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EXPANDING THE TECHNOLOGICAL POSSIBILITIES OF MULTILAYER MICRO-PLASMA POWDER DEPOSITION PROCESS BY OPTIMIZING THE QUALITY AND COMPOSITION OF PROCESS GASES

Introduction. *Mastering the micro-plasma powder deposition (MPWD) technology for refurbishing parts of nickel-based super alloy aircraft gas turbine engine (GTE) has been remaining a relevant task of the Ukrainian aircraft industry for, at least, 15 last years.*

Problem Statement. *MPWD or subsequent heat treatment of GTE parts made of nickel-based super alloy after long-term operating hours, with high* γ'*-phase content, might reveal increased cracking susceptibility. The search for ways to optimize the welding deposition technology has shown the necessity to scrutinize the positive technological effect of rational choice of the quality and content of process (shielding, plasma and transporting) gases.*

Purpose. *To study the effect of process gas content on the heat source parameters, the conditions of the formation of deposited metal and its quality.*

Material and Methods. *Comparative study of the micro-plasma (PPS04 plasmatron, UPNS-304M welding machine) and TIG (VSVU-315 power source) arc heat parameters depending on welding current and process gas has been conducted by the conventional flow calorimetry technology. Comparative estimation of the total work piece heat input parameters has been made based on the previously developed methodology with registering the welding current parameters based on m-DAQ14 analog-to-digital converter (ADC).*

Results. *The comparative research during MPWD of sample parts has shown that the content and quality of process gases can significantly (up to 2.5 times) affect the amount of heat transferred into the work piece and, respectively, the possibility to provide the technological strength of "base-deposited metal" welded joint.*

Conclusions. *The industrial MPWD process optimization by the criteria of work piece heat input parameters, technological strength of "base-deposited metal" welded joint and filler powder consumption,by means of increasing argon (plasma and transporting gas) quality by other gases impurities content and switch to 90% Ar + 10%* H_2 *argon-hydrogen mixture shielding gas has been established to be promising and expedient way to solve the problem.*

Keywords: micro-plasma powder welding deposition, nickel-based super alloys, process gas, weld ability, technological strength, heat transfer control.

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It is a well-known fact that the use of argon-hydrogen mixtures with a higher thermal conductivity, as compared with pure argon, as shield gas, with a small diameter of the plasma nozzle channel may create a needle-shaped micro-plasma arc [1, 2]. Because of the contraction of the arc pillar [3], there are achieved an increased welding current density in the anode spot and the electric field strength in the arc, as well as, accordingly, a higher concentration of the heat flow into the anode. Thus, in the case of welding austenitic materials, the shielding of the welding poolgets better, mixing of its molten metal gets intensified, and the wettability of the molten metal with the edges of the welded joint gets improved, which enhances the weld formation quality [1].

At the same time, with micro-plasma powder welding deposition (MPWD), hard-to-weld high-temperature strength nickel alloys with more than 45 vol. % strengthening γ′-phase content [3—7], despite a decrease in the welding current and an obvious improvement of the conditions for the formation of the “main-welded metal” weld joint, the problem of expediency for using argon-hydrogen mixtures of 95% Ar + 5% H_2 and 90% Ar + 10% H_2 shielding gas, which are serially produced by a number of Ukrainian enterprises has long been debatable. The opposing argument is based on the practical experience of achieving appropriate quality with pure argon as process gas in large-scale repair of GTE blades made of nickel-based super alloys, particularly ZhS32-VI [7].

Over the past few years, the problem of interest has been the development of multilayer MPWD technology or single-layer restoration of ZhS32 alloy high-pressure turbine (HPT) blades after several “operation-maintenance” cycles. In both mentioned cases, under certain conditions, we may observe an upward cracking tendency during welding process or subsequent heat treatments, caused respectively by increasing the affection zones and the level of temporary and residual stresses and deformations or by decreasing the base metal deformation capacity after long operating time. Demand for expansion of MPWD process practical application, considering widely-known inverse dependence between the amount of heat transferred into the work piece and hot cracking susceptibility of nickel-based super alloys [8—10], results in the necessity of search for additional ways of lowering the amount of heat transferred into the work piece and, moreover, decreasing the treatment complexity and cost price of MPWD repair. The search for efficient ways to optimize the MPWD technology for hard-to-weld nickel-based super alloys with a high γ′-phase content causes the necessity of more detailed study on the beneficial technological effect caused by quality and content optimization for gases used.

