

PECULIARITIES OF BEAD SHAPE REGULATION IN SINGLE-LAYER MICROPLASMA SURFACING ON EDGES OF AIRCRAFT GAS TURBINE ENGINE BLADES*

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It is a necessary to specify the dependencies of deposited metal shaping due to the need of 5–15 mm height increase of the dimensions of surfacing-repaired damaged areas of blade edges of aircraft GTE of high-temperature nickel alloys in microplasma bead surfacing on narrow substrate of less than 3 mm. A range of change of the process energy indices in «effective heat power of arc–heat input–cross-section area of deposited bead» system was investigated for conditions of corresponding single-layer surfacing, and effectiveness of process regulation of deposited layer cross-section was evaluated. It is determined that heat input change in 100–1600 J/mm range is the most effective regulation of cross-section area of the deposited bead under conditions of base metal limited penetration depth. It is assumed that the determined process relationship between heat input energy, height and cross-section area of the deposited bead will promote for formation of the additional criteria preventing crack formation in the «base–deposited metal» welded joint in repair of the parts of aircraft engines of high-temperature nickel alloys using multi-layer microplasma powder surfacing. 18 Ref., 4 Tables, 8 Figures.

Keywords: *microplasma powder surfacing, high-temperature nickel alloy and heat-resistant cobalt alloy, narrow substrate, effective heat power of arc, heat input, thermal efficiency, cross-section area of deposited bead*

One of the fields of application of arc surfacing on narrow substrate [1] of up to 3 mm width is the series repair of damaged or worn edges of aircraft gas turbine engine (GTE) blades [2–8]. The working blades of serially repaired aircraft engines D18T, D436, AI222, AI-450 are manufactured of nickel high-temperature alloys with polycrystalline structure (ZhS6U-VI, ZhS6K-VI) or of directionally-solidified alloys (ZhS32-VI and ZhS26-VI) [9]. These high-alloy materials, containing 55 and more vol.% of γ' -phase, are designed for operation at 1000–1100 °C temperatures and differ by high tendency to crack formation in fusion welding and/or further heat treatment [9, 10]. Argon-arc welding has been used for repair of such parts for more than 40 years, however, repair of the blade edges was limited by up to 2 mm depth and filler metal was inferior to base metal on heat resistance [2, 3].

Microplasma powder surfacing [4–8] has been successfully used for more than 10 years at JSC «Motor Sich» and SE «Ivchenko-Progress» for repair of aircraft working blades of given alloys with more than 3–5 thou. h. running. Several grades of filler powders,

in particular, high-temperature nickel alloy ZhS32 [4–8] and high-temperature cobalt and wear-resistant alloy V3K [5, 8], are widely used in this process.

Currently, serial repair production requires increase of dimensions of surfacing-repaired areas of blades (edges of platforms, labyrinth ends, Z-shape profiles and blade airfoil) to 5–15 mm height due to corresponding increase of size of wear zones, burn-through and thermal fatigue cracks, developing in process of operation of these parts. Their restoration can be characterized as process of multi-layer surfacing, in which «base–deposited metal» welded joint can under certain conditions be susceptible to formation of micro- and macrocracks [6, 10, 11]. In turn, the multi-layer surfacing at some approximation can be presented as collection of single-layer beads. Therefore, it is relevant to expand the knowledges on the boundaries of energy indices range in single-layer surfacing for reasonable selection of such level and methods of balancing of heat input in the part, which provide for process strength of given welded joint, i.e. susceptibility of mentioned above materials to crack formation in fusion welding is not developed.

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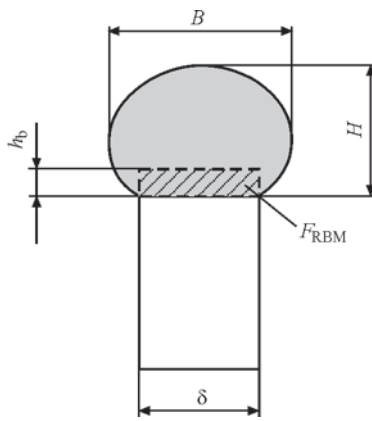


Figure 1. Scheme of measurement of deposited bead size: δ — width of narrow substrate, B — bead width; H — bead height; h_b , F_{rbm} — depth of penetration and cross-section area of remelted base metal

One of the constituents of this problem is detection of the dependencies and further optimizing the process regulation of shape of bead being deposited on narrow substrate. In addition to reasonable selection of volume of deposited metal in manual and automatic (robotic) surfacing, this allows also optimizing the dimensions of bead side reinforcement $p = 0.5 (B - \delta)$ in its cross-section (Figure 1).

In turn, side reinforcements of the deposited bead are the allowances being removed by mechanical treatment in formation of set geometry of the element repaired by surfacing. It is a danger of formation of burns and polishing cracks, therefore, abrasive treatment of the parts from high-temperature nickel alloys is carried out using special modes, equipment and abrasive disks [12, 13]. At that, reduced rates of rotation of abrasive tool (to 25 m/s) and feed (350–750 mm/min) are used for limiting removal intensity of the treated material [13]. Thus, mechanical treatment of the deposited metal, in spite of technical complexity of shaping of corresponding profile surfaces of the blade, is sufficiently laborious process, additionally requiring highly-qualified specialists, expensive equipment and materials. Therefore, reduction of width of the deposited bead promotes for significant extent decrease of laboriousness and increase of profitability of blade repair.

