relation to the direction of welding,
   - scatter of parameters in WPS.

c) Division of variables in relation to the heat input:
   - geometrical shape of the heat source,
   - current polarity,
   - impulse frequency,
   - AC balance,
   - current wavelength and its coupling with arc voltage,
   - filler metal transport type,
   - bead type.

An increase in linear welding energy should be reflected in the volume of a molten area, represented by weld cross-sectional area P_W. The change of linear welding energy and that of the weld area should be monotonic. Figure 2 presents

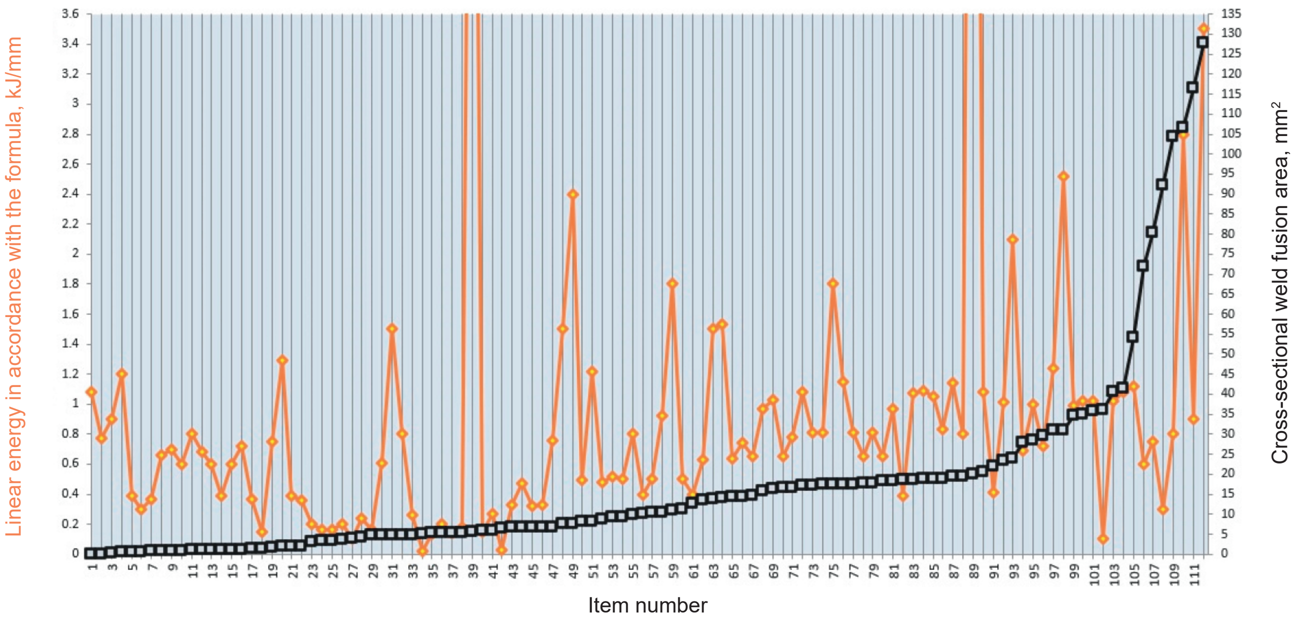


Fig. 2. Juxtaposition of values of E_L and values of P_W obtained from reference publications

information obtained from related reference publications. Data are presented in the ascending order in relation to the weld cross-sectional area corresponding to value of linear energy calculated by authors of reviewed articles [4]. The result provokes reflection concerning the range of application of the commonly adopted formula.

A new method enabling the determination of linear welding energy

The diagram indicates the lack of correlation between linear welding energy and the cross-sectional weld fusion area, which inspired the development of a new method aimed to determine linear welding energy. The new method enabling the determination of E_L comes down to the identification of the correlation between energy consumed during the welding process in order to melt the base material and the filler metal and the cross-sectional weld area obtained in the process. Knowing the actual amount of energy needed to melt a given weld cross-sectional area expressed in mm^2 enables, based on the measured value of P_W of any weld, the determination of the value of E_L without knowing welding parameters or conditions. The correlation between E_L and the weld cross-section is referred to as coefficient β, the value of which is identified by making a series of standard welds under conditions where the effect of external factors on the process is limited to a minimum. The programme of tests involved the design and making of standard specimens PR_{WZ} (angle joints with fillet welds made using method 135, determination of linear welding energy, the making of metallographic specimens and the calculation of cross-sectional weld areas). In addition, the agenda included designing and making control specimens PR_K (making metallographic specimens and calculating cross-sectional fusion areas). The final stage involved the tabulation of test results concerning the linear energy of control specimens as well as calculating E_L of the control specimens on the basis of PR_{WZ}, using standard specimen coefficient β. Figure 3 presents the method of measuring cross-sectional areas of individual zones of the weld, the area of the entire weld P_S, the area of the penetration of the base material P_P, the area of the functional part of the fillet weld P_{FW}, the area of excess weld metal (i.e. undesired part) P_N as well as the area of fusion P_W, i.e. the sum of the area of the functional part of the fillet weld and of the penetration area.