The purpose of this research, in the context of solving problems set by the aircraft industry of Ukraine, is to analyze the influence of argon-hydrogen mixture used as shielding gas on the heat parameters of welding arc [11], the amount of heat transferred into the work piece [12, 13], and the efficiency of filler powder consumption [14, 15].

COMPARATIVE EVALUATION OF WELDING ARC HEAT PARAMETERS

The micro-plasma arc heat parameters (effective heat arc power and specific heat flow concentration coefficient [11]) depending on welding current and shielding gas type have been studied by the flow calorimetry method [11, 16].To provide the micro-plasma arc stability, we have used PPS04 plasma torch [3—6] based on separated side-delivered filler powder supply construction type [11], with different nozzle channel arc contraction degree. The UPNS-304M installation [3—6] with thyristor-controlled direct polarity welding current is employed as a power source for the micro-plasma arc. For the additional interpretation of determined arc heat parameters, we evaluate the heat characteristics of the straight polarity non-constricted arc and non-melt electrode with welding modes that have been widely used in TIG GTE repair in recent past [17—18]. VSVU-315 power source ensures on-constricted arc burning in argon shielding gas flow and welding cur-

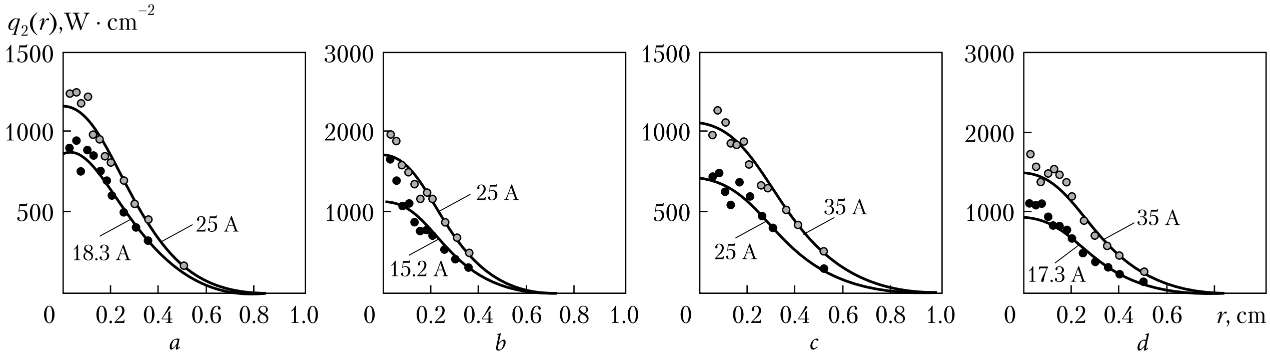


Fig. 1. Radial distribution of micro-plasma arc heat flow, depending on arc's constriction degree by nozzle channels: *a*, *b* — d_{pl} = = 1.8 mm and d_f = 2.5 mm; *c*, *d* — dp_l = 2.5 mm and d_f = 4.5 mm) and shielding gas type (*a*, *c* — argon; *b*, *d* — argon-hydrogen mixture 90% Ar + 10% H_2)

rent power regulation. The wolfram electrode diameter and the sharpening angle are equaled to 2 mm and 20°, respectively. The experimental data on the heat parameters are given in Figs. 1—5.

The heat flow radial distributions of non-constricted and constricted low-amperage arcs have been estimated in the welding current range 15–40 A (Figs. 1—2); the respective distributions of heat flows with equal welding current (20 A) and equal effective heat arc power (341 W) have been compared. It has been discovered that within the studied range for different arc burning conditions, the radial distribution for heat flow into the anode is described by normal distribution [19]. At 5—40...50 A, in all cases, the experimental data on the specific heat flow concentration coefficient (Fig. 4) and effective heat power (Fig. 5) are approximated by linear dependencies with a high degree of confidence (similar to known works [1, 11]).