Aim of the present work lied in evaluation of the range of effective heat power of microplasma arc (previously was determined using flow calorimetry method [1] for corresponding value of welding current) and heat input for conditions of single-layer surfacing on narrow substrate of $\delta = 0.3$ – 3.0 mm width on modes close to optimum ones, and determination of basic dependencies of process regulation of shape of deposited bead cross-section.

Specimens from steel 12Kh18N10T of 90–100×30–40 mm size and 0.3–3.0 mm thickness were

used as base metal. Surfacing on modes, described earlier in work [8], was carried out under conditions of free bead formation on the edge of plate being clamped in the jaws. The distance from deposited surface to copper jaws made not less than 20 mm, and that from plasmatron outer exit to specimen was 5 mm. The powders of ZhS32 and V3K alloys of 63–160 μm and 53–150 μm fraction, respectively, with different melting temperature (approximately by 70–90 °C) and fluidity of weld pool molten metal were used as fillers. Argon of higher grade on GOST 10157–79 was applied as plasmaforming and transporting gas. The experiments were carried out at two types of equipment, different by type of disperse filler feed, level of constriction of microplasma arc and relative pulse duration of welding current S :

- STARWELD 190H unit, plasmatron HPH80 (diameters of nozzle channels: plasma $d_{pl} = 2$ mm, focusing $d_f = 3$ mm), Kennametal Stellite GmbH company — continuous feed of powder (consumption of transporting gas $Q_{tr} = 3$ l/min, $S \approx 1.5$;

- UPNS304M2/M3 unit, plasmatron PPS04 ($d_{pl} = 2.5$ mm, $d_f = 4.5$ mm) — dosed feed of powder ($Q_{tr} = 2$ l/min), $S \approx 4.5$.

Processing of experimental data was carried out using the regression dependencies of value of efficient heat power of microplasma arc q_u from welding current I , received earlier using the flow calorimetry method [1]. Heat input q_u/v was determined by procedure of work [11]:

$$q_u / v = Q_{\Sigma} / L, \quad (1)$$

where Q_{Σ} is the heat input in the anode taking into account effective efficiency of part heating [1, 11]; L is the given length of elliptic bead cylinder. Cross-section areas of the deposited bead F_b and deposited metal in it $F_{db} = F_b - F_{rbm}$ were determined using calculation by procedure of work [14] based on measurement of width, height of bead and base metal penetration depth with up to 0.05 mm accuracy, according to Figure 1. Thermal efficiency for ZhS32 deposited metal was determined by calculation [11] proceeding from its cross-section area F_{db} :

$$\eta_{th} = \frac{M H_m}{q_u}, \quad (2)$$

where $H_m = 861.2$ and 1312.6 J is the specific enthalpy of 1 g of deposited metal ZhS32 and base metal 12Kh18N10T, respectively.

Firstly, the dependencies of change of the energy indices of process of microplasma powder surfacing and indices of bead shape for narrow substrate $\delta = 0.3$ – 2.0 mm (Figure 2 and Table 1) were evaluated. It is determined that the effective heat power of the microplasma arc varies in 30–330 W range, heat in-

