ENERGY APPROACH IN ANALYSIS OF MICROPLASMA POWDER SURFACING MODES

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A new procedure for analysis of microplasma powder surfacing modes was proposed on the basis of evaluation of the value of definite integral of welding current magnitude during the time of arc running on the item. It is realized by digital processing of signals from current and voltage sensors with galvanic decoupling from the welding circuit, registered using the analog-digital converter. Its algorithm allows evaluation of the amount of heat applied to the anode for different models of specialized surfacing equipment under the conditions of variation of welding current and of a number of stationary technological parameters, and correlating this value with micro- or macrocracking susceptibility of items from high-temperature nickel alloys in fusion welding. It is established that at limited welding current overall heat input of micropalsma arc into the anode is proportional to weld pool volume and surfacing efficiency. In the case of multilayer surfacing of airfoil edge of GTE blade from JS32 and JS26 alloys it is shown that optimization of the total amount of heat energy allows prevention of microcracking in such a welded joint. 24 Ref., 8 Figures.

Keywords: *data acquisition systems, microplasma powder surfacing, high-temperature nickel alloys, amount of heat applied to the anode, susceptibility to microcracking in fusion welding*

Measurement, recording and mathematical treatment of electric parameters of the welding arc have been applied for a long time to study the features of arcing, regularities of the process of electrode metal transfer, as well as welding equipment testing [1–10].

At the end of 1980s procedural fundamentals for statistical analysis of oscillograms of electric parameters of reverse polarity welding arcs were developed at PWI under the guidance of Prof. I.K. Pokhodnya [1, 2]. Values of mean root square deviation σ and variation coefficient K_V for welding current I, voltage U and short-circuiting time τ were calculated to evaluate their arcing stability in the interval between the short-circuits. As a rule, oscillographing of arc electric parameters was performed with the frequency of 0.1–20 kHz, and sampling dimensions were limited by recording time of 20–40 s, in view of acquisition of sufficient quantity of statistical data. This procedure enabled performance of comparative evaluation [2–4] of:

- technological properties of various models of consumable electrode welding equipment by criterion K_V^I, K_V^U, $K_V^\tau \to$ min;
- arcing stability for different grades of welding electrodes and wires by K_V^U, $\tau \to$ min criterion;
- stability of running of straight polarity plasma arcs during a continuous time interval.

Data acquisition systems [5–10] have become widely applied recently for recording, processing and analysis of process parameters of the welding arc. These systems allow:

- measuring current and voltage signals using sensors with galvanic decoupling from the welding circuit;
- recording them with discrete frequency of up to 100–200 kHz/channel for practically unlimited time using from 2 to 16 recording channels of analog-digital converters (ADC);
- using specialized programs to perform digital processing and analysis of electric signals, corresponding to process technological parameters: welding current, arc voltage, electrode wire feed rate, welding head displacement, shielding gas flow rate, etc.

Basic methodological support of data acquisition systems [1–4] was complemented by plotting arc dynamic volt-ampere characteristics [5], application of Fourier transforms for frequency analysis of electrode metal mass transfer [5, 6], neural networks for optimization of welding parameters during arcing [7].

At the present stage such systems are high-technology tools for recording the main parameters of welding processes, which alongside their monitoring [8] and analysis of welding equipment quality [9], also allow optimization of technological control of the welding arc [10].

In welding production, a traditional task is establishing a relationship between welding/surfacing parameters and dimensions and quality of welded joints. In a number of cases at nonstationary arcing modes their technological correction is difficult. Objective analysis and optimization of such modes requires establishing specialized criteria for their evaluation. This paper proposes for consideration a procedure for evaluation of mode parameters of nonstationary process of microplasma surfacing, based on application of data acquisition systems.

The process of microplasma powder surfacing [11, 12] is used in production in serial repair of aircraft GTE blades [13, 14] from high-temperature nickel alloys with high content of γ'-phase, having limited weldability [15, 16]. This process is characterized by up to 35 A welding current, up to 650 W effective power of microplasma arc, quantity of locally fed disperse filler of up to 9 g/min. Expansion of its technological capabilities is urgent to include multilayer surfacing and overlapping bead deposition [17]. During surfacing technology optimization, the welded joint can develop macro- or microcracks [14], detected by penetrant testing and/or metallographic examination. Hence the need to optimize both the modes of preliminary and subsequent heat treatment, and those of surfacing proper to ensure the quality and required properties of welded joints.