In the typical technological application range 5—40...50 A, there has been established a significant difference between the heat parameters of constricted and straight polarity non-constricted arc with W-electrode in argon atmosphere (Figs. 4—5). The specific heat flow concentration coefficient values are k = 6.0—10.3 cm^{-2}, for micro-plasma arc, and k = 32.4—35.3 cm^{-2}, for TIG non-constricted arc. Effective heat micro-plasma arc power q_i with similar current 1.7—2.4 times exceeds that of straight polarity non-constricted TIG arc. This is explained by the burning process difference in these low-amperage arcs (Fig. 3), namely different radial size of arc high-temperature zone at flow calorimeter copper water-cooled anode and different voltage (24—26 V and 10—12 V, respectively), which is particularly caused by different arc lengths.

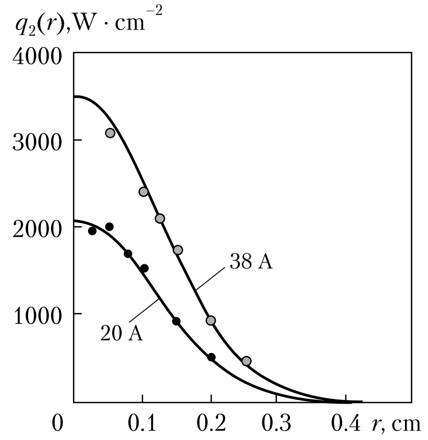


Fig. 2. Radial distribution of low-amperage arc specific heat flow with non consumable wolfram electrode in argon atmosphere

The analysis of known experimental data on the thermal characteristics of micro-plasma arc welding [20] and plasma arc for powder surfacing [11] has shown that for the micro-plasma arc burning conditions and constant ratio of the diameters of the plasma and the focusing nozzles, the switch from argon shielding gas to 90% Ar + + 10% H_2 argon-hydrogen mixture leads to a slight

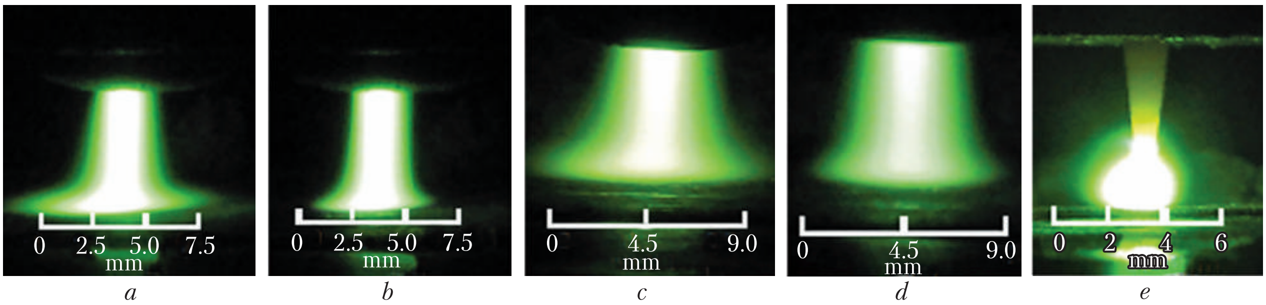


Fig. 3. Comparing appearances of micro-plasma arc with different constriction degrees by nozzle channels: *a, b* — d_{pl} = 1.8 mm and d_f = 2.5 mm; *c, d* – d_{pl} = 2.5 mm and d_f = 4.5 mm) and shielding gas type (*a, c,* — argon; *b, d* — argon-hydrogen mixture 90% Ar + 10% H_2) and straight polarity non-constricted arc with non consumable wolfram electrode in argon atmosphere (*e*).
Note: in every case effective arc power is 341 W; *a* — I = 18.3 A; *b* — I = 15.2 A; *c* — I = 20 A ; *d* — I = 17 A; *e* — I = 38 A; anode distance: *a—d* — 5 mm; *e* — 2 mm