The tests involved the making of six standard specimens under conditions maximally limiting the effect of external factors, the calculation of linear welding energy in relation to each specimens (using a general formula), the determination of the cross-sectional area of the weld, fusion, penetration as well as that of the functional part of the fillet weld and excess weld metal, the size of which should be limited to a minimum. The welding parameters and the values of the cross-sectional areas of individual weld zones are presented in Table 1.

The next stage consisted in the juxtaposition of the values of the cross-sectional areas of the welds with the linear welding energy of individual standard specimens. The results are presented in Figure 4.

The above-presented juxtaposition revealed the lack of heat losses triggered by external factors and, consequently, the proper quality of the specimens. The values of linear welding energy and of the cross-sectional areas of the welds (calculated using formula (2)) were used to identify the correlation between them in relation to each standard specimen, referred to as standard specimen coefficient β'. The subsequent step involved the calculation of the average (constituting the ultimate value of coefficient β) and that of the error. The results are presented in Table 2.

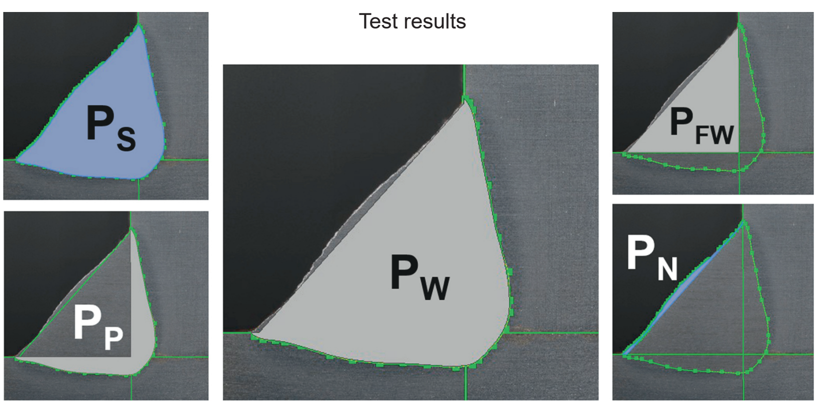


Fig. 3. Method used to determine the cross-sectional areas of the individual zones of the weld

Table 1. Standard specimen test results

No.	Design dimension of the fillet weld, mm	Filler metal wire feed rate v_d, m/min	Linear welding rate v, m/min	Linear welding energy E_L, kJ/mm	Cross-sectional areas of individual weld zones, mm²				
					P_S	P_W	P_P	P_{FW}	P_N
P_{WZ1}	a3	8.5	0.80	**0.313**	**16.73**	15.69	6.67	9.02	1.03
P_{WZ2}	a3	13	1.25	**0.339**	**19.82**	18.79	9.45	9.35	1.03
P_{WZ3}	a4	8.5	0.55	**0.456**	**24.76**	23.23	8.52	14.71	1.52
P_{WZ4}	a4	13	0.76	**0.558**	**31.49**	29.27	14.20	15.08	2.21
P_{WZ5}	a5	8.5	0.40	**0.630**	**34.97**	33.71	11.53	22.18	1.26
P_{WZ6}	a5	13	0.60	**0.720**	**42.01**	41.54	19.43	22.11	0.47