Depending on narrow substrate width [18] δ = 0.8–5.0 mm and required height of the deposited bead, the welding current and amount of powder fed to the weld pool are selected and periodically regulated in the above range [12], proceeding from the technical capabilities of the respective equipment for:

• limiting the penetration depth to less than 2 mm;

• ensuring in the surfacing forefront the wetting angle of base and deposited metal within 20–70°.

Features of welding current variation in a local area are due to successive formation of deposited bead section, and on the whole for the item — to the geometry of restored structural element of the blade (Figure 1). Thus, for this process the main technological factors of its parameter variation are [11–14]:

• kinds and amplitude of welding current variation (continuous, pulsed);

• powder feeding methods (portioned, continuous);

• plasmatron nozzle channel diameters;

• flow rates of plasma, carrier and shielding gases;

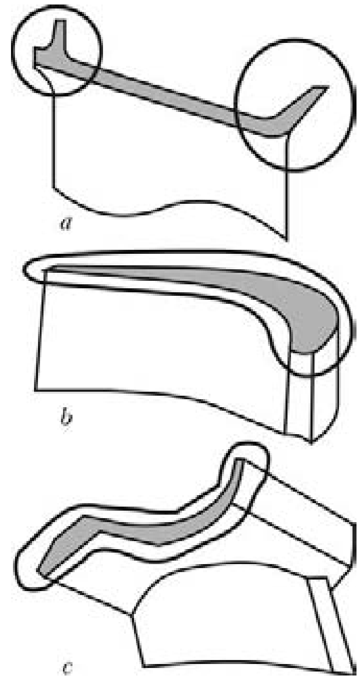

Figure 1. Main types of profiles of surfaced blades of aircraft GTE (on-line correction of surfacing mode is required in marked sections)

• shielding gas compositions (in Ar + 0–10 % H_2 system).

All the abovementioned variable factors make it difficult to perform subjective analysis and selection of the possible technological variants of surfacing.

PWI developed and tried out a special procedure for recording and analysis of parameters of microplasma powder surfacing modes, using a data acquisition system. It allows correlation of

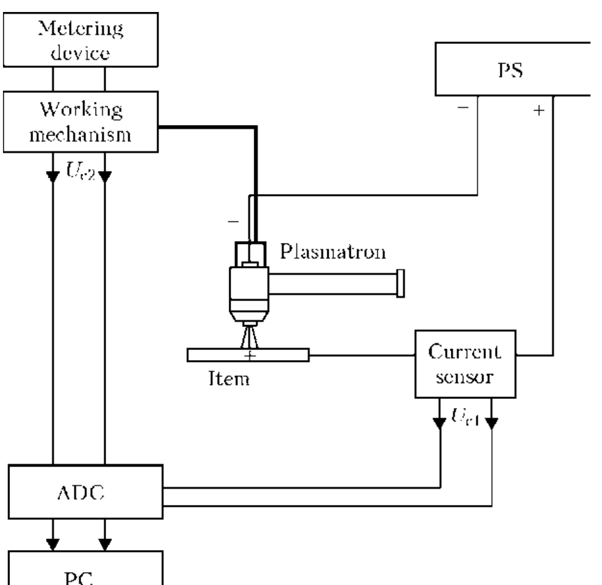

Figure 2. Schematic of measurement and recording of microplasma powder surfacing mode parameters: ADC — analog-digital converter; PC — personal computer; U_{c1}, U_{c2} — measured signals of voltage from current sensor and powder metering device working mechanism, respectively

