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Determination of Welding Linear Energy by Measuring Cross-Sectional Areas of Welds

Abstract: The article proposes the method of estimating heat input to materials by measuring the cross-sectional area of volumes melted during fusion or pressure welding. In addition, the article describes methods presently used to estimate linear energy involving the fixing of wattmeters to arc power sources and referring this energy to the linear dimensions of welds. The article justifies the necessity of changing the approach to methods of calculating linear energy by the development of new welding methods and the launching of new materials sensitive to heat. The introduction of numerous impulse and hybrid (laser-based) welding methods contests the conventional methods of linear energy calculation (illustrated by examples). The article proposes a manner of calculating heat input during spot welding.

Keywords: welding linear energy, heat input, methods of measurement

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Welding linear energy is a conventional measure of energy supplied to a weld length unit [1]. As welding linear energy belongs to principal welding parameters, it is increasingly often recorded independently of other welding process indicators such as welding current and voltage, preheating temperature affecting elements to be joined, interpass temperature, diameter, filler metal wire feeding rate etc. The primary and commonly adopted dependence used when calculating welding linear energy is the following:

$$E_l = \eta \frac{U \cdot I}{v} \tag{1}$$

where η – efficiency (coefficient) dependent on a welding method [%], U – welding voltage [V], I – welding current [A], v – linear welding rate [mm/s].

In various methods of non-electric welding, such as gas or laser welding as well as in electric non-arc welding methods such as electron beam welding or slag welding and in numerous hybrid methods, pressure welding, spot welding etc., linear energy cannot be defined in the manner presented above. Furthermore, the development of arc welding methods, particularly those involving the use of impulse power sources, has led to the situation where the traditional manner of measuring heat input is at least disputable, if possible at all.

Numerous research works and tests performed at the Welding Department of the Częstochowa University of Technology [2÷8] revealed that actual heat input is affected by a number of electric parameters independent of one another, i.e. the manner of heat input,

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and, in particular the geometry of a heat source [2÷4], the type and shape of a current waveform, current polarity and the manner of material transport in arc [5÷7]. The actual heat input to elements subjected to welding is also affected by other, i.e. material-related factors such as the chemical composition of weld deposit and base materials, the type of shielding gas and flux, the chemical composition of activator, the diameter of an electrode, the thickness of elements being welded as well as technological factors including ambient temperature, preheating temperature affecting a joint and filler metal, the type of joint, the manner of bevelling, the position and direction of welding, the type of a run, electrode extension etc. [8].

Therefore, taking into consideration all factors affecting the actual heat input to materials being welded or surfaced is extremely difficult or even impossible if "external" process parameters such as voltage, current and welding rate are taken into consideration. In such a case, dependence (1) would have to take the following form:

$$E_l = k_1 \cdot k_2 \cdot \ldots k_n \frac{P_{rz}}{v} \qquad (2)$$

where $k_1 \div k_n$ – material and technological coefficients dependent on the heat source, P_{rz} – actual power of the heat source, v– linear welding rate.

If dependence (2) includes many corrective coefficients k_n determined with various accuracy, usually ranging from ten to tens of percent, the final sufficiently accurate determination of welding linear energy is not possible. Taking into consideration the constant development of welding engineering leading to new, often very complex, welding and surfacing technologies, it is necessary to properly define the linear energy of such processes. Another problem results from the fact that new structural materials are usually characterised by limited weldability leading to the necessity of using strictly specified welding conditions and parameters. Such a situation can be depicted by the Hauser diagram, also known as "funnel" or "glass mountain". Although the diagram was developed for materials used in power engineering, its range can be extended to include all newly launched steels and alloys [9].

Overly low welding linear energy can result in the formation of incomplete fusions, hardenings in the HAZ or the lack of penetration in a joint. In turn, excessively high welding linear energy can lead to excessive penetration, overheating and grain growth in the HAZ as well as to the occurrence of unfavourable precipitation phenomena within the HAZ (Fig. 1) [1].