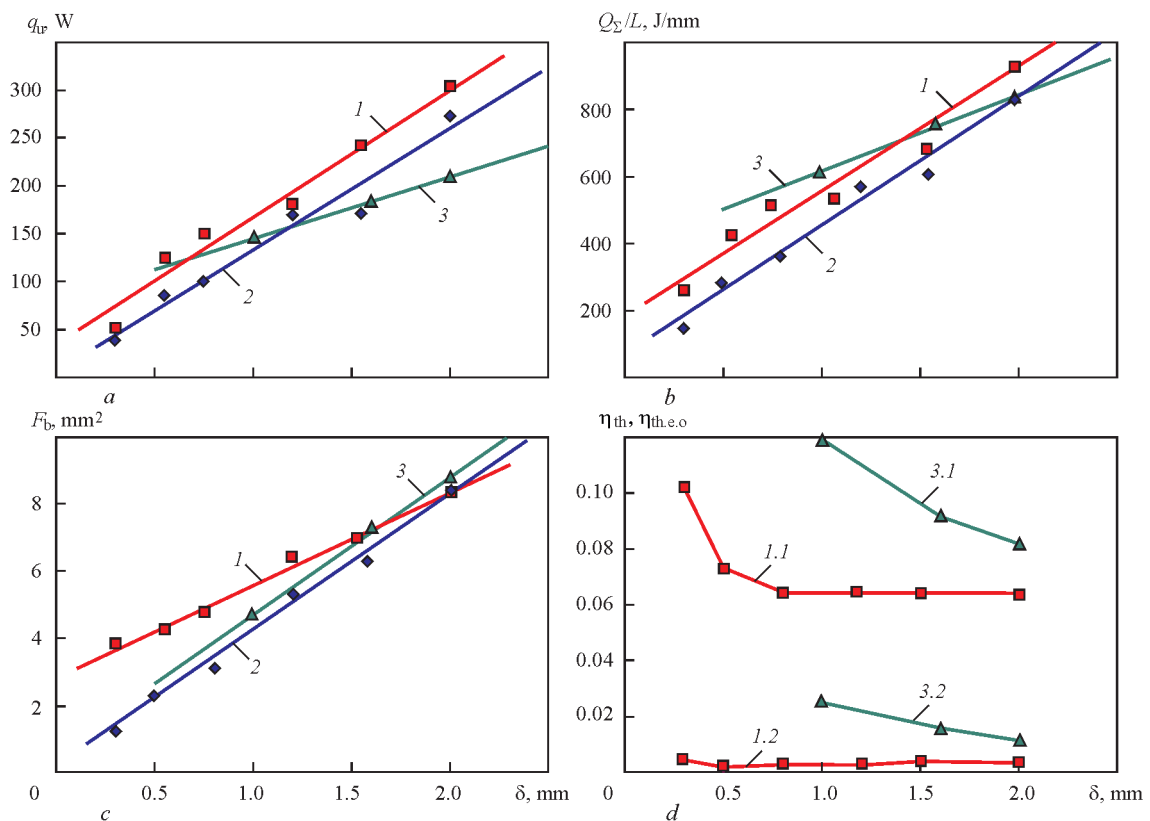


Figure 2. Effect of narrow substrate width δ on effective heat power of microplasma arc q_u (a), heat input Q_Σ/L (b), cross-section area of deposited bead F_b (c) and thermal efficiency η_{th} (d): 1 — surfacing of ZhS32 alloy, Starweld 190H unit, continuous wire feed, shielding gas Ar; 1.1 — complete thermal efficiency η_{th} of process; 1.2 — component of thermal efficiency used for base metal melting; 2 — surfacing of V3K alloy, Starweld 190H unit, continuous powder feed, shielding gas Ar; 3 — surfacing of ZhS32 alloy, UPNS-304M2/M3 unit, dosed wire feed, shielding gas 95 % Ar + 5 % H₂; 3.1 — complete thermal efficiency η_{th} of process; 3.2 — component of heat efficiency used for base metal melting

put of the process makes 100–1000 J/mm, surfacing efficiency is 0.3–1.3 g/min; bead cross-section area makes 1–9 mm². $q_u(\delta)$, $Q_\Sigma/L(\delta)$ and $F_b(\delta)$ dependencies are close to linear. Obtained data indicated the specific effect on the process energy indices of filler composition (ZhS32, V3K) and method of disperse wire feed (continuous, dosed), that allows expanding a notion on known methods of process regulation of heat input in the part (welding current, level of plasma arc constriction, reasonable selection of shielding gas composition [1, 4]). Indicated process factors in $q_u < 150$ W and $\delta < 1.2$ mm range also influences the reduction of deposited bead cross-section. A com-

plete thermal efficiency of the process of surfacing on narrow substrate $\delta = 0.3$ – 0.2 mm, as a rule, does not exceed $\eta_{th,e} = 6$ – 10 %, besides, part of the effective power q_u , being spent for melting of base metal, makes $\eta_{th,e.o} = 0.16$ – 2.5 %. Fraction of the base metal in the deposited one is limited in 5–15 % range, that corresponds with the optimum modes of plasma-powder surfacing [1].

A set range of values of bead shape coefficient B/H in 0.77–1.22 limits (see Table 1) allowed specifying technologically possible schemes of shaping of deposited bead [14] varying a series of process factors of microplasma powder surfacing: width of

Table 1. Effect of width of narrow substrate δ on portion of base metal γ_b , surfacing efficiency M_s and coefficient of bead shape B/H in microplasma powder surfacing of alloys ZhS32 and V3K

δ , mm	γ_b , %			B/H			M_s , g/min		
	ZhS32 (c)	ZhS32 (d)	V3K (c)	ZhS32 (c)	ZhS32 (d)	V3K (c)	ZhS32 (c)	ZhS32 (d)	V3K (c)
0.3	9.97	–	9.26	0.787	–	1.054	0.351	–	0.157
0.55	5.11	–	5.04	0.772	–	1.041	0.645	–	0.333
0.75	8.98	–	8.5	0.857	–	0.930	0.639	–	0.366
1.0	–	14.16	–	–	1.201	–	–	1.043	–
1.2	11.46	–	13.55	0.933	–	0.936	0.826	–	0.534
1.55	12.11	13.37	15.39	1.216	1.113	1.000	1.013	0.872	0.711
2.0	11.19	10.64	10.31	1.032	1.206	0.969	1.276	0.958	1.261

Note: (c) and (d) are continuous and dosed powder feed, respectively.