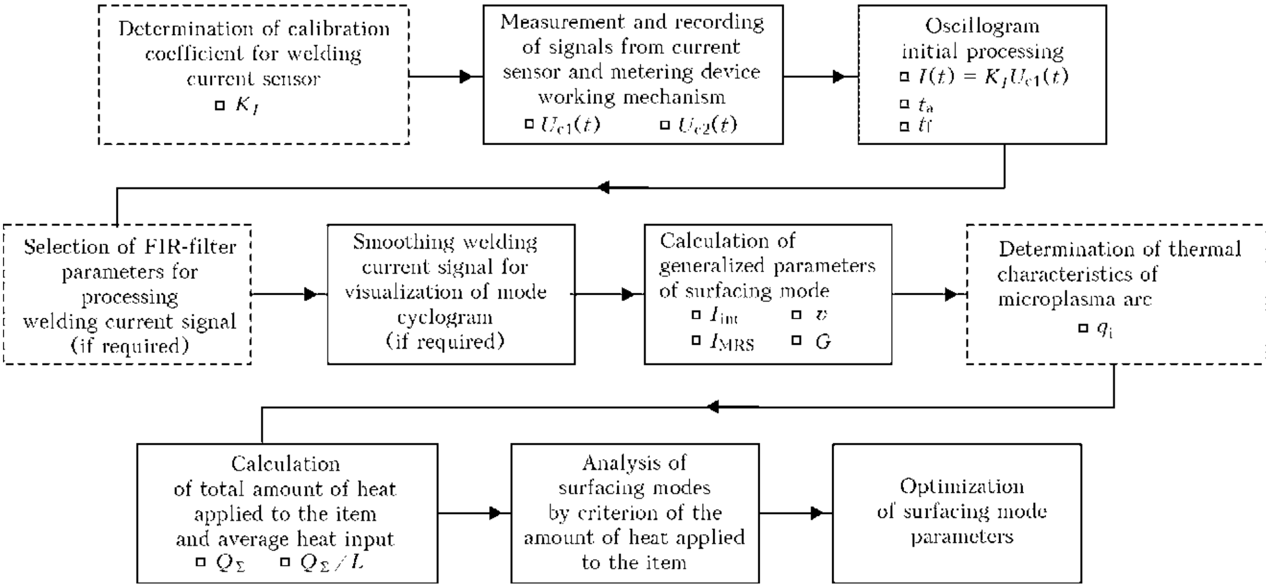

Figure 3. Algorithm for digital processing of signals at analysis and optimization of microplasma powder surfacing modes (dash lines designate preliminary preparation stages)

micro- and macrocracking susceptibility, revealed in the base–deposited metal joint by penetrant testing and metallographic examination, and the amount of heat applied to the item during the surfacing process.

Schematic of measurement and recording of process parameter signals and their digital processing algorithm are given in Figures 2 and 3. The following was used in the data acquisition system:

- ADC, allowing signal recording with 1–10 kHz/channel frequency;
- current sensors of LEM Company designed for measurement of up to 100 A welding current;
- voltage sensor LV-25P for recording U_{c2} signal from metering device working mechanism, ensuring disperse filler feeding during surfacing;
- PowerGraph 3.3 software for digital processing and analysis of data.

Shape of $I(t)$ dependence, as well as time of microplasma arc running on the item t_a and time of disperse filler feeding t_f were determined as a result of initial processing of oscillogram signals, measured and recorded in the welding circuit during item surfacing. Appearance of fragments of such welding current oscillograms for various microplasma arc power sources is given in Figure 4.

In the case of recording signals of unstabilized welding current (Figure 4, *b*) visual analysis of welding current oscillogram is difficult, and further digital processing of the respective signal is required with application of a smoothing digital filter with finite impulse response (FIR-filter) [19, 20]. Smoothing window size was selected, proceeding from the condition of preservation of the same amplitude and shape of welding current pulses (Figure 4, *c*). Errors introduced into this signal by digital processing were assessed at computation of mean-root-square value and definite integral for welding current during a fixed time interval:

$$I_{MRS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} I_i^2}, \quad (1)$$

$$I_{int} = \int_0^t I dt. \quad (2)$$

Error value was determined for signal averaging functions with the following types of weight factors W_i [20]: for mean-root-square, triangular and biquadratic windows. Their analysis showed that the integral characteristic of welding current I_{int} practically does not change at smoothing. Error, introduced into the signal by this kind of digital processing, does not exceed 0.2 %. A more significant error of up to 15 % is superposed on the mean-root-square value of welding current I_{MRS} during digital processing of welding current signal by smoothing. This error can be eliminated by linear correlation.

Surfacing rate v and amount of disperse filler G fed to the plasmatron were calculated, proceeding from the time of micropalsma arc running t_a and functioning of metering device working mechanism t_f determined at initial processing of mode oscillogram:

$$v = \frac{L}{t_a}; \quad (3)$$

for continuous feeding:

