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Thermal Coefficients of the GTAW Process

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Abstract

The paper presents a discussion on the issue of thermal efficiency of the process of superficial remelting of castings by means of the gas tungsten arc welding (GTAW) process. Described and characterized are calorimeters used in research studies on efficiency of welding processes and the obtained results. Example results are presented from the measurements aimed at determination of thermal efficiency of the welding process carried out with the use of the flow calorimeter.

Keywords: Thermal efficiency, Remelting, Flow calorimeter

1. Introduction

Numerous industrial manufacturing processes involve application of structures welded out of cast components. The structure and service properties of welded joints depend on chemical composition and structure of joined cast iron components, phase transitions, width of the heat-affected zone (HAZ), chemical composition of the liquid metal pool, and conditions prevailing in the course of primary solidification of the casting alloy.

Conditions of primary crystallization of the weld material depend significantly on the quantity of introduced heat energy, geometry of remeltings, and cooling conditions.

In scientific research projects carried out for practical purposes it is important to gain knowledge of the effect of quantity of the introduced heat energy on geometry and structure of the weld as well as width and structure of HAZ at determined cooling conditions. Therefore, it is an essential issue to be able to determine the actual quantity of heat intercepted by the heated material in the course of scanning with a stream of heat energy.

2. Heat balance of the GTAW process

In the course of electric arc welding with the use of tungsten electrode in a gas shield, the heat supplied to the heated surface is carried by a stream of fast electrons and a jet of ionized gases.

A heat balance of the GTAW process proposed by Du Pont and Marder [1] is shown schematically in Fig. 1.

Most of the overall heat amount is generated in the electric arc (Q_{arc}), and only small quantity of heat (Q_e) occurs in the electrode. A portion of the generated heat Q_{env} is transferred to the environment, and another portion $Q_{mat} + Q_{pool}$ penetrates the heated material. The heat intercepted by the material is used partly to create the liquid metal pool Q_{pool}, while the remainder Q_{mat} penetrates deep into the material. The quantity of heat penetrating into the material depend on its thermophysical properties and the period of interaction of the electric arc.

The welding process thermal efficiency is a measure of heat effectiveness of the welding operation defined as a percentage fraction of the total heat intercepted by the heated material:

$$\eta = (Q_{mat} + Q_{pool})/Q \times 100\% \quad (1)$$

The key issue in heat efficiency calculations consists in determining the quantity of heat intercepted by the scanned surface.

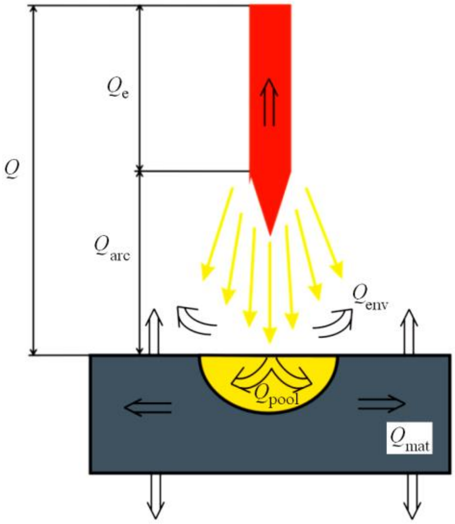

Fig. 1. Heat energy distribution in the GTAW process. Q — total amount of heat generated in the GTAW process; Q_{arc} — amount of heat generated in electric arc; Q_e — heat generated in electrode; Q_{env} — amount of heat transferred to the surrounding environment, Q_{pool} — quantity of heat necessary to heat up and remelt the material, and then overheat the liquid metal pool; Q_{mat} — amount of heat conducted to the native material and possibly radiated out from its surface; thus Q_{mat} + Q_{pool} — the quantity of heat intercepted by the heated element

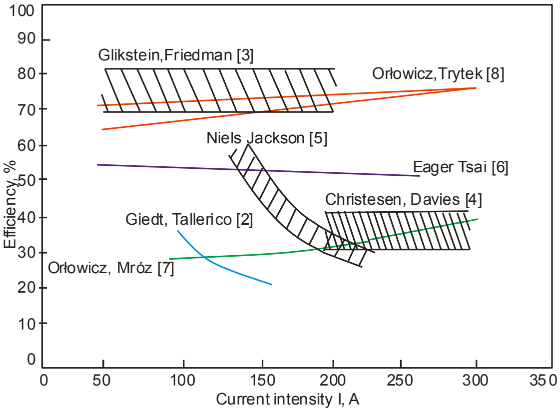

Fig. 2. A comparison of published calculation and measurement results concerning thermal efficiency of welding processes