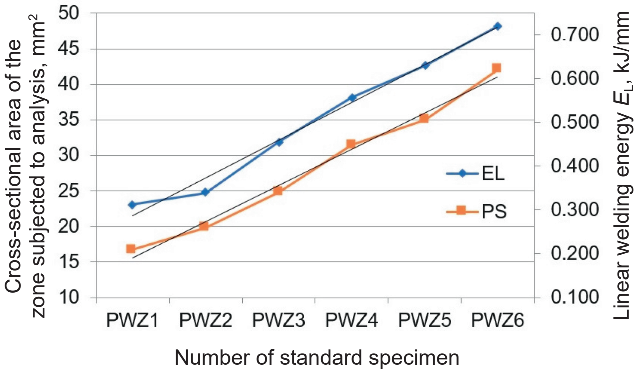


Fig. 4. Juxtaposition of the values of the cross-sectional areas of the welds and the values of linear welding energy in relation to individual standard specimens

$$\beta' = \frac{E_L}{P_S}, \quad \frac{J}{mm^3} \tag{2}$$

Table 2. Coefficient β calculation results

Number of standard specimen	Linear welding energy E_L, kJ/mm	Weld cross-sectional area P_S, mm²	Standard specimen coefficient β', kJ/mm³
P_{WZ1}	0.31	16.73	0.0187
P_{WZ2}	0.34	19.82	0.0171
P_{WZ3}	0.46	24.76	0.0184
P_{WZ4}	0.56	31.49	0.0177
P_{WZ5}	0.63	34.97	0.0180
P_{WZ6}	0.72	42.01	0.0171
Arithmetic average of all β' – standard specimen coefficient β:			**0.0179**
Error Δ:			**3%**

The transformation of formula (2) led to the obtainment of formula (3), enabling the determination of linear welding energy, calculated on the basis of the cross-sectional area of the weld.

$$E_{L\beta} = \beta P_S, \quad \frac{kJ}{mm} \tag{3}$$

where

$E_{L\beta}$ – linear welding energy in relation to coefficient β, kJ/mm,

β – standard specimen coefficient, kJ/mm³,

P_S – cross-sectional area of the weld, mm².

The values of E_L and $E_{L\beta}$ for PR_{K1} and PR_{K2} were very similar. The convergence of both results justified the statement that the Rapid process was very effective as regards the heat input to the joint. The values of E_L and $E_{L\beta}$ for PR_{K3} and PR_{K4} were divergent, which could imply the significant inaccuracy of linear welding energy assessment in relation to the tandem process (in terms of the commonly applied principle). The tandem process is characterised by one weld pool for two arcs, whereas the commonly adopted principle of calculating linear welding energy (summation of E_L in relation to each filler metal wire separately) does not take this fact into account. In relation to PR_{K5} – PR_{K7}, $E_{L\beta}$ was higher than E_L by 12% and 15% as well as lower by 1% respectively. The above-presented differences could be attributed to the so-called thermal severity, the theory of which states that heat in overlay welds propagates in 2 directions, whereas heat in angle joints propagates in 3 directions. As a result, in relation to PR_{K5} and PR_{K6} the value of $E_{L\beta}$ was higher. The value of E_L and that of $E_{L\beta}$ in relation to PR_{K8} – PR_{K10} coincided with the conclusions resulting from the aforementioned thermal severity, i.e. in relation to the above-named specimens, $E_{L\beta}$ was higher than E_L by 15%, 18% and 25% respectively. The value of linear welding energy calculated using the commonly adopted formula was underestimated. In relation to PR_{K11} – PR_{K14}, $E_{L\beta}$ was lower than E_L by 72%, 67%, 63% and 60% respectively. The value of E_L was identical for all of the specimens, yet the change of welding current significantly affected the final effect (having the form of material penetration). The value of E_L was significantly higher than that of $E_{L\beta}$, which could indicate significant heat losses in the above-named process.

It should be noted that by adopting the system of estimating the value of linear welding energy