$$G = G_0 t_f; \quad (4)$$

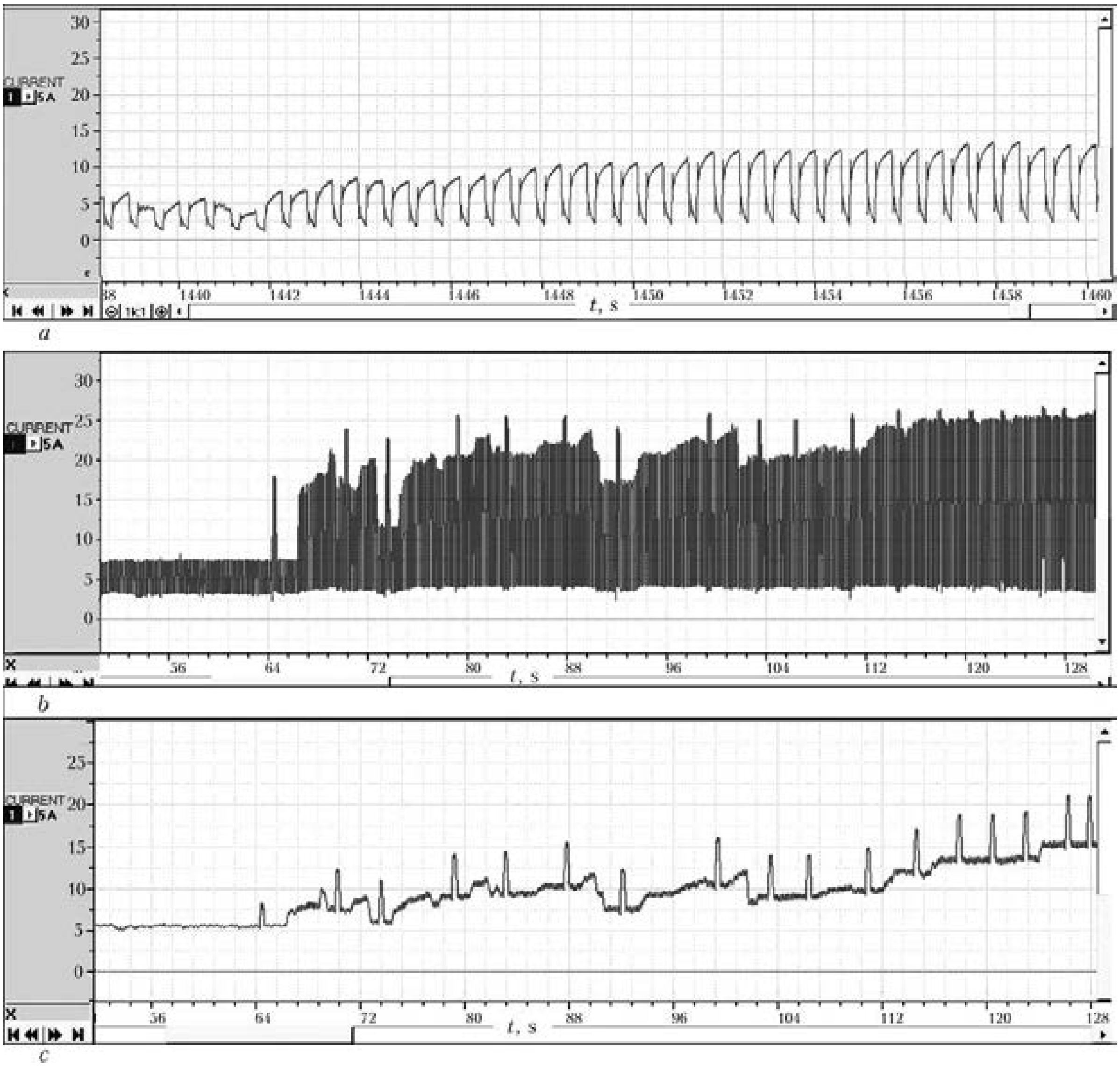

Figure 4. Appearance of fragments of microplasma powder surfacing mode cyclogram $I(t) = U_{c1}(t)$ after initial digital processing at signal recording frequency of 2.5 kHz: *a* — stabilized welding current, Kennametal Stellite system STAR-WELD PTA 190H; *b*, *c* — unstabilized welding current, UPNS-304M2/M3 system; welding current pulse frequency of 150 Hz

for portioned feeding:

$$G = M_0 N_{\rm mp}, \qquad (5)$$

where L is the deposited bead length; G_0 is the metering device working efficiency at continuous feeding of filler; M_0 is the mass of microportion at continuous feeding of disperse filler; $N_{\rm mp}$ is the number of powder microportions fed to the plasmatron at surfacing during time $t_{\rm f}$.

The final stage of the proposed algorithm for surfacing mode analysis is determination of the amount of heat Q_Σ, applied to the item. It is known that specific heat input values of welding arcs are characterized by effective power of item heating $q_{\rm i}$ [21]. In the range of plasmatron optimum thermal load (duty cycle of 100 %), dependence $q_{\rm i}(I)$ is linear [11, 12, 18] and is given by the following equation:

$$q_{\rm i} = k_q I \pm c_q, \qquad (6)$$

where k_q and c_q are the coefficients of linear regression.