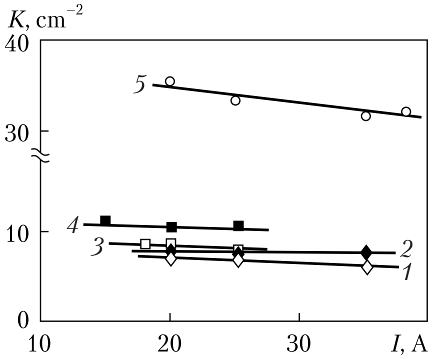
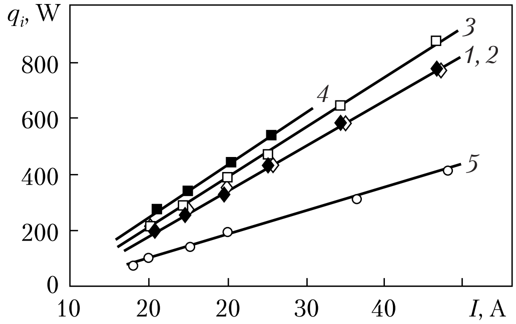


Fig. 4. Specific heat flow concentration coefficient k, depending on welding current I for micro-plasma arc (*1—4*) and non-constricted arc with W-electrode in argon atmosphere (*5*).
◇ — d_{pl}= 2.5 mm, d_{ϕ} = 4.5 mm, argon shielding gas; ◆ — d_{pl} = 2.5 mm, d_f = 4.5 mm, 90% Ar + 10% H_2 argon-hydrogen mixture shielding gas; □ — d_{pl} = 1.8 mm, d_f = = 2.5 mm, argon shielding gas; ■ — d_{pl} = 1.8 mm, d_f = 2.5 mm, 90% Ar + 10% H_2 argon-hydrogen mixture shielding gas; ○ — straight polarity non-constricted arc with W-electrode and argon shielding gas

Fig. 5. Effective heat arc power q_i, depending on welding current I for micro-plasma arc (*1—4*) and non-constricted arc with W-electrode in argon atmosphere (*5*).
◇ — d_{pl}= 2.5 mm, d_{ϕ} = 4.5 mm, argon shielding gas; ◆ — d_{pl} = 2.5 mm, d_f = = 4.5 mm, 90% Ar + 10% H_2 argon-hydrogen mixture shielding gas; □ — d_{pl} = 1.8 mm, d_f = 2.5 mm, argon shielding gas; ■ — d_{pl} = 1.8 mm, d_f = 2.5 mm, 90% Ar + 10% H_2 argon-hydrogen mixture shielding gas; ○ — straight polarity non-constricted arc with W-electrode and argon shielding gas



change in the thermal characteristics (see Figs. 4, 5), as compared with the previous case. For the micro-plasma with lower arc column constriction degree (d_{pl} = 2.5 mm, d_f = 4.5 mm),the switch to argon-hydrogen mixture results in increasing specific heat flow coefficient, at similar welding current, by roughly 1.5 cm^{-2}; and by 2.0—2.5 cm^{-2}, in the case of higher constriction degree (d_{pl} = 2.5 mm, d_f = 4.5 mm). The analysis of approximated dependencies of microplasma arc effective heat power on 40—50 A welding current has shown (Fig. 5) that provided the effective heat values are equal, using 90% Ar + 10% H_2 argon-hydrogen mixture shielding gas results in a decrease in the welding current, as compared with pure argon shielding gas: by 1.1—3.7 A, at d_{pl} = 2.5 mm, d_f = 4.5 mm; and by 2.5—7.0 A, at d_{pl} = 1.8 mm, d_f = 2.5 mm.

ESTIMATION OF ARGON-HYDROGEN MIXTURE EFFECT ON HEAT TRANSFER AND POWDER CONSUMPTION EFFICIENCY

At the next stage of the research, we have recorded welding current with 1—10 kHz registration frequency by mDAQ-14 ADC, made a comparative evaluation of the total amount of heat transferred into the work piece under conditions of actual nickel-based super alloys MPWD process. With the use of previously developed integrated estimations methodology for welding current-time dependency [12—13] we have analyzed:

- effective arc heat power q_i [W] that is proportional to the welding current;
- average heat input q_i/v [J/mm] that simultaneously characterizes the welding current intensity and the deposition speed;
- total heat input $\Sigma Q_\Sigma/L$ [J/mm], given the number of deposited layers.

