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TOWARDS THE SPECIFICS OF DISTRIBUTION OF HEAT FLOWS IN NEAR-WELD ZONE IN SUBMERGED ARC WELDING (CALCULATED AND EXPERIMENTAL DETERMINATION OF THERMO-PHYSICAL PROPERTIES OF SOME FLUXES)

Анотація

Представлені результати дослідження теплоємкості зварювальних флюсів. Розроблено установку, методику калориметрії сипучих матеріалів. Виконано термодинамічні розрахунки теплоємкостей. Показано, що теплоємкості флюсів приблизно вдвічі перевищують теплоємкість низьковуглецевої сталі. Пропонується враховувати це явище в теплових розрахунках при зварюванні.

Abstract

The results of study of heat capacity of welding fluxes are shown. Special welding equipment and the method of calorimetry of bulk materials were developed. The thermodynamic calculations of heat capacity were done. It was shown that the heat capacity of fluxes approximately twice exceed the heat capacity of low-carbon steel. It was proposed to consider this phenomenon during thermal calculations in welding.

Introduction

Calculation of temperatures in near-weld zone in submerged arc welding is accepted to fulfill using the general (standard) diagrams of heating taking into account only the fact that in case of a submerged arc the effective efficiency factor of arc is taken somewhat higher than that in other methods of welding, sometimes approaching this value almost to unity (Рыкалин, Н., Rosenthal, D., Christensen, N., Myers, S. [1-4]) .

According to standard calculation schemes and also to more complicated ones in which the distributed heat sources are used (normal-circular, volume, Goldak, J.

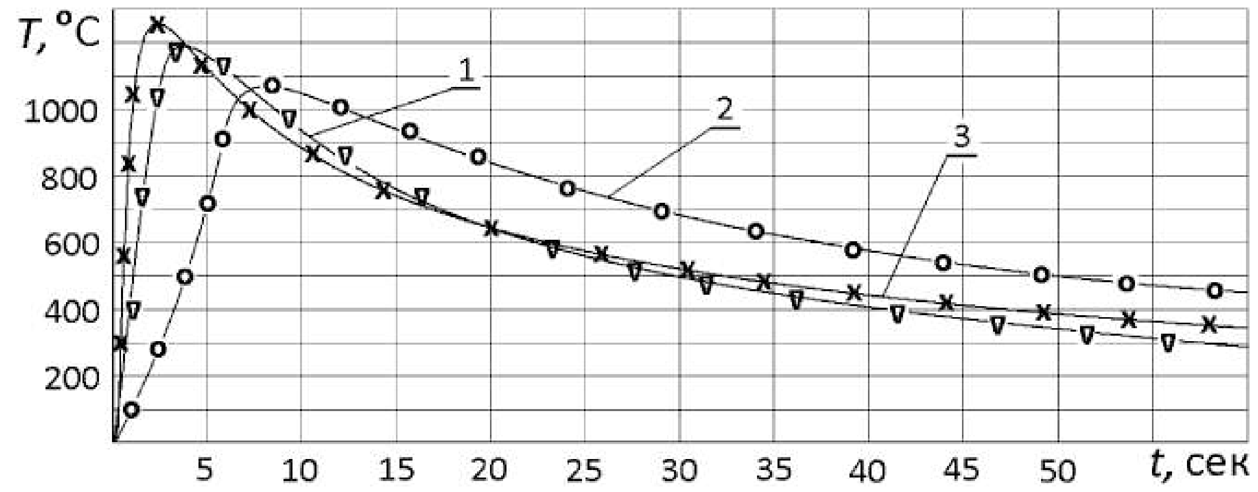

Fig. 1. Comparison of typical thermal cycles (Welding of plates of low-carbon steel of 8 mm thickness, 407 A current, 29 V voltage, point is located at 2 mm from fusion line)

1 — experiment: CO_2 welding with activated wire; *2* — experiment: mechanized welding using flux АН-348А; *3* — calculation: using scheme of powerful quickly-moving heat source in plate with a heat dissipation

[5]), the calculation schemes deal with heat flows from heat source to the parts being welded and further those inside them, irrespectively to specifics of heat exchange with environment. This heat exchange is either neglected (in schemes of mobile and powerful quickly-moving heat sources on the surfaces of massive bodies), or considered as a value being known and constant (implying the heat exchange with air, whose heat conductivity is much lower than heat conductivity of metals and alloys).