Then, allowing for dependencies (2), (6) Q_Σ value can be determined as follows:

$$Q_\Sigma = \int_0^{t_{\rm a}} q_{\rm i} dt = k_q I_{\rm int} \pm c_q t_{\rm a}, \qquad (7)$$

and mean heat input at bead deposition as Q_Σ / L.

Variation of such stationary technological parameters of the process of microplasma powder surfacing as the ratio of plasmatron nozzle channel diameters, process gas flow rate and shielding gas composition affects microplasma arc thermal characteristics [12], and is preliminarily taken into account at experimental determination of

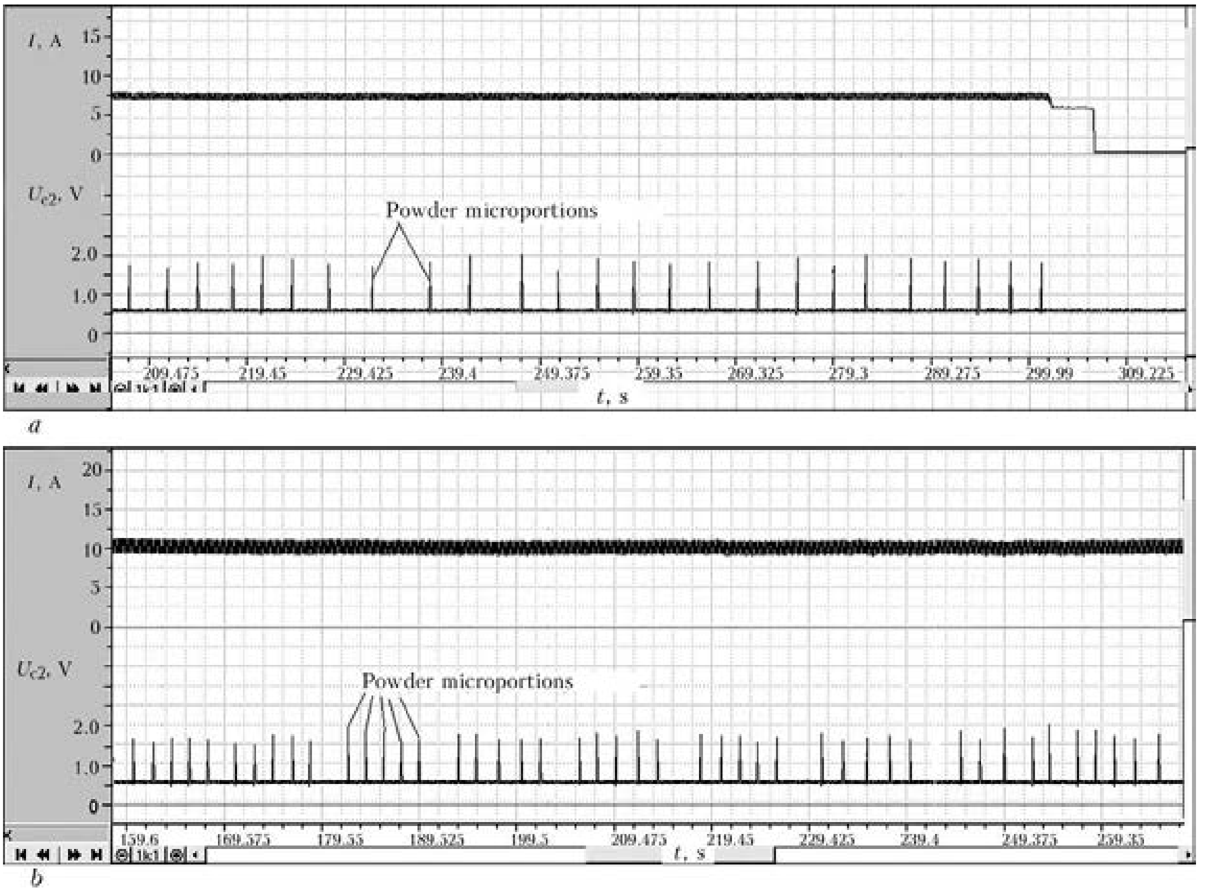

Figure 5. Fragments of oscillgorams of micropasma powder surfacing a narrow substrate δ = 1.6 mm with 1 (*a*) and 5 (*b*) disperse filler microportions fed into the weld pool

dependence $q_i(I)$ by the procedure of flow calorimetry [12, 18]. Note that in view of the mismatch between the conditions of microplasma arc running on a water-cooled copper anode and in real surfacing with weld pool formation, Q_Σ value determined by us will have a certain systematic error. Its value, according to the data of [22], is roughly estimated as +7 %.