There are two methods, numerical and calorimetric, that can be used to calculate the amount of heat introduced to the heated material. The numerical method is based on equations of the temperature field developed on the grounds of adopted heat source models and heat concentration. Calculated values are however always ambiguous in view of the fact that the values of thermophysical parameters adopted for calculations differ sometimes significantly from actual ones being the quantities difficult to determine by their nature. Therefore, results of calculations concerning the quantity of heat introduced to the heated material should be verified by means of calorimetric methods.

Example results of calculations concerning calorimetric parameters characterizing thermal efficiency of welding processes are shown in Fig. 2.

3. Calorimeters for studies on heat parameters in welding processes

Technical literature offers very little studies concerning calorimetric measurements of welding processes. Various measurement techniques are used for this purpose. For instance, Havalda [9] has placed a specimen for pad welding over a table of water filling a calorimetric vessel (Fig. 3). A suitable holding mechanism allowed to immerse the specimen in water immediately after completion of the run and close the cover. Based on the water equivalent of the calorimeter determined earlier (the heat quantity corresponding to the increase of temperature of water filling the calorimeter vessel by 1°C) and measurements of water temperature increase at the outlet, the amount of heat introduced to the calorimeter was established. In the measurements, heat quantities used to evaporate water as a result of interaction of the electric arc and in the course of immersing the specimen were taken into account.

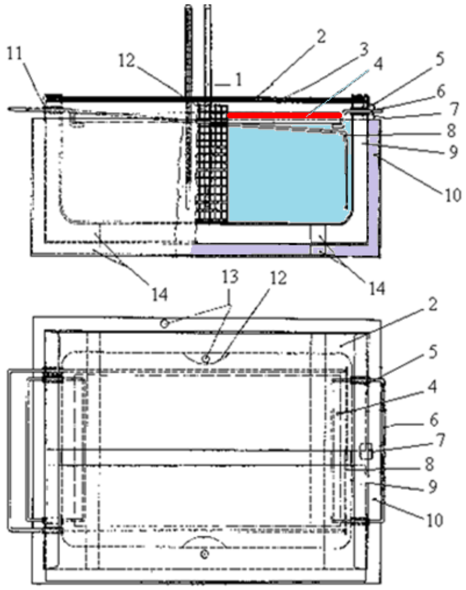

Fig. 3. Havalda’s calorimeter. 1 — thermometer; 2 — calorimeter cover; 3 — gasket, 4 — sample; 5 — holder guides; 6 — sample holders; 7 — plug; 8 — agitator; 9 — inner insulated shell; 10 — outer removable water jacket; 11 — agitator guide; 12 — thermometer shield; 13 — thermometer bores; 14 — base

Du Pont and Marder [1], Giedt, Tallerico and Fuerschbach [2], Niles and Jackson [5], and Eager and Tsai [6] have published results of calorimetric studies concerning the process of remelting steel specimens with the use of the Seebeck envelope calorimeter (Fig. 4).

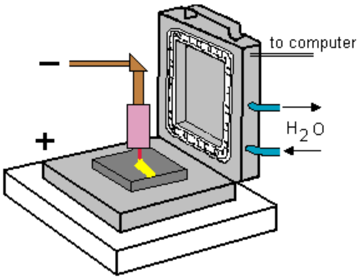

Fig. 4. The Seebeck envelope calorimeter

With the calorimeter cover open, a segment of remelting was performed on a plate placed on the calorimeter base. Next, the cover was closed. Properly oriented heat flow in the base and in the cover was forced by water flow in cooling ducts. The temperature drop across calorimeter walls was also assessed and measured by means of sets of thermocouples.

The voltage values obtained from the system of thermocouples multiplied by a calibration constant taking into account the calorimeter material heat conductivity and thickness of the layer on which the measurements were carried out allowed to measure the quantity of heat introduced to the specimen. The measurement period was 6 hours. It has been assumed that heat losses on account of radiation and convection were at the level of 1% of the energy supplied by the arc.

Krzyżanowski [10] used a flow calorimeter in the from of a rotating cylinder made of sheet brass (Fig. 5). In the course of measurements, outer surface of the cylinder was scanned. The quantity of introduced heat was estimated by measuring the water flow through the cylinder and increase of its temperature measured at the calorimeter outflow.