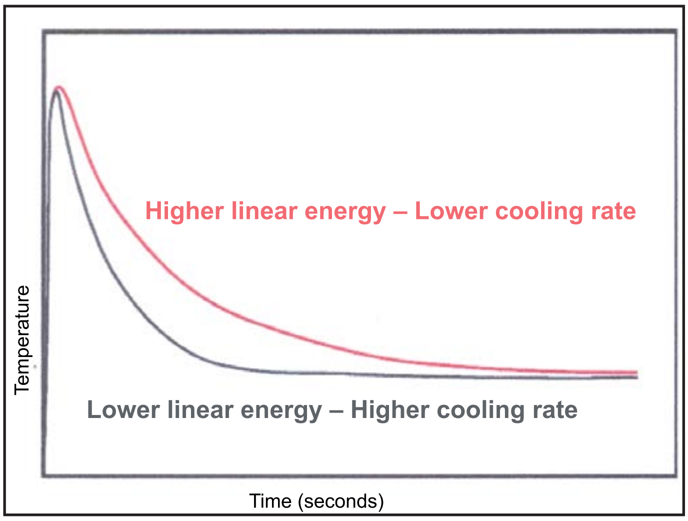

Fig. 1. Effect of welding linear energy on welding rates [1]

The issues presented above have inspired efforts undertaken in order to estimate welding/surfacing linear energy more accurately and properly than before.

Many new-generation arc power supplies are provided with wattmeters calculating the momentary power of welding power sources. If referred to a welding rate related to a measurement weld section, the knowledge of the above named momentary power makes it possible to directly and roughly calculate welding linear energy using dependence (1) and eliminate some of the inaccuracies connected with the measurement of current-related quantities.

Another method of assessing welding linear energy is the association of weld geometric features with heat input to materials being joined. The above-named attempt led to the

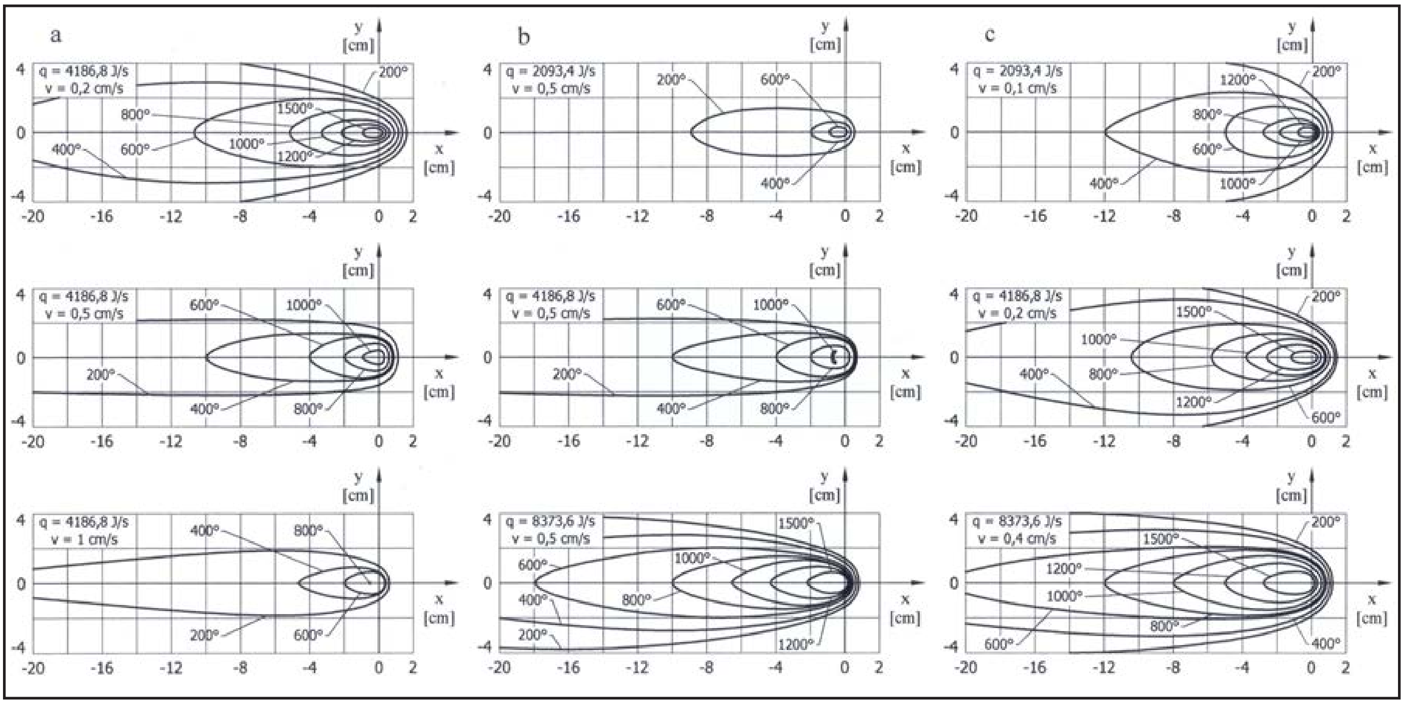

Fig. 2. Nearly stabilised thermal field in relation to various welding parameters [11]