Thus, nonstationary processes of welding current variation during arcing, also for pulsed modes with different principles of their realization, are allowed for through the value of definite integral of welding current magnitude, and most of the possible combinations of stationary process parameters of microplasma arc are determined with acceptable accuracy through application of coefficients k_q and c_q of linear regression $q_i(I)$ at calculation of heat applied to the anode. Procedure of energy analysis, presented in the paper, allows evaluation of applied amount of heat not only for surfacing the item as a whole, but also at any of its local areas (right up to weld pool dimensions). In combination with determination of deposited metal mass by weighing and measurement of base metal penetration depth, it further allows, at portioned feeding of filler, evaluation of a number of parameters given below that characterize weld pool dimensions and pool energy.

Volume of deposited metal in the weld pool is

$$V_{\mathrm{wpd}} = \frac{M_{\mathrm{d}}}{\rho(N_{\mathrm{mp}}/N_0 - k_n)}, \quad (8)$$

where M_{d} is the deposited metal mass; ρ is the deposited material density; N_0 is the number of filler microportions in one series of weld pool filling; $k_n = 1$ is the coefficient, allowing for the correction for initial stage of bead formation.

Length of weld pool region in the base metal is

$$L_0 = \frac{Lk_0}{(N_{\mathrm{mp}}/N_0 - k_n)}, \quad (9)$$

where L is the deposited bead length; $k_0 = 2$ is the coefficient, allowing for overlapping of molten metal volumes at weld pool displacement.

Volume of base metal being remelted is

$$V_{\mathrm{bmp}} = L_0 h_0 \delta, \quad (10)$$

where h_0 is the base metal penetration depth; δ is the narrow substrate width.

Total weld pool volume is

$$V_{\mathrm{wp}} = V_{\mathrm{wpd}} + V_{\mathrm{bmp}}. \quad (11)$$

Thermal efficiency [21] for deposited metal is

$$\eta_d = \frac{M_d H_d}{q_i}, \qquad (12)$$

where H_d is the specific enthalpy of 1 g of deposited metal.

To reveal the general regularities of the change of heat energy applied to the item depending on microplasma arc power and weld pool dimensions, a series of experiments were performed on bead deposition on a narrow substrate from austenitic stainless steel of width δ = 1.6 mm at I = 6–13 A. Powder of JS32 alloy with 63–160 μm particle size was used as disperse filler. Weld pool volume in different experiments was successively increased due to addition of series of filler microportions from 1 up to 6 (see Figure 5). Frequency of portioned powder feed and welding current magnitude in the above-mentioned range were selected so as to ensure at surfacing forefront the wetting angle of base and deposited metal of 30–60° and limit base metal penetration depth within 2 mm.

In this case in the range of welding currents I = 6–13 A and effective power of item heating q_i = 140–260 W, this procedure enabled more precise determination of the region of optimum surfacing modes, which corresponds to welding current of 9–10 A and deposited bead height of 3.0 to 3.5 mm (determined as the distance from fusion line with base metal to bead upper boundary) (Figure 6). In the other cases, increase of heat input into the item is observed, which is due to lowering of surfacing speed below 0.85–0.90 m/h, as a result of increase of time of:

• sample heating by microplasma arc in the intervals between feeding the powder microportions (up to 6–8 s), required for stable formation of the deposited bead;

• required for feeding into the weld pool 4–6 microportions of disperse filler at further increase of deposited bead volume (up to 12–18 s).