Calculations of temperatures in near-weld zone in mechanized submerged arc welding, made by authors over a long period, and experimental data obtained by us, show the radical systematic discrepancies between experiment results and calculated values. They are shown in a generalized form in Figure 1.

Experimental curve of temperatures change in case of submerged arc welding (2) shows always the significantly lower maximum values of temperatures, rates of heating and cooling as compared to calculations. It is evident that the real distribution of heat flows in submerge-arc welding significantly differs from premises, accepted in calculation schemes.

Really, in submerged arc welding for one pass of plates, for example of 8—12 mm thick, the thickness of flux layer can be 20 mm, and, sometimes, even larger (Figure 2) [6].

It is seen that in this case the flux isolates the place of welding from atmospheric air, thus radically changing here the heat exchange conditions. During welding the intensive heating firstly occurs both of a workpiece Q_1, and also a bulk flux $Q_2\uparrow$ (Figure 2a). Heat transfer from metal to flux granules is not surely so intensive as inside the metal. But even the simple logic of common sense assumes that it should be much higher than the heat dissipation from metal to air (because the flux is a solid body, or liquid near the weld axis). After arc passing the intensive leveling of temperatures is occurred. Moreover, due to high heat conductivity of metal and much lower assumed heat conductivity of flux (nonmetal), the direction of flux-metal heat flow should change for the opposite one $Q_2\downarrow$ (Figure 2 b).

The known methods of calculation of temperature fields in welding (Рыкалин, Н., Rosenthal, D., Goldak, J. et.al [7, 8, 5]) do not take into account in any way the effect of flux which undertakes a part of heat flows in welding heating limiting either by imparting the adiabatic properties to boundaries surfaces of workpiece or giving the heat exchange of boundaries surfaces with air by Newton's law [9]. But it is evident that in cases when the mass of the auxiliary welding material, i.e. flux, is commeasurable with a mass of metals being welded, the mentioned methods of calculation of temperatures in the zones of welding heating are not able to give a real result.

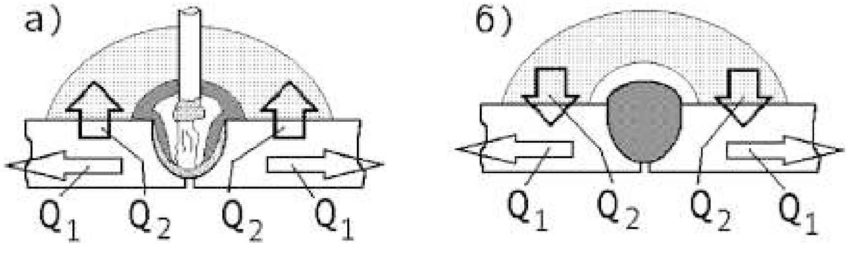

Fig. 2. Distribution of heat flows during submerged welding

At the same time, the calculations, which could account for the capability of flux to absorb or dissipate the heat in welding heating and subsequent cooling, cannot be fulfilled without knowledge of real thermo-physical properties of flux as a bulk granulated material.

Table 1

Example of calculation of heat capacity of welding flux

AH-348A	SiO_2	MnO	Al_2O_3	Fe_2O_3	CaF_2	CaO	MgO
Mass fraction of component[1]	0.4	0.32	0.06	0.02	0.05	0.1	0.05
Molecular mass of component [11], A.m.u.	60	72	102	160	78	56	40
Molecular fraction of component	0.430	0.286	0.037	0.008	0.041	0.115	0.080
Table molar heat capacity of component [12], J/(kg-mole·K)	44480	44830	79000	103700	67030	42800	37410
Table mass heat capacity of component (recalculation), J/(kg·K)	741.3	622.6	774.5	648.1	859.4	764.3	935.3
Fraction of component in general heat capacity of flux substance proportional to a mass one	296.5	199.2	46.5	13.0	43.0	76.4	46.8
Calculated heat capacity of flux (additively: total sum of components)					721.4 J/(kg·K)		

Note: 1) Averaged values from data of chemical compositions of different literature sources [13-16]

Theory and calculations

The first this property, which is encountered at the attempts of realistic calculations of temperature fields in automatic submerged arc welding, is the flux heat capacity. However the authors did not manage to find any information about heat capacities of welding fluxes, used in practice, in available literature.