The typical samples used in this research are given in Fig. 6.

It has been determined that MPWD process on ZhS32 nickel-based super alloy 3 mm thin base using 90% Ar + 10% H_2 argon-hydrogen mixture results in a lower total amount of heat transferred into the work piece (Fig. 7): by 15—25%, for the single-layer MPWD; and by 30—50%, for the four-layer one. Furthermore, using this mixture as shielding gas significantly limits the total amount of transferred heat growth during the MPWD process with ZhS32 powder having ([O] > 250 ppm and [N] > 40 ppm), namely lowers the process sensitivity to powder quality deviations.

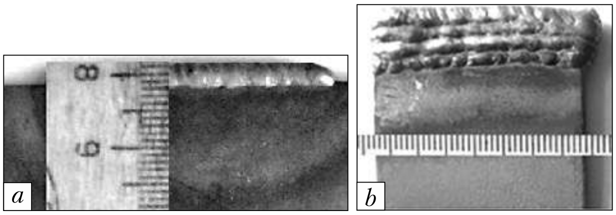


Fig. 6. Samples, used in comparative evaluation of total heat input parameters into the work piece under conditions of actual ZhS32 nickel-based super alloy MPWD process: *a* — single-layer 3 mm thin base; *b* — 4-layer 3 mm thin base

A reduction in the total heat input into the work piece during MPWD process with the use of 90% Ar + + 10% H_2 argon-hydrogen mixture shielding gas is mostly achieved by increasing the deposition speed. This, in its turn, according to visual observation results, is achieved by increasing the welding pool metal flowability and improving its wettability with the base and previously crystallized weld metal.

Practically, MPWD process is realized with 30—60% powder usage coefficient [14, 15] because of relatively small bead width $B \leq 4.0...5.0$ mm and constructive limitations of minimal plasma-

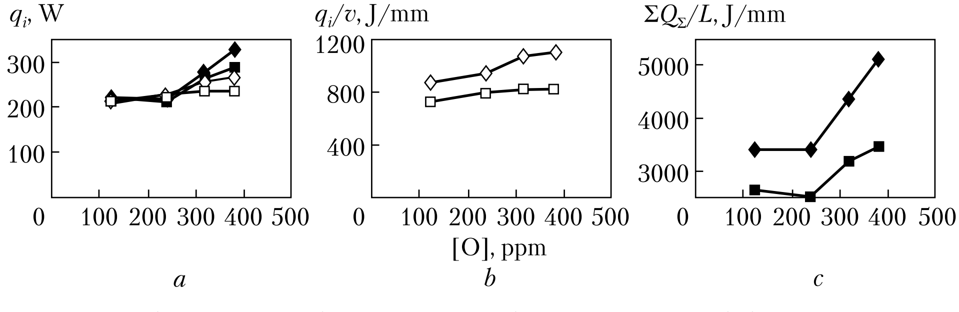


Fig. 7. Dependence of micro-plasma arc effective heat power q_i (provided v = *const),* average heat input q_i/v and total heat input into the work piece $\Sigma Q_\Sigma/L$ during MPWD process with portion wise feeding of ZhS32 nickel-based super alloy powder (UPNS-304 M2/M3 welding machine) on average-weight oxygen content. ◇ ◆ — Ar shielding gas; □ ■ — 90% Ar + 10% H_2 shielding gas; ◇ □ ○ — single-layer deposition; ◆ ■ ● — 4-layer deposition

tron focusing nozzle diameter $d_f \geq 2.5$—3.0 mm, through which the filler powder is brought into micro-plasma arc. Considering the high cost of ZhS32 and ZhS6 nickel-based super alloy filler powders (USD 300—600 per kg), similar to global trends in 3D-deposition processes [21, 22], for MPWD, it is appropriate to carry out technological measures aimed at raising the effectiveness of filler powder usage. The easiest way to accomplish this is to collect part of filler powder, which does not reach the weld pool, and to reuse it several times [15].