Calculations performed by dependencies (8)–(12) for deposited metal JS32 (H_d = 861.2 J calculated on the basis of [18, 23, 24]) allowed analyzing the regularities of variation of effective heating power of the item q_i, thermal efficiency for deposited metal η_d and base metal fraction γ_{bm}, depending on weld pool volume for a series of experiments described above. They demonstrate that (Figure 7) beginning from a q_i certain value, somewhat greater than the minimum possible value for the start of a stable surfacing process, weld pool volume can increase 5–6 times, due to feeding disperse filler into it. Here, specific heat input into the anode, and base metal

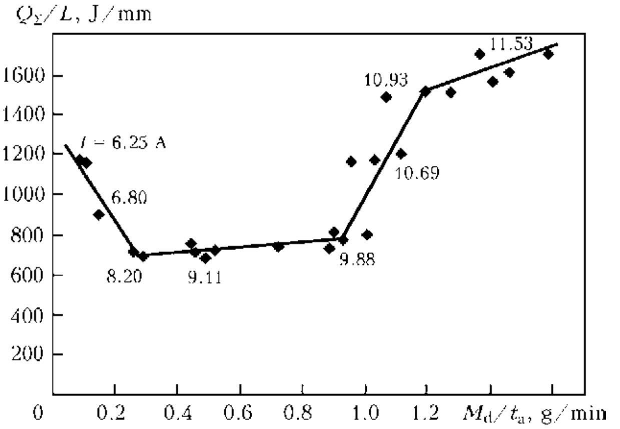

Figure 6. Dependence of heat input Q_Σ/L on efficiency M_d/t_a and change of welding current average value at surfacing a narrow substrate 1.6 mm wide

fraction in the weld pool do not change significantly. Under the conditions of limited arc power, bead deposition duration depends on the time of weld pool metal staying in the molten state, which is, in its turn, determined by the duration of the series of portioned filler feeding (see Figure 5). Therefore, amount of heat applied to the item is proportional to bead deposition time, and to pool volume and deposited metal mass, respectively. In view of the known dependence of weld pool metal staying in the molten state on heat input magnitude [21], the modes of microplasma powder surfacing may require op-

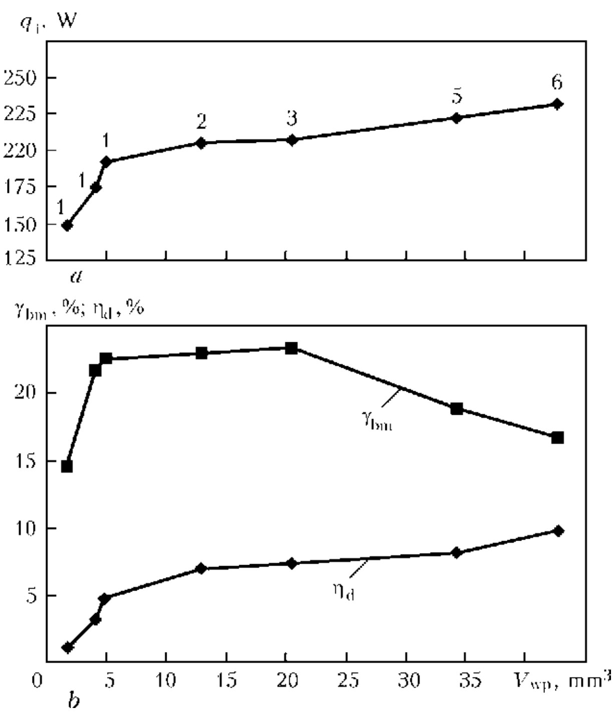

Figure 7. Dependence of effective power of item heating q_i (*a*), base metal fraction γ_{bm} and thermal efficiency for deposited metal η_d (*b*) on weld pool volume V_{wp} at deposition on narrow substrate 1.6 mm wide: 1–6 — quantity of disperse filler microportions fed into the weld pool