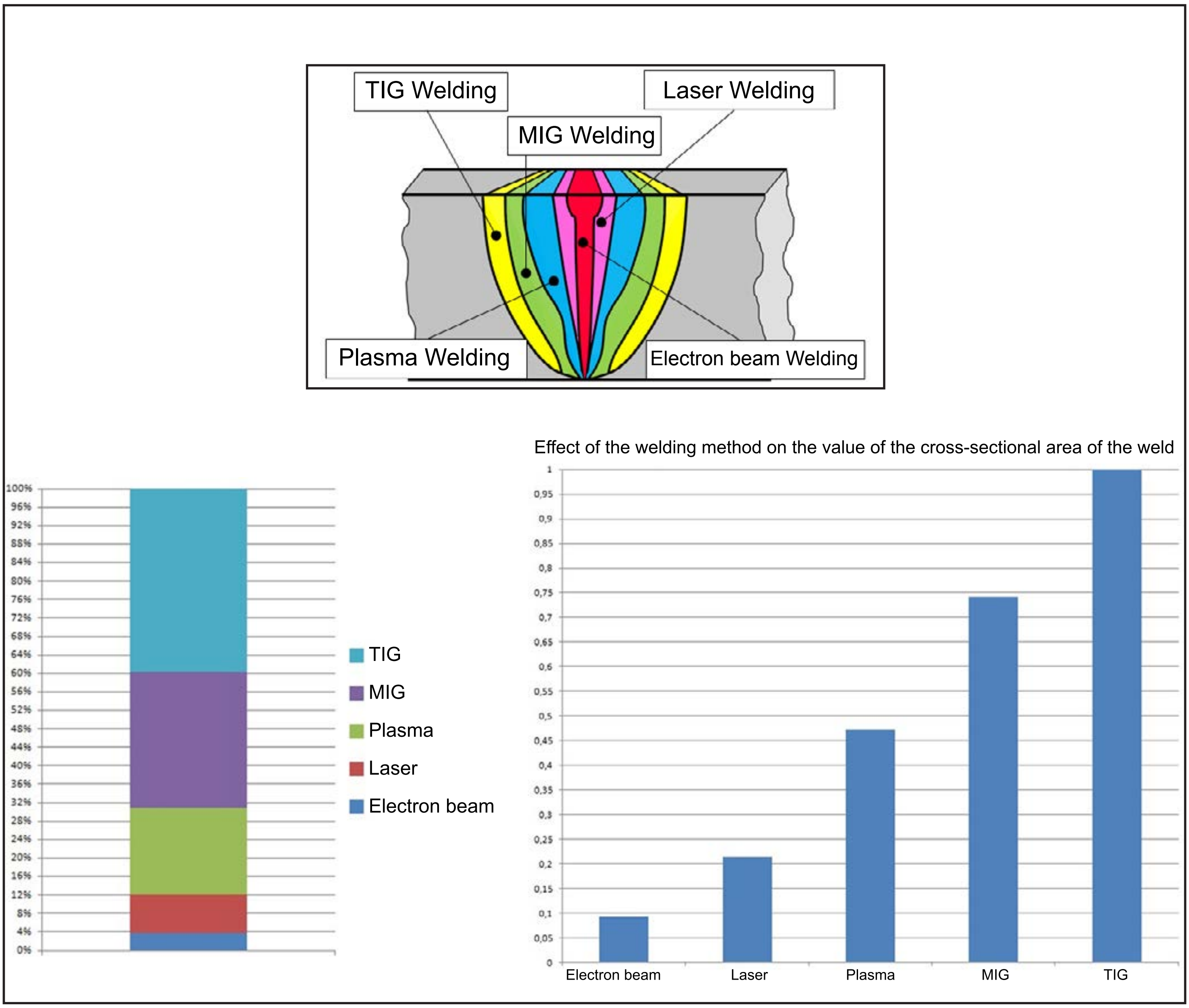

Fig. 3. Comparison of heat input supplied during TIG, MIG, plasma, laser and electron beam welding [14]

development of dependence (3) commonly known in the USA in relation to fillet welds [1]:

$$z = \sqrt{\frac{E_l}{500}} \tag{3}$$

where z – weld side [in inches], E_l – welding linear energy [kJ/cal].