Given the above, comparative study of the heat input parameters alteration patterns during single-layer deposition process with re-used ZhS32 filler powder with $[O] = 239$ ppm and $[N] = 20$ ppm with different shielding gas types (Ar and 90% Ar + + 10% H_2) has been conducted. The weld bead cross-section area is determined by direct measurements of its height, width, and subsequent calculation by the previously published method [23].

The experimental data from Table 1 show that multi-cycle usage of filler powder during MPWD, regardless of shielding gas type, only slightly affects the weld oxygen content and actually does not bring it beyond the requirements of specifications [24] ($[O] \leq 30$ ppm, 2003 update) for ZhS32 super alloy, but is followed by a subsequent increase in the total amount of heat transferred into the workpiece. The use of 90% Ar + 10% H_2 shield gas, as compared with Ar, may provide 1—2 additional reuse cycles for ZhS32 nickel-based super alloy filler powder, which results in an increase by 20—30% (as compared with the initial weight of "new" powder) in the consumption efficiency without critical increase in the relative heat input level and with quality weld formation. Considering the market prices for ZhS32 nickel-based super alloy filler powder (≈USD 500/kg) and 90% Ar + 10% H_2 (≈USD 60/cylinder), for MPWD process, this may bring an economic effect that is estimated as approximately 2...3 times with respect to powder and gas purchase costs.

EFFECT OF PROCESS GAS QUALITY AND CONTENT ON MPWD PROCESS APPLIED TO AIRCRAFT GTE PARTS REFURBISHMENT

Similar study of MPWD process has been conducted on real modern GTE parts (Fig. 8), particularly during the imitation of industrial refurbish-

Table 1. **Alteration Patterns of Total Work piece Heat Input Parameters under Conditions of ZhS32 Nickel-Based Super Alloy Filler Powder Re-Use During 2 mm Thin Base Single-Layer Deposition with Argon and 90% Ar + 10% H_2 Argon Mixture Shielding Gas**

I_{RMS} is the effective welding current; q_i is the effective heat power of micro-plasma arc; Q_Σ/L is the heat input of MPWD process; v is the MPWD speed; F_B is the weld bead cross-section area

Re-usage cycle	Shielding gas	I_{RMS}, A	q_i, W	Q_Σ/L, J/mm	v, m/h	F_B, mm²	Deposited metal	
							$[O]$, ppm	$[N]$, ppm
0	Ar	10.7	189.5	582.1	1.18	4.87	21	8.5
1	Ar	11	197.4	759.9	0.94	5.80	–	–
2	Ar	12.5	222.8	864.6	0.93	6.27	–	–
3	Ar	15.3	266.4	1089.8	0.89	8.27	–	–
4	Ar	16.2	292.1	1247.3	0.84	9.50	35	12
0	90% Ar + 10% H_2	6.92	156.7	465.9	1.29	3.95	17	4.7
1	90% Ar + 10% H_2	7.17	160.3	484.5	1.23	4.65	–	–
2	90% Ar + 10% H_2	7.72	169.9	490.2	1.24	5.05	–	–
3	90% Ar + 10% H_2	7.92	173.1	520.6	1.19	5.81	–	–
4	90% Ar + 10% H_2	8.4	182.0	600.4	1.1	6.45	24	7.6

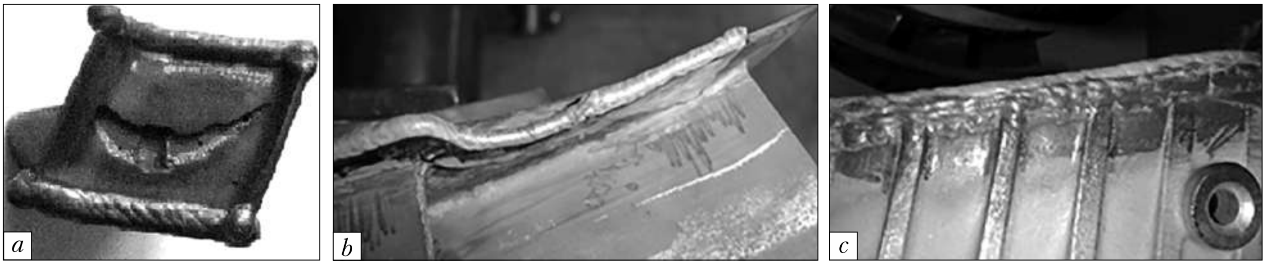


Fig. 8. Studied modern GTE part samples, used to research effect of process gas quality and content effect on nickel-based super alloy MPWD process: *a* — D-18T GTE HPT blade, ZhS32-VI super alloy; *b* — HPT nozzle vanes sector, ZhS6K super alloy; *c* — jet nozzle sash, VH4L super alloy

ment technology for D-18T aircraft GTE HPT ZhS32 blade bandage shelves with the use of copper shaping fixture [3—6].