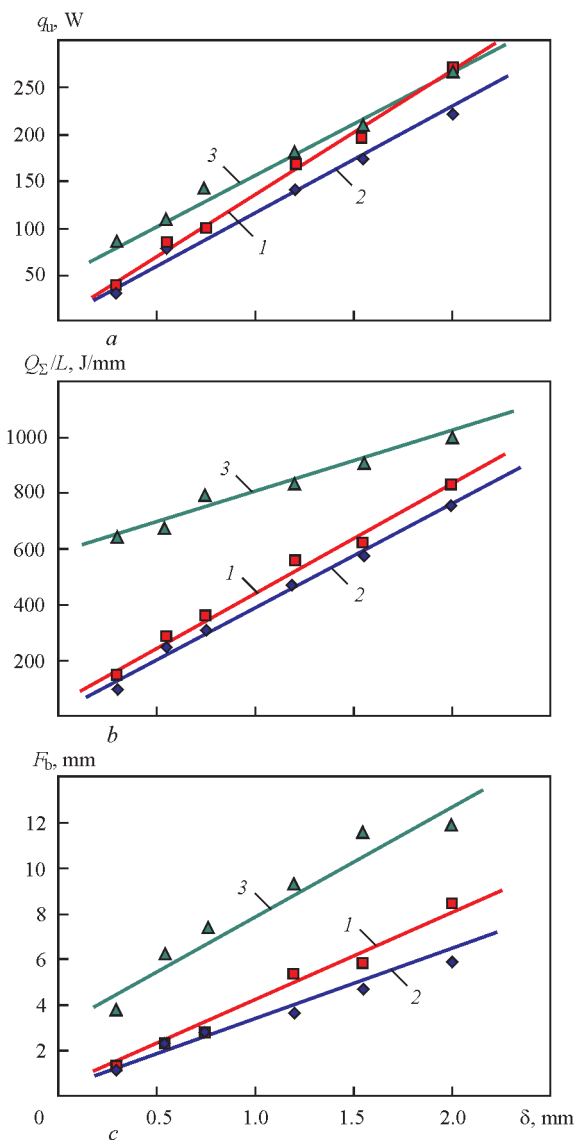


Figure 3. Effect of width of narrow substrate δ on effective heat power of microplasma arc q_u (a), heat input Q_z/L (b), cross-section area of deposited bead F_b (c). Surfacing of V3K alloy, shielding gas Ar, Starweld 190H unit, continuous powder feed: 1 — direct; 2, 3 — pulse welding current

narrow substrate; effective heat power of arc and efficiency.

$\delta = 0.3\text{--}2.0$ mm depending on toughness of weld pool molten metal (i.e. deposited metal, since $\gamma_0 \rightarrow \min$) is characterized by the following changes of shape of deposited beads cross-section:

- at increased toughness (alloy ZhS32) — under the law of increasing ellipse with $H > B$ at $\delta < 0.8$ mm and $B > H$ at $\delta > 1.5$ mm;

- at increased fluidity (alloy V3K) — under the law of increasing circle with $H \approx B$.

Considered above methods of process effect on shape and dimensions of bead being deposited on narrow substrate shall be referred to passive ones, since they can be selected only before surfacing. It is known fact [1, 4] that welding current is the process parameter of constricted arc, first of all determining its effective heat power. Respectively, it can have sufficiently easy technological regulation in process of repair surfacing, in particular, at change of width of narrow substrate at local repair of complex geometry blades [4–8]. Therefore, this work also studied the possibility of regulation of bead shape due to application of pulse welding current with different relative pulse duration S .

In parallel the investigations were carried out for disperse filler materials V3K (STARWELD 190H unit, $S \approx 1.5$) and ZhS32 (UPNS304M2/M3 unit, $S \approx 4.5$). Additionally, 2 types of pulse modes were considered, except surfacing with direct welding current (mode 1):

mode 2: $I_{pul} < I_b, I_p < I_b$;

mode 3: $I_{pul} > I_b, I_p < I_b$.

where I_b is the basic value of direct welding current; I_{pul}, I_p are the values of welding current at pulse and pause, respectively.

The dependencies of change of energy parameters of the process of microplasma powder surfacing and bead shape for narrow substrate $\delta = 0.3\text{--}2.0$ mm are presented in Figure 3, Table 2 and Figure 4, Table 3 for conditions of surfacing of V3K and ZhS32 alloys, respectively. Different position of dependencies $q_u(\delta), Q_z/L(\delta)$ and $F_b(\delta)$ relatively to similar ones in direct current surfacing (see Figures 3, 4) is noted at mode 3 depending on value of relative pulse duration of welding current in surfacing on narrow substrate $\delta \leq 2$ mm.

Obtained results indicate the possibility of efficient regulation of the dimensions of cross-section of bead being deposited on narrow substrate, due to reasonable selection of parameters of pulse welding current. Also, pulse current surfacing of V3K alloy promotes for somewhat reduction (per 2–5 %) of base metal

Table 2. Effect of width of narrow substrate δ on portion of base metal γ_b , surfacing efficiency M_s and coefficient of bead shape B/H in microplasma powder surfacing of alloy V3K using continuous (mode 1) and pulse current (modes 2 and 3)

δ, mm	$\gamma_b, \%$			$M_s, \text{g/min}$			B/H		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
0.3	9.26	7.47	4.73	0.157	0.116	0.251	1.05	0.71	0.72
0.55	5.04	7.31	1.67	0.333	0.287	0.332	1.04	0.90	0.85
0.75	8.50	13.37	4.64	0.366	0.329	0.456	0.93	1.06	0.74
1.2	13.55	14.12	8.20	0.534	0.485	0.785	0.94	0.92	0.83
1.55	15.39	8.47	6.48	0.711	0.616	1.042	1.00	0.92	0.79
2.0	10.31	11.32	6.74	1.260	0.678	1.496	0.97	1.16	0.80