The authors of the above-presented formula realised that the size of a weld also depends on other variables such as the type of a welding process or current polarity.

The direction of research resulting in the strict dependence of the weld pool size on thermal energy actually used to create this pool seems appropriate, yet colliding with dependence (1). The authors of publication [11] demonstrated it is possible to obtain variously sized weld pools using the same welding linear energy identified using dependence (1) (Fig. 2).

The authors of the publication mentioned above explained the obtainment of variously sized weld pools using the same welding linear energy by various effects of welding current and the linear rate of the welding power source on heat input to the weld. However, the above-presented explanation precludes the possibility of using the linear energy defined by dependence (1) as the universal and primary welding process parameter.

In order to solve the above named paradox, the Welding Department of the Częstochowa University of Technology undertook multi-directional research including analyses of current quantities and thermal traces after welding and surfacing [2÷8, 12, 13, 15]. These analyses led to the conclusion that the volume of a weld/overlay weld obtained in the process of welding/surfacing should be strictly associated with the actual heat input to the material subjected to welding/surfacing.

All "external" process parameters do not matter as welded products exclusively contain the volume of material (limited by the fusion line) undergoing melting followed by recrystallisation and leading to the formation of the heat affected zone (HAZ), as demonstrated in Figure 1. Therefore, the unequivocal criterion of welding/surfacing linear energy could be the volume of material melted by this energy or its representation assuming the constant welding rate, i.e. the cross-sectional area of the weld/overlay weld within elements subjected to welding or surfacing. Such a manner of ordering the heat input to materials subjected to heat treatment makes it possible to unequivocally order linear energy used in various welding procedures. This manner enables the comparison of heat inputs obtained using electric and non-electric as

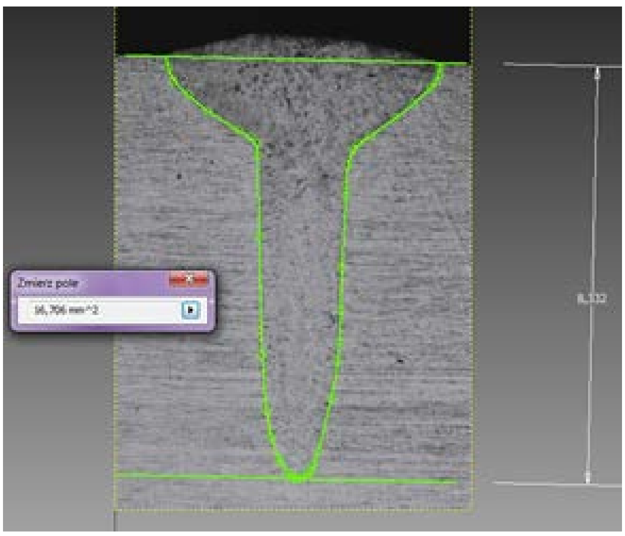

Fig. 4. Planimetric measurement of the area of the butt weld made using electron beam welding; the measurement was performed using the Autodesk Invertor Professional software programme – student's version

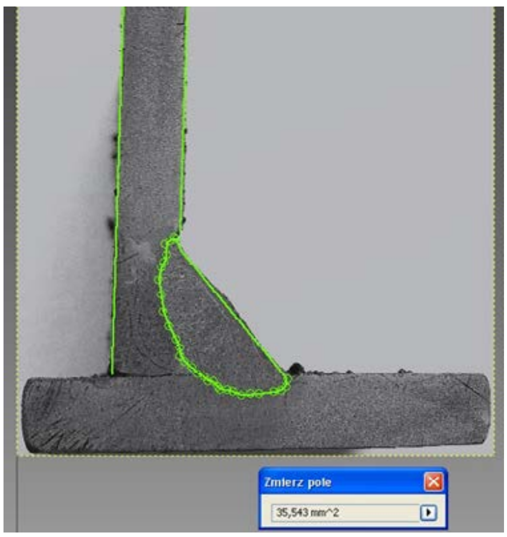

Fig. 5. Planimetric measurement of the area of the fillet weld made using the MAG method; the measurement was performed using the Autodesk Invertor Professional software programme – student's version