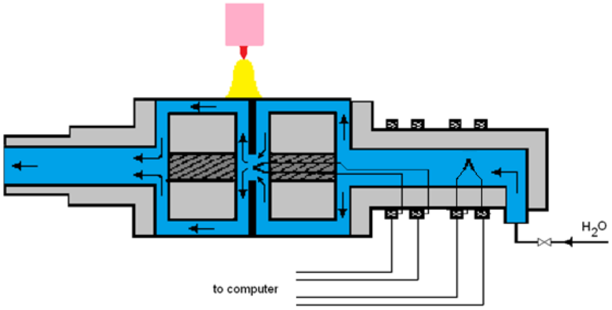

Fig. 5. Krzyżanowski’s calorimeter

Papers [7, 8] report on the use of a flow calorimeter in the form of a tank made of a transparent plastic (Fig. 6). The remelted specimen was placed at the top. Water flowing through the calorimeter lipped the bottom surface of the specimen. Water flow rate monitored with the flowmeter was selected so that neither turbulence nor gas bubbles were observed on the specimen-water boundary. Water was supplied via a slit-shaped inflow. Water temperature was measured at both inlet and outlet conduits. Actual measurements were started after stabilization of the outflowing water temperature which occurred typically after several seconds from the start of the specimen remelting process.

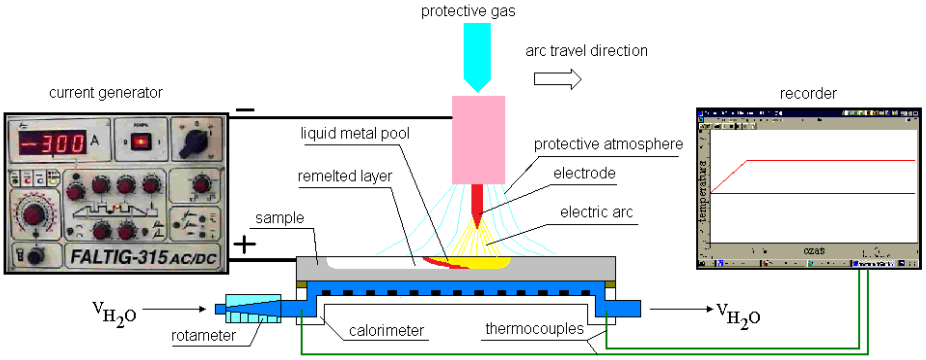

Fig. 6. An outline of the set-up for measurements with the use of flow calorimeter

Once the quantity of heat introduced to the remelted specimen is determined by means of calorimetric measurement, thermal efficiency η of the process is calculated from the formula:

$$\eta = \frac{Q_{cal}}{U\,I\,t} \tag{2}$$

where: Q_k - amount of heat intercepted by the calorimeter in the course of performance of an assumed remelting (bead) length; (J); U - electric arc voltage (V); I - current intensity (A); t - electric arc scanning period required to perform an assumed remelting (bead) (s).

Parameters of the welding process should be selected in a way allowing to maximize the thermal efficiency and melting efficiency value, reduce energy losses, and minimize width of the heat-affected zone.

The melting efficiency η_t characterizes the degree to which the heat intercepted by the material is utilized to form a remelting run with unit length. It can be calculated from the formula

$$\eta_{\mathrm{t}} = \frac{Q_{\mathrm{pool}}}{Q_{\mathrm{pool}} + Q_{\mathrm{mat}}} \tag{3}$$

$$\eta_{\mathrm{t}} = \frac{V_{\mathrm{n}} \rho Q_{\mathrm{H}}}{Q_{\mathrm{cal}}}$$

$$Q_{\mathrm{H}} = Q_{\mathrm{t}} + \int_{T_{\mathrm{amb}}}^{T_{\mathrm{melt}}} c_p dT \tag{4}$$

where: V_{n} — remelting volume (mm^3); ρ — alloy density (g/mm^3), Q_{H} — heat required to heat a unit alloy volume from ambient temperature T_{amb} up to the melting point T_{melt} and to melt it (J/ mm^3); Q_{t} — heat of fusion (J/g), c_p — specific heat (J/gK).