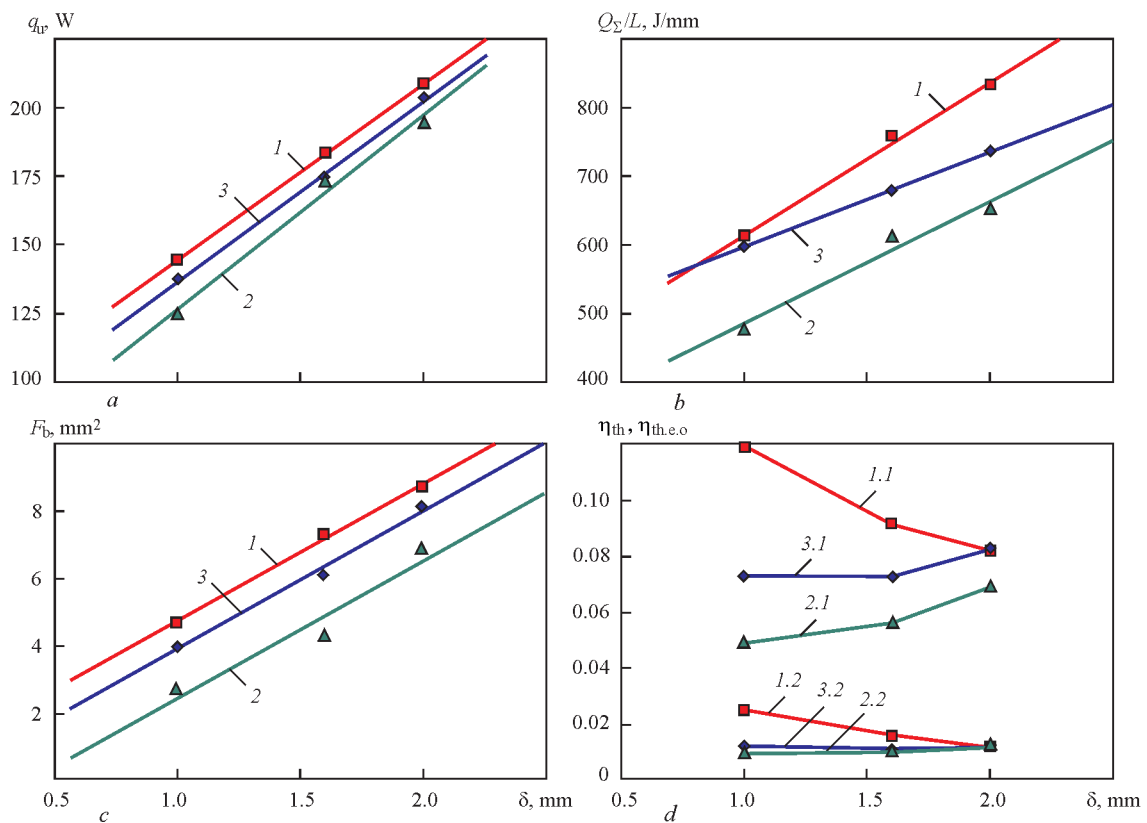


Figure 4. Effect of width of narrow substrate δ on effective heat power of microplasma arc q_w (a), heat input Q_Σ/L , cross-section area of deposited bead F_b (c) and thermal efficiency η_{th} (d) in variation of narrow substrate width δ . Surfacing of ZhS32 alloy, shielding gas 95 % Ar + 5 % H₂, UPNS-304M2/M3 unit, dosed powder feed: 1 — direct welding current; 2, 3 — pulse welding current (modes 2 and 3); 1.1, 2.1, 3.1 — complete thermal efficiency η_{th} of process; 1.2, 2.2, 3.2 — component of thermal efficiency $\eta_{th,e.o.}$ used for base metal fraction in comparison with direct current surfacing (see Table 2). It becomes possible to shape deposited bead under increasing ellipse law with $H > B$ for all range of width of narrow substrate $\delta = 0.3\text{--}2.0$ mm. Possibilities of decrease of base metal fraction and regulation of bead shape coefficient due to application of pulse modes is somewhat limited (see Table 3) in pulse current surfacing of ZhS32 alloy.

The investigations of effect of rate of microplasma powder surfacing of ZhS32 and V3K alloys on energy indices of the process and bead cross-section area were carried out in a mode of automatic direct current surfacing using robotic unit 190HP. It is determined (Figure 5) that increase of rate of surfacing on $\delta = 0.3\text{--}3.0$ mm width narrow substrate from 1.2 to 3.6 m/h promotes for on average 3 times reduction of cross-section area of the deposited bead F_b , and 4 times decrease of heat inputs in the part Q_Σ/L . The productivity of surfacing on $\delta = 3.0$ mm narrow sub-

strate in the considered rate range on data of Figure 5 makes approximately 3 g/min and reaches the powder feed productivity.

It is additionally shown (see Table 4) that application of disperse filler in microplasma surfacing is more preferable in comparison with filler from microwire, since allows reducing the effective heat power of arc more than 2 times, decreasing 1.8 time heat input, and rising 1.8 time surfacing efficiency. Also, following from work [15], reduction of heat input to laser-powder surfacing level in microplasma powder surfacing is possible with rise of its rate approximately to 22.6 m/h.