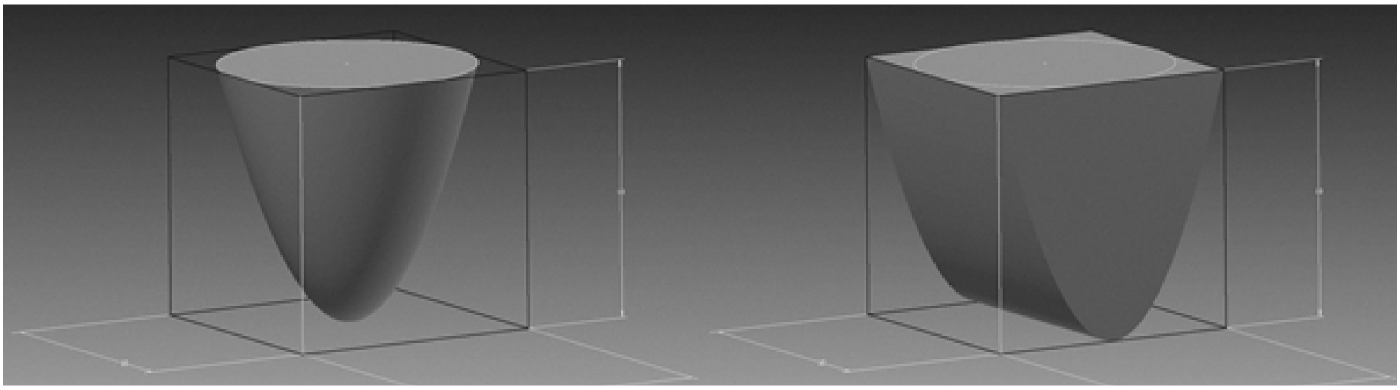

Fig. 6. Manner of assessing the heat input during spot welding

well as arc and non-arc methods and include hybrid methods, spot welding (!) and various surfacing technologies in the comparison. For instance, it is possible to compare linear energy related to TIG, MIG, plasma, laser and electron beam welding (Fig. 3) [14].

The ordering can concern both butt and fillet welds (Fig. 4 and 5). At the same time, the classification can also include heat input during spot welding (Fig. 6).

After adopting the presented manner of assessing linear energy, weld cross-sectional areas can be treated as the heat input equivalent when developing welding-related standard values, eliminating errors still existing in them (Fig. 7) [15].

However, the method of assessing the linear energy of welding/overlay welding is characterised by several disadvantages:

– it requires the performance of the planimetric measurement of the weld/overlay weld cross-sectional area;
– single and multilayer welds as well as welds made using various techniques having the same cross-sectional area can have different structures, HAZs and mechanical properties, therefore they should be differentiated using another manner than that based on welding linear energy,
– linear energy values used when making welds joining materials characterised by different physical properties, i.e. specific heat or thermal conductivity, should be compared taking into consideration the above named criteria.

As most welding operations are concerned with steels, the specific heat and thermal conductivity of which are similar, the above-presented reservations should not preclude the implementation of the proposed method enabling the assessment of welding linear energy. In order to