4. Example results of welding process efficiency tests with the use of flow calorimeter

Example results of the study on the effect of distance between the tungsten electrode face and the ductile cast iron plate surface on the quantity of heat released in electric arc, amount of heat intercepted by the specimen, and thermal efficiency of the GTAW process are presented in Fig. 7. The study was carried out within the electric arc length range securing stable burning.

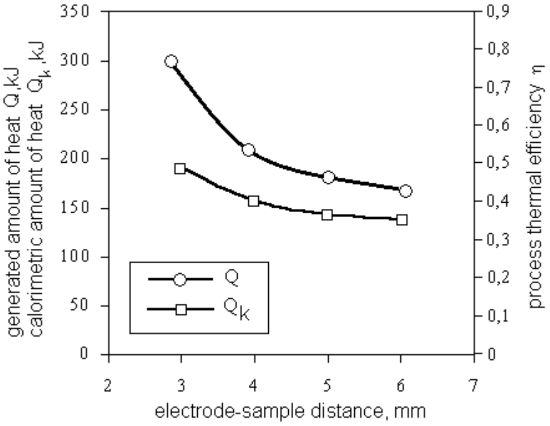

Fig. 7. The effect of distance between the tungsten electrode face and the ductile cast iron plate surface on the amount of heat intercepted by the specimen Q_{int} and thermal efficiency η of the GTAW process (tungsten electrode with diameter ø = 2.4 mm, argon atmosphere, gas flow rate 8 l/min, arc current intensity I = 300 A, arc scanning speed v_{s} = 200 mm/min)

It has been found that in the used range of electric arc lengths, the highest thermal efficiency of the process was obtained for the 3-mm long arc. The use of shorter arc was connected with excessive deflection of the liquid metal pool table, whereas increased length of the arc meant high heat losses.

Results of tests aimed at determining the effect of the welding current intensity on thermal efficiency and melting in the GTAW process used to superficially remelt ductile cast iron samples are presented in Fig. 8.

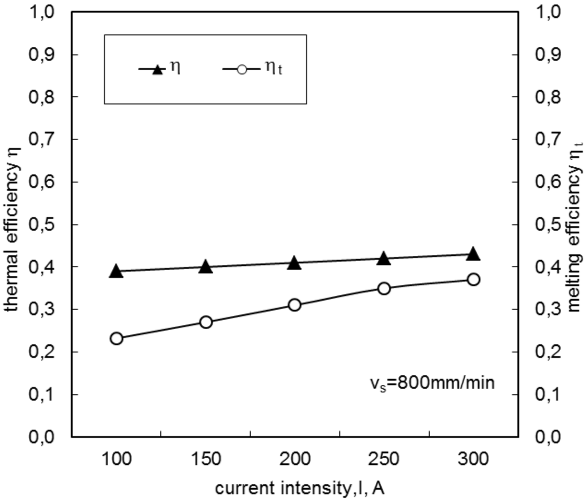

Fig. 8. Thermal efficiency coefficients η and η_{t} of the GTAW process as functions of the current intensity. Process parameters: argon atmosphere, gas flow rate 8 l/min; tungsten electrode with diameter 2.4 mm; current intensity I = 100–300 A; scanning speed v_{s} = 800 mm/min

It has been found that at constant speed of scanning with the electric arc, increase of the welding current intensity has a small effect on thermal efficiency and slightly more noticeable effect on the melting efficiency.

Results of tests aimed at determination of the effect of the rate of scanning with electric arc on heat efficiency and melting efficiency in the GTAW process used to superficially remelt ductile cast iron samples are presented in Fig. 9.

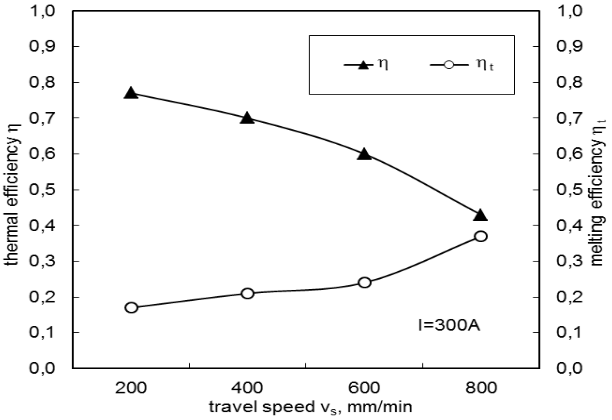

Fig. 9. Thermal efficiency coefficients η and η_{t} of the GTAW process as functions of the electric arc scanning speed. Process parameters: argon atmosphere, gas flow rate 8 l/min; tungsten electrode with diameter 2.4 mm; current intensity I = 300 A; scanning speed v_{s} = 200–800 mm/min

It has been found that thermal efficiency of the GTAW process decreases with increasing electric arc scanning speed. On the other hand, the melting efficiency increases with increasing electric arc scanning speed which can be attributed to the short time in which the heat flows deep into the material.