Evaluation of common and separate effect of the process factors of microplasma arc effective heat power and heat input on bead cross-section shape was carried out by means of analysis of goal functions [18] ε_{q_w} , $\varepsilon_{Q_\Sigma/L}$, and ε_F in form of relationship of effective heat power of microplasma arc, heat input and

Table 3. Effect of width of narrow substrate δ on portion of base metal γ_b , surfacing efficiency M_s and coefficient of bead shape B/H in microplasma powder surfacing of alloy ZhS32 using direct (mode 1) and pulse current (modes 2 and 3)

δ , mm	γ_b , %			M_s , g/min			B/H		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
1.0	17.17	15.09	11.57	0.950	0.344	0.585	1.04	0.89	0.79
1.55	12.61	15.9	13.64	0.970	0.557	0.750	1.11	1.07	1.22
2.0	10.63	13.7	11.08	1.020	0.773	1.004	1.21	1.11	1.07

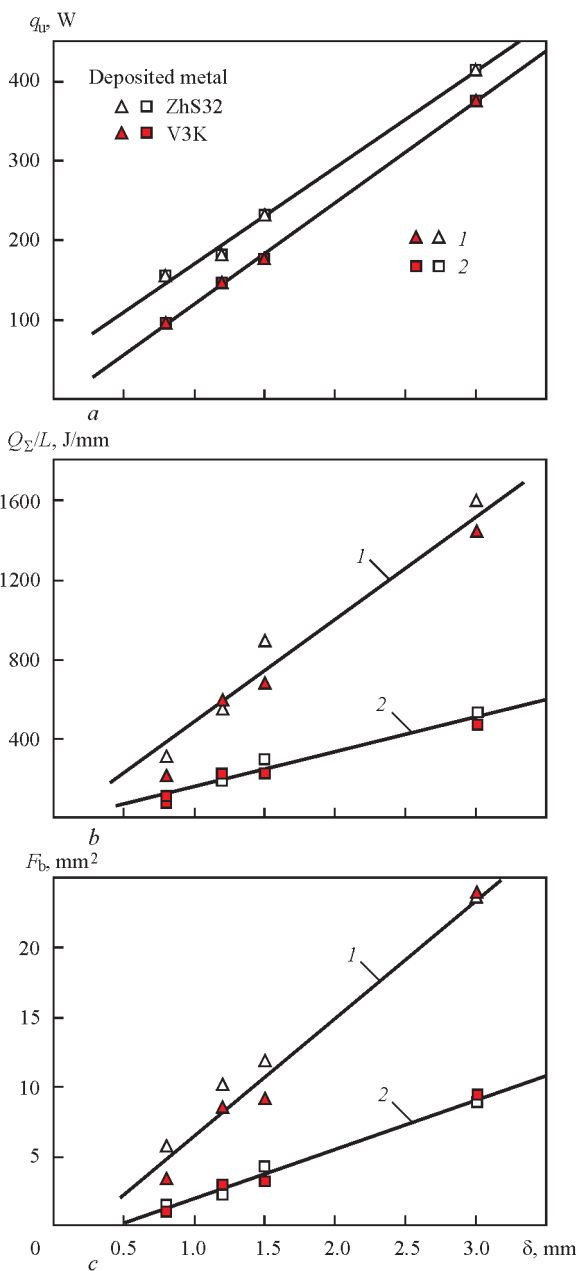


Figure 5. Effect of width of narrow substrate δ and average surfacing rate on effective heat power of microplasma arc q_u (a), heat input Q_z/L (b), cross-section area of deposited bead F_b (c): 1 — 1.2; 2 — 3.6 m/h. Robotic unit Starweld 190H, continuous powder feed, shielding gas Ar

cross-section areas of the deposited bead at current and basic modes of surfacing, respectively. The basic mode was, as a rule, a direct current surfacing mode. The values of goal function ϵ_F were evaluated at varying process factors in form of different modes of pulse welding current ($I_{pul} < I_b, I_p < I_b$ and $I_{pul} > I_b, I_p < I_b$) and surfacing rate, which were considered through the indices of effective heat power of microplasma arc and heat input. The regression dependencies of change of goal functions $\epsilon_F = f(\epsilon_{q_u})$ and $\epsilon_F = f(\epsilon_{q_u}, \epsilon_{Q_z/L})$, relatively to their basic level ($\epsilon_{q_u} = 1, \epsilon_{Q_z/L} = 1, \epsilon_F = 1$) are presented in form of 2D and 3D (contour) plots in Figures 6 and 7.