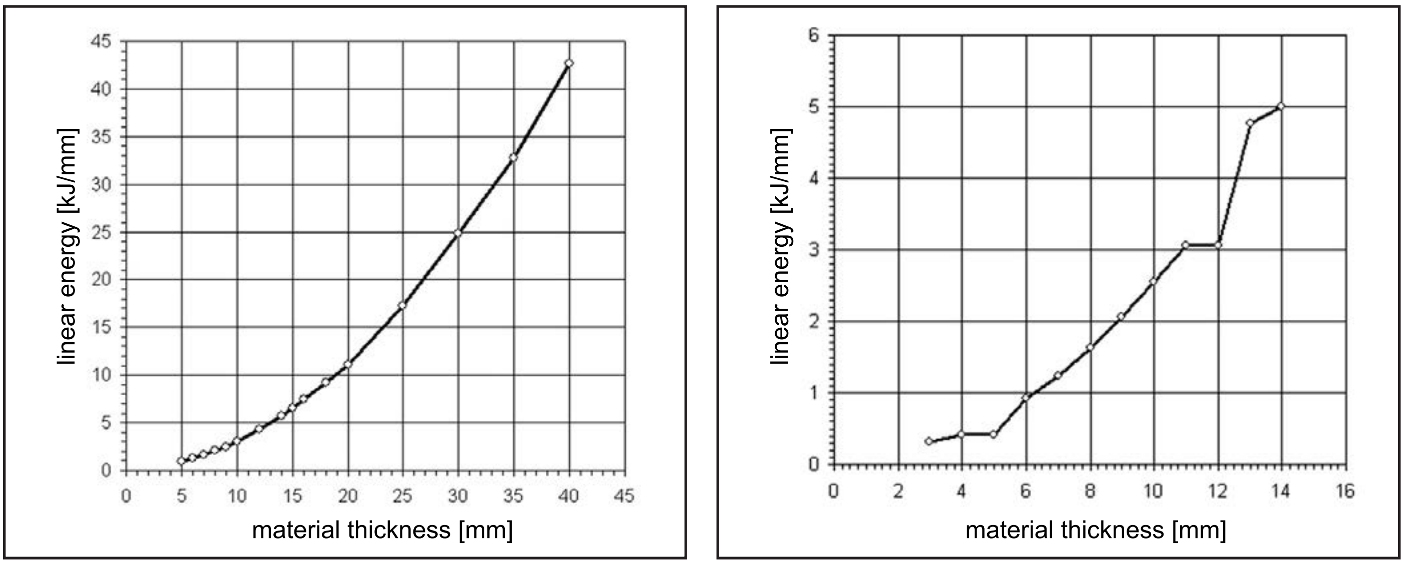

Fig. 7. Change in linear energy when welding unalloyed and low-alloy structural steels, a – standardising through the measurement of cross-sectional areas, b – standardising through the estimation of external parameters [15]

put the present state in order, it is worth putting effort into redefining welding linear energy so that this parameter could become really useful and acceptable in each situation requiring the application of strictly specified heat input to elements being welded, regardless of technology and welding parameters. The present state is illustrated by Table 1 demonstrating the estimation of linear energy in today's engineering practice; the table contains a selection of data presented in Przegląd Spawalnictwa (Welding Technology Review) and Biuletyn Instytutu Spawalnictwa (Bulletin of Instytut Spawalnictwa) in recent years. The table presents a comparison

Table 1. Estimation of linear energy in today's engineering practice

No.	Cross-sectional area of weld, mm²	Linear energy according to authors of publications, kJ/mm	Welding/surfacing procedure	Type of weld/ overlay weld	Linear energy according to proposed concept, kJ/mm	Source
1	2	2	2	5	6	7
1.	4.708	1.5	MAG	Overlay weld	1	Przegląd Spawalnictwa 2/2016
2.	4.741	0.8	MAG	Overlay weld	1.007	Przegląd Spawalnictwa 2/2016
3.	5.598	8.3 (J/m)	MAG	Overlay weld	1.189	Biuletyn Instytutu Spawalnictwa 1/2014
4.	6.626	0.32	PLASMA	Butt weld	1.207	Biuletyn Instytutu Spawalnictwa 2/2016
5.	7.637	2.4 (J/m)	LASER	Overlay weld	1.622	Biuletyn Instytutu Spawalnictwa 1/2014
6.	8.599	0.48	PLASMA	Butt weld	1.826	Biuletyn Instytutu Spawalnictwa 2/2016
7.	9.926	0.8	MAG	Overlay weld	2.108	Przegląd Spawalnictwa 2/2016
8.	13.835	1.5	MAG	Overlay weld	2.239	Przegląd Spawalnictwa 2/2016
9.	19.972	5.7 (J/m)	HYBRID (LASER + MAG)	Overlay weld	4.242	Biuletyn Instytutu Spawalnictwa 1/2014
10.	54.137	1.12	HYBRID (PLASMA + MAG)	Butt weld	11.499	Przegląd Spawalnictwa 1/2016

of linear energy calculated conventionally (column 3) and its estimation based on the planimetric method. The smallest melting area was adopted as 1 (column 2 and 6) and was used as the reference for all the remaining areas of welds and overlay welds expressed proportionally in kJ/mm (column 6).

Conclusions

1. The previously used method of estimating the heat input to materials subjected to welding and surfacing does not meet today's technological requirements.

2. The assessment of heat input through the measurement of the cross-sectional areas of welds or overlay welds enables the comparison of the actual thermal efficiency of various welding and surfacing procedures.

3. The method presented above could prove particularly useful when assessing modern, i.e. hybrid, impulse and spot, welding procedures.

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