Table 3. Control specimen test results

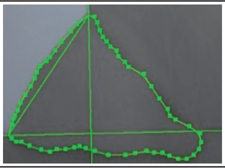
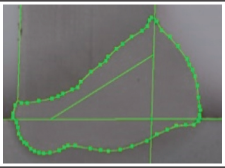
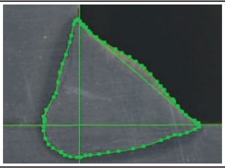
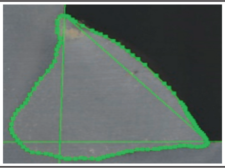
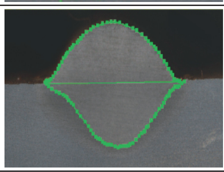
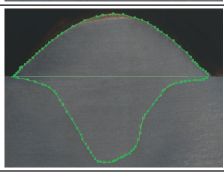
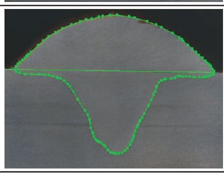
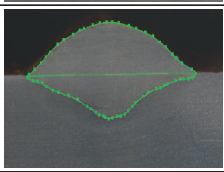
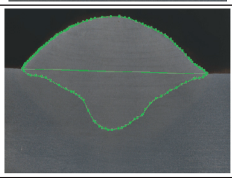
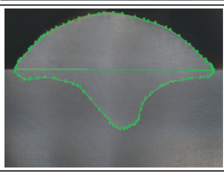
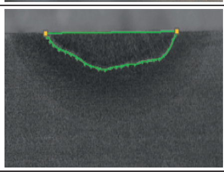
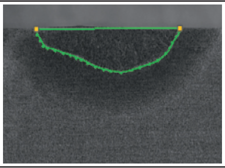
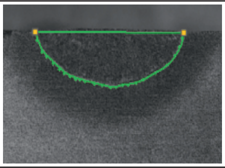
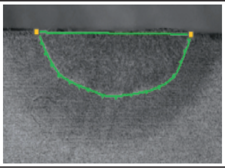
Spec. no.	Metallographic specimen	Description	E_L kJ/mm	$E_{L\beta}$ for P_S kJ/mm	Difference %
PK1		T-joint with the single-run fillet weld; MAG-rapid deep-penetration welding process	1.24	1.26	+1
PK2		T-joint with the single-run butt weld; MAG-rapid deep-penetration welding process	0.78	0.82	+5
PK3		T-joint with the single-run fillet weld; MAG-tandem multi-wire welding process	0.31	0.34	+10
PK4		T-joint with the single-run fillet weld; MAG-tandem multi-wire welding process	0.89	0.59	-34
PK5		Plate with the single-run overlay weld; standard MAG welding process	0.31	0.35	+12
PK6		Plate with the single-run overlay weld; standard MAG welding process	0.87	1.00	+15
PK7		Plate with the single-run overlay weld; standard MAG welding process	1.30	1.28	-1
PK8		Plate with the single-run overlay weld; MAG-tandem multi-wire welding process	0.31	0.36	+15
PK9		Plate with the single-run overlay weld; MAG-tandem multi-wire welding process	0.89	1.05	+18
PK10		Plate with the single-run overlay weld; MAG-tandem multi-wire welding process	1.18	1.48	+25
PK11		Plate with the single-run overlay weld; TIG-rapid welding process	0.50	0.14	-72

Table 3. cont.

Spec. no.	Metallographic specimen	Description	E_L kJ/mm	$E_{L\beta}$ for P_S kJ/mm	Difference %
PK12		Plate with the single-run overlay weld; TIG-rapid welding process	0.50	0.17	-67
PK13		Plate with the single-run overlay weld; TIG-rapid welding process	0.50	0.18	-63
PK14		Plate with the single-run overlay weld; TIG-rapid welding process	0.50	0.20	-60

on the basis of formula (3) it was possible to determine the value of $E_{L\beta}$ for each zone of the weld, expressed by simplified formula (4):

$$E_{L\beta} = \beta P_{POW}, \quad \frac{kJ}{mm} \tag{4}$$

where

$E_{L\beta}$ – linear welding energy in relation to coefficient β, kJ/mm,

β – standard specimen coefficient, kJ/mm^3,

P_{POW} – cross-sectional area of a selected weld zone, mm^2.

As a result, it was possible to identify the following directions of further research-related tests:

- making PR_{WZ} using other welding methods (e.g. 141, 121, laser, hybrid) – in order to identify and compare values of coefficients β,
- testing E_L in relation to welds made using special methods such as, strip cladding or MAG-tandem or TIG-rapid welding, where the number of tests was low and results were ambiguous,
- making PR_K using methods, for which it was not previously possible to estimate the value of linear welding energy (e.g. gas welding), determine the value of $E_{L\beta}$ for such methods and compare with standard methods,
- development of comparative tables for linear energy not only in relation to various welding/cladding methods but also in relation to various materials.

One of the more practical examples concerning the application of the above-presented method is the possibility of calculating the heat input to the material when making spot welds. Because of the fact that spot welds are not made by moving the welding torch along the joint, which means that one of the components of formula (1) is lacking, it is not possible to calculate the heat input to such a weld. One might try to identify the correlation between applied welding parameters and welding arc burning time, yet the final effect in the form of the area or volume of penetration could be more accurate and reliable. To calculate the heat input to the spot weld it was necessary to determine the volume of the weld and, on this basis, calculate the value of E_β. Figure 5 presents the cross-section of the spot weld and the area of P_W.