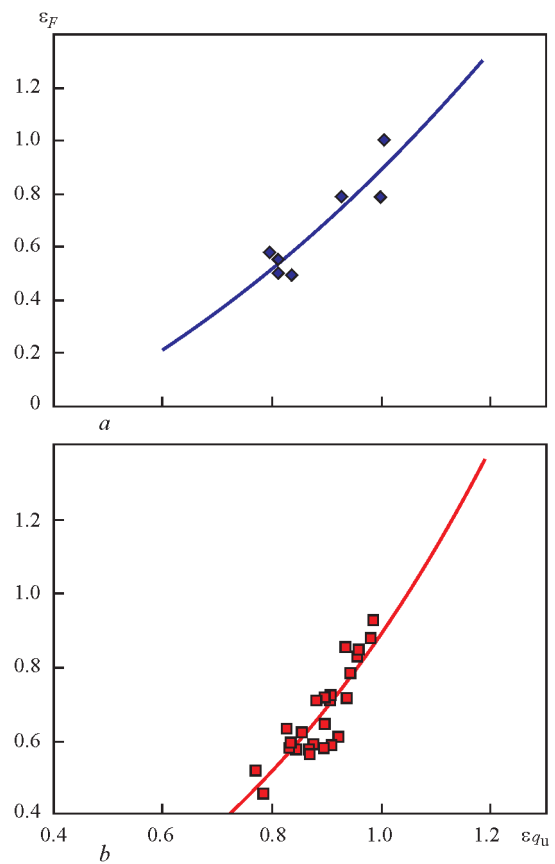


Figure 6. Dependence of relative cross-section area of deposited bead ϵ_F on relative effective heat power of microplasma arc ϵ_{q_u} in microplasma powder surfacing on narrow substrate: a — alloy V3K, unit Starweld 190H, continuous powder feed, shielding gas Ar, $\delta = 0.3-3.0$ mm; b — unit UPNS-304M2/M3, dosed powder feed, shielding gas 95 % Ar + 5 % H_2 , $\delta = 1.0-2.0$ mm

It is determined that 20 % reduction of effective heat power of microplasma arc promotes for 30–50 % decrease of cross-section area of the deposited bead for V3K and ZhS32 alloys, respectively. At that, the relationship of width B to height of deposited bead H for pulse welding current lies, as a rule, in 0.7–0.92 ranges.

Change of surfacing heat input (mainly due to its rate), in particular in combination with some increase of effective heat power of microplasma arc, has more significant effect on shape of the bead, deposited on narrow substrate (see Figures 6 and 7). 2–3 times increase of heat input in surfacing with continuous feed of powder allows receiving the same rise of bead cross-section area, and up to 3.6 times growth in combination with simultaneous increase of effective heat power of microplasma arc by 70 % (see Figure 7, a). In surfacing with dosed powder feed, 2.5 times increase of heat input allows rising cross-section area of the deposited bead up to 3.5 times and to 5.5–6 times (see Figure 7, b) in combination with simultaneous increase of effective heat power of microplasma arc by 10–30 %.

Simultaneous reduction of effective power of the microplasma arc and heat input per 20–30 % relative-

Table 4. Comparison of characteristics of bead cross-section (B, H, γ_b), effective power of part heating q_u , heat input Q_{Σ}/L and surfacing efficiency M_s in microplasma and laser surfacing

Surfacing process	Deposited metal	B, mm	H, mm	q_u, W	$\gamma_b, \%$	$Q_{\Sigma}/L, \text{J/mm}$	$M_s, \text{g/min}$	Source
Microplasma, $\approx 22.6 \text{ m/h}$	Powder H13 tool steel	2.0	0.2	$\approx 280^{*1}$	–	$\approx 45^{*1}$	1.0	Wang H. et al. (2003). [15] ^{*3}
Microplasma, $\approx 3.6 \text{ m/h}$	Wire AISI P20 $\varnothing 0.3 \text{ mm}$	1.9 ± 0.06	0.9 ± 0.04	400	5.12 ± 0.12	380.95	0.47	Jhavar S. et al. (2014). [16] ^{*3}
	Powder V3K, 53...–160 μm	2.0	1.8	≈ 15	211.7	0.87	1.87	This work ^{*2}
Yb:YAG Laser $\approx 24 \text{ m/h}$	Powder Ti–6Al–4V	1.9–2.1	0.15–0.22	400	–	48	1.0	Gharbi et al. (2012). [17] ^{*3}

Notes. ^{*1} — estimation of authors of paper on data of mode parameters [15]; ^{*2} — single-layer surfacing on narrow substrate $\delta = 1.2 \text{ mm}$; ^{*3} — multi-layer surfacing.

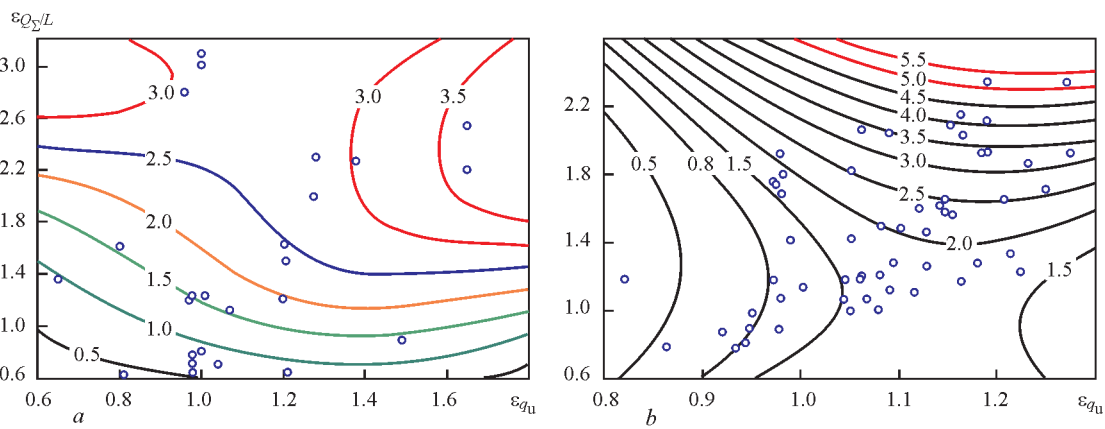


Figure 7. Contour diagram of change of relative area of deposited bead cross-section ϵ_r on relative effective heat power of microplasma arc ϵ_{q_u} and relative heat input of microplasma surfacing $\epsilon_{Q_{\Sigma}/L}$: a — V3K alloy, unit Starweld 190H, continuous powder feed, shielding gas Ar, δ — 0.3–3.0 mm; b — UPNS-304M2/M3 unit, dosed powder feed, shielding gas 95 % Ar + 5 % H₂, $\delta = 1.0$ –2.0 mm

ly to the basic level of $\epsilon_{q_u}, \epsilon_{Q_{\Sigma}/L}$ values allows 1.5–2.0 times decrease of bead cross-section (see Figure 7).