Theory allows calculating the heat capacity of flux, as well as of any other solid or liquid substance by thermodynamic methods [10], using for example the law of Dulong-Petit for molecular substances and law of additivity for their mixtures.

Example of such calculation for most widely-spread welding flux AH-348A is given in Table 1:

Similarly, it is possible to determine theoretically the probable values of heat capacities also for other welded fluxes (see Table 3).

However, the thermo-dynamic method of calculation makes it possible to determine the thermo-physical properties of substances only as monolithic — solid (indissoluble) media. Moreover, these calculations do not account in any way for possible interaction between flux components (with formation of new substances), as well as a rather high probability of formation of regular structures in the flux substance [17]. It is evident that these factors, as well as physical state of granulated mixture, which is the welding flux at its application, will produce the final properties somewhat different from properties of a monolithic homogeneous mixture of components. These differences can be determined only experimentally. These experiments were made by the authors.

Experiments

The experiments were conducted using water calorimeter (20 kg of distilled water in the vessel of thin-sheet brass). The principal of experiment consisted in the following: the portion of flux of known volume and mass was heated in furnace up to the specified fixed temperature and placed into the calorimeter (into water). The difference of temperatures of water in calorimeter before and after pouring of flux there was measured, which allowed judging about amount of heat, put into the calorimeter by a portion of flux. In its turn, this gave an opportunity to determine the heat capacity of a flux portion, considering that it was cooled in the process of experiment from the heating temperature in furnace down to the temperature of calorimetric liquid (which was accepted equal to the temperature in the room, where experiment was held).

At the first stage the following industrial fluxes in as-delivered state were investigated: AH-348A, AH-44, AH-45, AH-60. The amount of flux being investigated was controlled by a bulk volume, which was 80.0 ml. In this case the bulk mass can be different depending on the type of flux and random distribution of granules in bulk mass within the ranges of 0.12...0.14 kg. The portions of fluxes were heated in a drying furnace up to temperatures ~330...370 °C, the equal temperature of heating was not required according to the experiment conditions, however for each test its initial temperature was recorded rather strictly.

The increment of temperature of calorimetric liquid was measured by a specialized Beckmann thermometer at an accuracy up to 0.01 °C and it was varied from experiment to experiment in the limits of about ΔT_l = 0.38...0.46 °C.

Temperature in the room where the experimental equipment was located, changed during the period of experiments within the ranges from T_0 = +15 °C to T_0 = +18 °C. Moreover, the trend of changing the temperature of calorimetric liquid inside the calorimeter amounted to the value of not more than ~$1{,}7 \cdot 10^{-4}$ °C/min at duration of the procedure of calorimetry proper of 15...20 minutes.

These parameters of the calorimeter allowed accepting the process of calorimeter in the first approximation as isentropic, and this, in turn, gave the opportunity to simplify the equation of heat balance to the form:

$$Q_l + Q_m + Q_v = Q_f - Q_{loss}$$

where: Q_l is the heat absorbed by calorimetric liquid:

$Q_l = m_l \cdot c_l \cdot \Delta T_l$, where: m_l is the mass of calorimetric liquid (water, m_l = 20 kg); c_l is the specific heat capacity of calorimetric liquid (water, c_l = 4184 J/(kg·K)) [9]; ΔT_l is the increment of temperature of calorimetric liquid;

Q_m is the heat absorbed by metallic parts of calorimeter:

$Q_m = m_m \cdot c_m \cdot \Delta T_m$, где: m_m is the mass of metallic parts of calorimeter (vessel for water and mixer, made of thin-sheet brass, m_m = 2,54 kg); c_m is the heat capacity of metallic parts of calorimeter (brass, c_m = 394 J/(kg·K) [11]); ΔT_m is increment of temperature of metallic parts of calorimeter: $\Delta T_m = \Delta T_l$;

Q_v is the heat, lost for vapor formation, at the moment of heated flux immersion into water this parameter was determined from the sum of many experiments, averaged and taken equal for all experiments: Q_v = 1120 J.