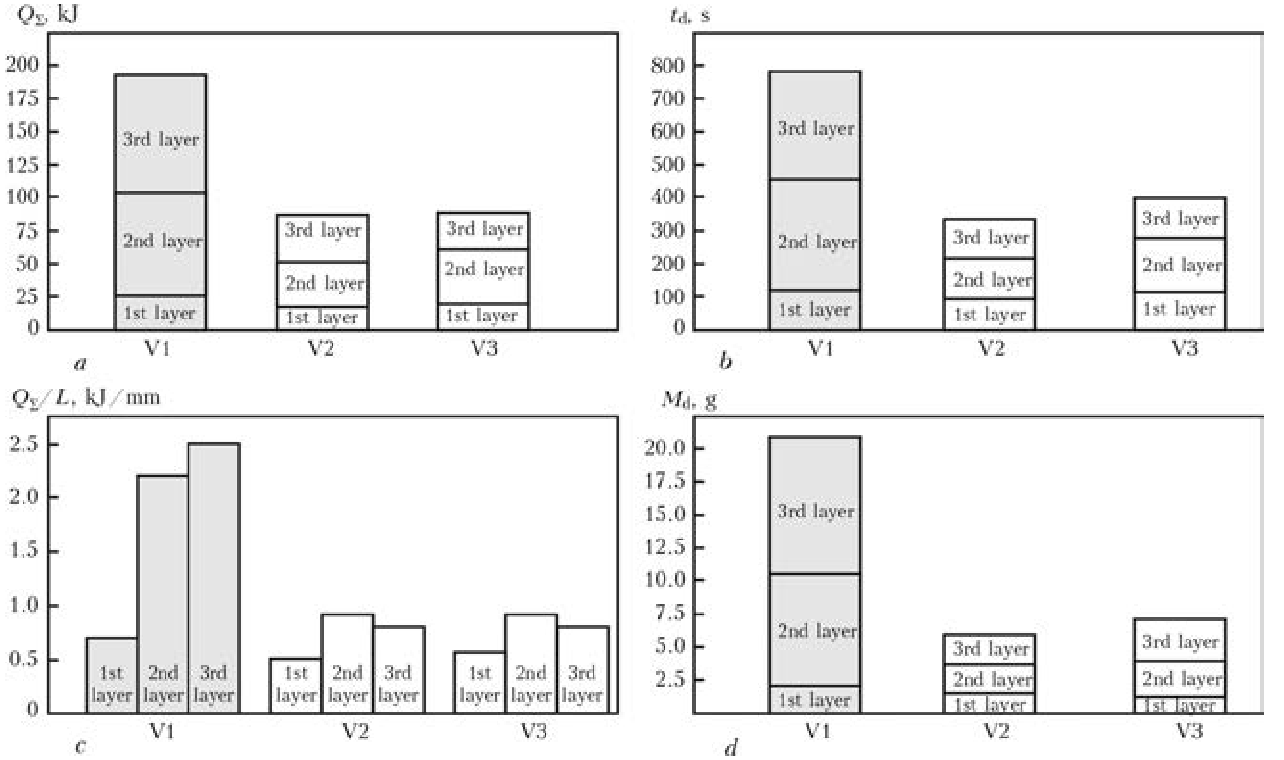

Figure 8. Regularities of variation of amount of heat Q_Σ applied to the item, surfacing time t_d and average value of welding current at correction of the modes of deposition on a narrow substrate of width δ = 2.5–6.0 mm: V1 — UPNS-304M2/M3 system, shielding gas Ar + 10 % H_2: V2 — UPNS-304M2/M3 system, shielding gas Ar + 5 % H_2; V3 — STARWELD PTA 190H system, shielding gas is Ar (filler powder is JS32 alloy; dark colour marks surfacing mode, where microcracking susceptibility is manifested)

timization of their parameters by the criterion of weld pool volume (deposited metal mass).

The above approach was applied for analysis of the modes of multilayer microplasma powder surfacing of airfoil edge of hollow shroudless blades from JS32 and JS26 alloys (see Figure 1, *b*). At the stage of technology verification, it will allow optimizing the heat input into the item at average welding current of 11–16 A, due to limitation of weld pool dimensions, deposited metal mass and layer deposition duration by the criterion of average heat input $Q_\Sigma/L < 1$ kJ/mm (Figure 8, technological variants V2 and V3). By the results of metallographic examination this enabled prevention of microcracks (see Figure 8, V1) at 3-layer deposition of JS32 alloy on a narrow substrate δ = 2.5–6.0 mm. Modes were corrected in two types of specialized equipment with different principles of pulsed mode formation (see Figure 4, *a*, *b*) and disperse filler feeding.

Conclusions

In the case of analysis of the modes of surfacing a narrow substrate of 1.6 mm width it was established that starting with a certain value of microplasma arc effective power, somewhat greater than the minimum possible value for the start of a stable process, weld pool volume can increase 5 to 6 times without any significant increase of arc power, due to increase of the amount of added disperse filler. As total heat input into the item is proportional to weld pool dimensions and surfacing efficiency, optimization of the modes of microplasma surfacing by the criteria of deposited metal mass and heat input may be required.

Application of the developed procedure of evaluation and analysis of the amount of heat, applied to the item, allowed at the stage of technology verification eliminating microcracking in the deposited metal at 3-layer surfacing of airfoil edge 2.5–6.0 mm wide for hollow shroudless blades from JS32 and JS26 alloys. Optimization of total heat inputs into the anode by $Q_\Sigma/L <$ < 1 kJ/mm and $M_d < 3$ g criteria was realized in two types of specialized equipment with different principles of pulsed welding current formation and disperse filler feeding method.

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