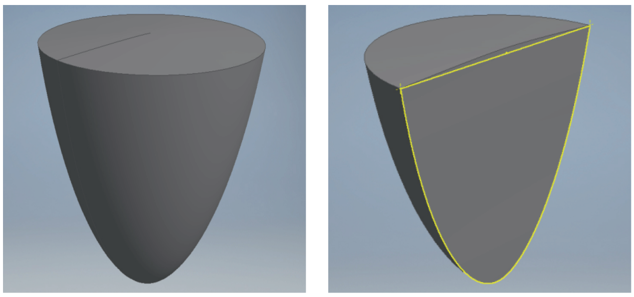


Fig. 5. Cross-section of the spot weld and the marked area of P_W

To determine the volume of the spot weld it was first necessary to identify the length of the parabola located along the fusion line (see Fig. 6) [5].

The next step involved the calculation of volume V of the body formed through the rotation of the diagram of function $y = f(x)$ around the Oy-axis. The value of the volume was determined using formula (5)

$$|V| = 2\pi \int_0^h x f(x)\, dx \tag{5}$$

The replacement of P_{POW} with V in formula (4) changed the result of energy supplied in the linear

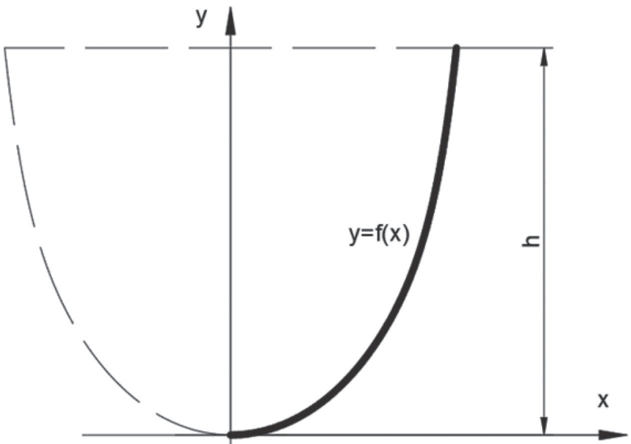


Fig. 6. Determination of the length of the parabola located along the fusion line

manner into that supplied to the entire joint/overlay weld. As a result, the transformation of the aforementioned formula led to the obtainment of formula (6), enabling the calculation of energy supplied to the volume of molten material referred to as $E_β$:

$$E_β = βV, \quad \text{kJ} \qquad (6),$$

where

$E_β$ – energy supplied in relation to coefficient $β$, kJ,

$β$ – standard specimen coefficient, kJ/mm^3,

V – volume of molten material, mm^2.

Formula (5) could also be expressed in the ultimate version as formula (6) presented below:

$$E_β = β2π\int_0^h x\mathrm{f}(x)\,\mathrm{d}x, \quad \text{kJ} \qquad (6).$$

The above-presented method of enabling the determination of energy supplied to spot welds made using fusion welding could also be applied to spot welds made using pressure welding processes.

Other possibilities resulting from the application of coefficient $β$ and formula (4) included the determination of $E_{Lβ}$ for overlay welds made using the filler metal strip, welds made using hybrid methods, welds made using process 311 as well as welds and overlay welds made using the tandem process. The estimation of linear welding energy on the basis of areas of penetration also enabled the juxtaposition and comparison of various welding processes, where values of E_L were previously determined using various methods. The comparison based on the calculation of the heat input to the material using one system of calculations was more reliable and enabled the obtainment of more accurate results.

Conclusions

1. The value of E_L calculated on the basis of the general formula did not include many variables affecting the value of the cross-sectional fusion area. The aforesaid method is not suitable for the estimation of E_L in cases of steels sensitive to the heat input and special processes.
2. The estimation of $E_{Lβ}$ based on the melting of materials (ultimate effect) proved to be a more reliable and accurate method, enabling the obtainment of the actual heat input to the joint (in view of the fact that the method should provide a measurable and unquestionable final effect).
3. It is not obvious whether one coefficient $β$ would be universal for various welding methods. The tests revealed that the above-named coefficient was useful as regards different variants of the same method. However, the use of the coefficient to determine the value of $E_{Lβ}$ in relation to welds made using different methods requires the extension of the research.
4. The new method of determining linear welding energy enables the estimation of the heat input to welds or overlay welds in previously non-measurable cases as well as opens new research pathways providing better understanding of welding processes and, consequently, helping improve the quality of joints or overlay welds, particularly in cases of high-alloy steels (sensitive to the heat input).

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