Q_{loss} are the losses of heat by a flux portion during transfer from furnace into calorimeter, which were determined by the Newton law [10]: $Q_{loss} = \alpha \cdot (T_{in} - T_r) \cdot F \cdot t$, where: α is the coefficient of full-surface heat dissipation was determined by the authors experimentally for welding consumables, like fluxes [18] and in these series of experiments was taken as: for light grades of fluxes (type АН-45, АН-60) α = 65 J/(s·m²·K), for dark grades of fluxes (type АН-348А, АН-44) α = 75 J/(s·m²·K); T_{in} is the initial temperature of flux portion (temperature of its heating in furnace); T_r is the temperature in room where the experiment took place; is the area of flux pouring, dissipating heat into air in transfer to calorimeter (it was taken as F = 0,02 m² for all test portions of fluxes; t is the time of transfer of flux portions from furnace to calorimeter (taken equal in all cases t = 2 s — by the lowest index);

Q_f is the heat accumulated by a flux portion in furnace during heating:

$Q_f = m_f \cdot c_f \cdot \Delta T$, where: ΔT is the difference of temperatures of flux at the beginning of measurement, where: T_{in} is the temperature to which the flux portion was heated in the furnace before its placing to calorimeter; T_0 is the temperature to which the flux was cooled at the end of measurement (the final temperature of calorimetric liquid was taken equal to room temperature $T_0 = T_r$); m_f is the mass of flux portion; c_f is the heat capacity of flux, unknown value which should be determined during the experiment.

Below as an example the components of heat balance of one of experiments: flux АН-348А, are given (Table 2).

Table 2

Typical components of heat balance on the example of one of the experiments (flux АН-348А)

Flux grade	Mass of flux portion, kg	Room temperature, °C	Temperature of flux portion after furnace exposure, °C	Increment of temperature of calorimetric liquid, °C	Mass of calorimetric liquid, kg	Specific heat capacity of calorimetric liquid, J/(kg·K)	Heat, absorbed by calorimetric liquid, J	Mass of metallic parts of calorimeter (brass), kg	Heat capacity of brass, J/(kg·K)	Heat, absorbed by metallic parts of calorimeter, J	Heat of vapor formation, J	Coefficient of full surface heat dissipation, J/(s·m²·K)	Area of surface, through which convection is performed, m²	Time of transfer of flux portiona to calorimeter, s	Heat losses during time of transfer to calorimeter, J	Full heat, accumulated by flux portion in the furnace, J	Specific (mass units) heat capacity of flux, J/(kg·K)
	m_f	T_r	T_{in}	ΔT_l	m_l	c_l	Q_l	m_m	c_m	Q_m	Q_v	α	F	t	Q_{loss}	Q_f	c_f
АН-348А	0.129	17	366	0.38	20	4184	31798.4	2.54	394	380.3	1120	75	0.02	2	1047	34346	761

Similar experiments were carried out also for other grades of fluxes and the statistically sufficient result was considered using not less than seven similar experiments. The obtained results after processing are given in Table 3. This Table has also results of measurements of heat capacity of building sand, they were made as analogue to test measurements because this sand was

Table 3

Comparative results of calculations and experiments for determination of heat capacities of welded fluxes

Flux (grade) or material	Heat capacity		
	mass (calculation), J/(kg·K)	mass (experiment), J/(kg·K)	
		Average value	Absolute deviations
АН-348А	721.4	841.5	+ 45.5 – 41.0
АН-44	737.3	932.3	+ 19.1 – 20.2
АН-45	800.0	862.2	+ 5.1 – 4.2
АН-60	710.5	904.5	+ 27.3 – 34.4
Building sand (reference substance)	741.3	Reference data	
		820.0	± 15.0
Low-carbon steel (for reference)	Calculation was not performed	Reference data	
		460.5	± 7.5

occurred to be the most accessible bulk substance (by properties and consistency is very similar to welding flux), whose data about heat capacity are given in handbooks (see, for example [19]). In addition, to compare the values of Table 3 the value of specific heat capacity of conventional low-carbon steel is given [20]. This comparison did not give any benefit to the authors of calculation methods of determination of temperatures in near-weld zone in particular in submerged arc welding: heat capacity of fluxes occurred to be twice higher on average than that for steel. And evidently, that it is not efficient to neglect the phenomenon of «heat battery», which in this case is the flux in principle.