Author of the study [11] has collected a number of calculated and measured values of the GTAW process thermal efficiency published in the period 1955–2011 (Table 1).

Table 1.
Results of studies on thermal efficiency of the GTAW process collected by the author of [11]

No.	η	Material	Ref.
1	0.60–0.78	Armco iron	[12]
2	0.80–0.90	Copper anode	[13]
3	0.36–0.46	Mild steel	[14]
4	0.58–0.83	Steel	[15]
5	0.77–0.90	Mild & stainless steel	[16]
6	0.80–0.90	Copper anode	[17]
7	0.79–0.84	Stainless 360L	[2]
8	0.80–0.85	Stainless & Ni200	[18]
9	0.62–0.72	A36 Steel	[1]
10	0.66–0.77	Spheroidal cast iron	[19]
11	0.76–0.89	Aluminum	[20]
12	0.63–0.77	Copper Anode	[21]

The above-quoted author has found that the presented thermal efficiency values fall into the range between 0.36 and 0.90. The obtained data allowed to state that thermal efficiency of the process decreases with increasing length of electric arc, which can be explained by larger heat losses to the environment. On the other hand, the author notes that the collected source data are ambiguous as far as the effect of current intensity and welding speed on thermal efficiency values is concerned. It seems to be quite likely that contradictory results of different studies are connected to adoption of different research methodologies and the use of calorimeters which are characterized with excessive heat losses to the environment. Such problems can be minimized by using the calorimeter described in patent [22] (Fig. 10) which is an improved version of the calorimeter used for studies reported in [7, 8, 19].

5. Conclusions

Improved precision to which thermal efficiency of the welding process can be evaluated is of large importance for designing welding processes and monitoring their correctness.

A new flow calorimeter presented in this paper has been successfully used for assessment of the effect of the electric arch length, the welding current intensity, and the electric arc scanning speed in the process of remelting of cast iron, aluminum alloys, cobalt alloys, and steel by means of TIG method and for examination of the effect of parameters characterizing the laser steel remelting process on its thermal efficiency and melting efficiency.

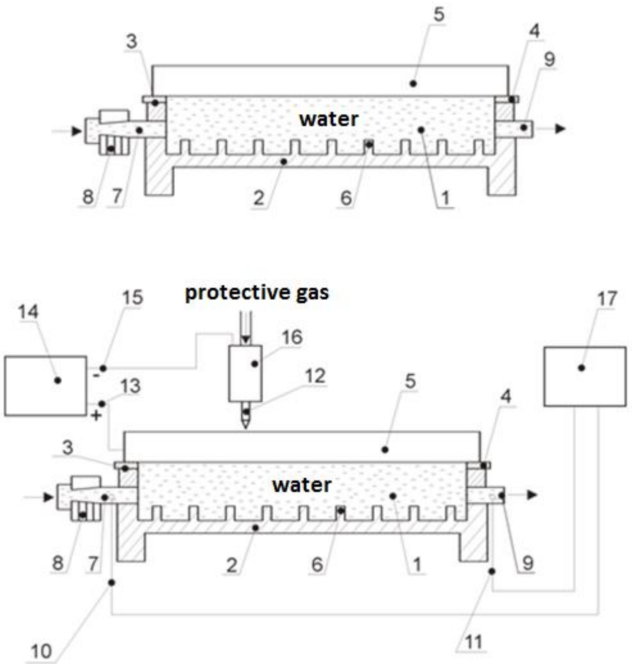

Fig. 10. Construction of the flow calorimeter dedicated to heat measurements in welding processes, patent No. 211283 [22]. 1 — water; 2 — flow chamber; 3 — chamber's upper edge; 4 — gasket; 5 — remelted specimen; 6 — partitions; 7 — water inlet conduit; 8 — flow rotameter; 9 — water outlet conduit; 10, 11 — thermocouples; 12 — tungsten electrode; 13 — positive pole; 14 — current source; 15 — negative pole; 16 — shielding has holder; 17 — temperature recording

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