Analysis of experimental data, given in Figures 2–7, allowed outlining 3 basic laws of change of cross-section of the bead deposited on narrow substrate of $\delta = 0.5$ –3.0 mm width. First of them is caused by variation of width of narrow substrate (Figure 8, a) at continuous rate of surfacing: its 6 times extension promotes for 4–8 times increase of effective heat power of the microplasma arc necessary for surfacing, that is accompanied by 8–12 times rise of bead cross-section area. The second is caused by change of effective heat power of microplasma arc per $\pm 20\%$ at constant width of narrow substrate and surfacing rate (Figure 8, b), that is accompanied by 1.3–2.0 times change of bead cross-section area. The third is promoted by 3–4 times variation of surfacing heat input due to its rate at constant width of narrow substrate and effective heat power of microplasma arc (Figure 8, c), that is accompanied by 3–4 times corresponding changes of bead cross-section area. Present laws of change of bead cross-section, as a rule, simultaneously match on practice to that or another degree.

It was assumed earlier in argon-arc welding [2, 3, 10] that the process strength in welding of high-temperature nickel alloys with high content of strengthening γ' -phase is determined with a condition of extreme limitation of welding current and base metal penetration depth. Experience of application of the microplasma powder surfacing [4–8] indicates that the pro-

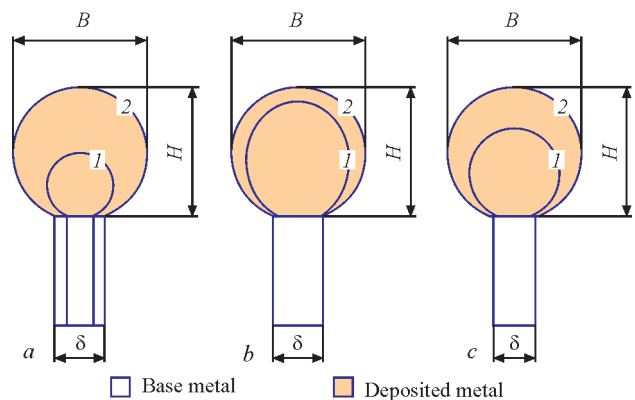


Figure 8. Basic dependencies of change of bead cross-section shape in surfacing on narrow substrate depending on: width of narrow substrate (a), varying effective heat power of microplasma arc (b), changing heat input (c); 1 → 2 — direction of bead cross-section change

cess strength in single-layer surfacing of blade edges can be provided in sufficiently wide range of mode parameters ($I = 2-35$ A, $v = 0.2-5.0$ m/h, $F_b < 30-35$ mm²), where the base metal penetration depth, as a rule, does not exceed 1 mm.

Analysis of corresponding modes of surfacing on narrow substrate $\delta \leq 3$ mm, which are supposed to be close to optimum, showed that 2–4 times change of cross-section area of a bead being deposited promotes for insignificant variation of portion of base metal in the deposited one and it does not exceed 15 %. Respectively, portion of heat consumed for base metal melting does not exceed 2.5 % of effective heat power of the microplasma arc. Therefore, it is relevant to formulate additional criteria of the process strength at transfer to multi-layer surfacing of the blade edges.

A surfacing heat input can be such an additional criterion of the process strength based on stated in works [11, 14] relationship of tendency to crack formation for considered welded joints and total heat input in the part as well as stated in this work dependencies of regulation of cross-section of the deposited bead. Thus, cross-section area of the deposited layer in multi-layer surfacing shall be selected taking into account heat input for determination of narrow substrate width.

Conclusions

1. Process range of energy indices was specified for single-layer microplasma powder surfacing on narrow substrate of width less than 3 mm. In keeping with other technological recommendations, it is possible to provide the process strength of welded joint «base-deposited metal», in which at least one of the materials is high-temperature nickel alloy containing more than 55 vol.% of γ' -phase, using 30–420 W effective heat power of microplasma arc; 100–1600 J/mm surfacing heat input; 0.3–3.0 g/min surfacing efficiency; 1–25 mm² deposited bead cross-section area.

2. In this case under conditions of limited base metal penetration depth, the process regulation of shape and size of cross-section of deposited bead can be done by means of change of effective heat power of the microplasma arc, surfacing heat input, reasonable selection of deposited metal composition and powder feed method (dosed, continuous). The most efficient among them at constant width of narrow substrate are 2.5–4 times variation of heat input, 30–50 % change of effective heat power of the microplasma arc as well as 3.5–6 times variation at their combination. Detected dependencies of the bead shape regulation are used at JSC «Motor Sich» under conditions of serial repair of GTE blades.

3. Additional criteria of the process strength in repair multi-layer microplasma powder surfacing of

blade edges of high-temperature nickel alloys can be the value of heat input and related with it height and cross-section area of the deposited metal layer.

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