Conclusions:

1. Revealed was the significant systematic discrepancy between results of calculated and experimental determinations of temperatures in near-weld zone in automatic submerged arc welding.
2. It was found that the source of a systematic discrepancy between the results of calculated and experimental determinations of temperature in near-weld zone in submerged arc welding can be probably the presence of flux in the mass commeasurable with the mass of base metal which accumulates a part of welding arc heat in the period of heat saturation, thus decreasing the thermal effect of arc on metal, while in the period of temperatures levelling it imparts the heat to metal, thus delaying the rate of its cooling.
3. The thermodynamic calculations of probable value of heat capacity of a series of welding fluxes were made.
4. The procedure was developed, the experimental equipment was designed and manufactured for a direct calorimetric measurement of heat capacity of welding fluxes and other bulk materials.
5. Heat capacity of a series of widely-spread fluxes which occurred to be in their averaged value approximately twice higher as compared to heat capacity of conventional low-alloy steel were determined.
6. To provide the more accurate and real calculation of temperatures in submerged arc welding it is necessary to take into account adequately the phenomenon of «heat battery»: effect on distribution of heat flows of the presence of flux mass, commensurable with metal mass, but having, as was revealed, the heat capacity being twice higher than that of metal.

References

1. *Рыкалин Н. Н.* Расчеты тепловых процессов при сварке. — М: МАШГИЗ, 1951. — 358 с.

2. *Rothental D.* Theoretical Study of the Heat Cycle During Arc Welding // Welding Journal. — 1936, № 4. — P. 64—73.

3. *Christansen N., Davies V.* The temperature in Arc Welding // Brit. Welding Journal. — 1967. — V.12. — P. 45—53.

4. *Myers P., Uyehara O., Borman G.* Fundamentals of Heat Flow in Welding // Welding Research Council Bulletin. — 1967. — No.123. — July 1967. — P. 50—56.

5. *Goldak J., Chakravarti A., Bibby M.* A new finite element Model for Welding Heat sources // Welding Journal. — 1984. — V.15B. — No.6. — P. 299—305.

6. *Патон Б. Е.* Технология электрической сварки металлов и сплавов плавлением. — М: Машиностр., 1974. — 400 с.

7. *Рыкалин Н. Н.* Расчет тепловых процессов при сварке. — М: Машиностр., — 1957. — 68—69 (b). — P. 100—105.

8. *Rosenthal D.* The theory of Moving Sources of Heat and Its Application to Metal Treatments// Trans. ASME. — 1948. — No11. — P. 849—866.

9. *Балдин А. М., Бонч-Бруевич А. М.* Физическая энциклопедия // Советская энциклопедия. — № 3 (5). — С. 137—141.

10. *Казачков Е.* Расчёты по теории металлургических процессов: Учеб. пособие для вузов. — М.: Металлургия, 1988. — 272 с.

11. *Кнунянц И. Л., Зефиров Н. С.* Химическая энциклопедия // Советская энциклопедия. — № 2 (5). — С. 117—118.

12. *Гурвич Л.* Термодинамические свойства индивидуальных веществ: т. 1...4., М.: Наука. — 1978. — 1982 с.

13. *Підгаєцький В. В.* Флюси для механізованого електрозварювання, Держлітвидв., Київ, — 1961. — 92 с.

14. *Патон Б. Е., Коперсак В. Н. и др.* Флюс для дуговой сварки / Авторское свидетельство СССР. № 1230779, — 1984.

15. *Флюс сварочный плавленый марки АН-45*, Технические условия, ТУ 14-146-15-75/ Киев, — 1978

16. *Подгаецкий В. В., Кузьменко В. Г.* Сварочные шлаки, К.: Наукова думка, — 1988. — 252 с.

17. *Волков С. В., Гришенко В. Ф., Делимарский Ю. К.,* Координационная химия солевых расплавов, К.: Наукова думка, — 1977. — 329 с.

18. *Коперсак В. М., Старова Ю. О.* Розрахунок температури електрода при електродуговому зварюванні // III Всеукраїнська міжгалузева науково-техн. конф. «Зварювання та споріднені системи і технології». — К.: НТУУ «КПІ», 2010. — С. 114

19. *Стрижко В. С., Меретуков М. А.* Химическая энциклопедия // Советская энциклопедия. — Т. 2. — 117—118.

20. *Кудинов В. А., Карташев Э. М.* Техническая термодинамика — М: Высшая школа, 2000. — 430 с.