The experimental data from Table 2 show that for MPWD process, the switch from argon to argon-hydrogen mixture results in a decrease in the work piece-anode total transferred heat amount: approximately by 20%, including a decrease by 12% in the micro-plasma arc effective heating power, for separate welding pool existence period; by approximately 40%, including 10% decrease in effective heat arc power by 10%, for full bandage shelve refurbishment process. Combination of 90% Ar + 10% H_2 usage with more effective welding current regulation method increases by 5—10% the respective values of MPWD heat input parameters.

A decrease in the total amount of heat transferred into the work piece with the use of 90% Ar + + 10% H_2 mixture has been also observed during ZhS6K super alloy MPWD process (Fig. 8b, Table 3) with higher power values. The total work piece heat input $[Q_\Sigma/L]_\Sigma$ with the use of 90% Ar + + 10% H_2 mixture decreases by approximately 42% for single-layer deposition and by approximately 65% for two-layer deposition, with the effective micro-plasma arc heat power remaining almost unchanged (up to 10%).

We have conducted a series of experiments on studying the effect of process gas quality and content on the MPWD total heat input values, with the use of modern STARWELD PTA 190H welding machine, at a constant powder feeding rate, while developing a technology forVH4L alloy jet nozzle sash refurbishment (Fig. 8, *c*, Table 4).

The experimental data in Table 4 show that during nozzle sash edge MPWD refurbishment proc-

Table 2. **Total Heat Input Parameters Alteration Patterns for D-18T HPT Blades Microplasma Refurbishment Process Imitation on 1.5 mm Thin Base with the Use of Argon Shielding Gas and 90% Ar + 10% H_2 Mixture**

Exp. №	Shielding gas	Anode heat input parameters							Welding bead cross-section characteristics	
		During separate weld pool existence period*			Total heat input parameters during single-layer MPWD					
		t_B, sec	q_i, W	Q_Σ, J	I_{RMS}, A	q_i, W	Q_Σ/L, J/mm	v, m/h	Fв, mm²	γ_o, %
1	Ar	3.56	247.77	880.50	12.59	241.03	1172.32	0.74	11.47	12.44
2	90% Ar + 10% H_2	3.22	219.37	705.21	11.02	220.12	719.67	1.1	11.23	10.60
3	90% Ar + 10% H_2**	3,27	156.20	509.60	10.17	211.45	691.9	1.1	10.64	10.46

Note: I_{RMS} is the effective welding current; q_i is the effective heat power of micro-plasma arc; Q_Σ/L is the heat input of MPWD process; v is the MPWD speed; Fв is the weld bead cross-section area, γ_o is the base metal part in the deposited bead

* — in central part of blade's bandage shelve; ** — with cyclic impulse current regulation in 7.5—15 A range

ess with ChS40 filler powder, there is an essential effect of a decrease in the total heat amount transferred into the work piece takes place after switch from First Grade Argon to Highest Grade according to [25]. Considering similar deposited bead height, we might observe: a reduction in the number of deposited metal layers from 3 to 2; a decrease in the effective micro-plasma arc heating power by approximately 24%; an approximately 2.1-time decrease in the total work piece heat input $[Q_\Sigma/L]_\Sigma$. The further switch to 95% Ar + 5% H_2 argon-hydrogen mixture results in a certain increase in necessary effective arc heating power (≈6.5%), but the total heat input into the work piece $[Q_\Sigma / L]_\Sigma$ additionally decreases by 28%, as compared with the process with Highest Grade argon.

It should be also mentioned, that while optimizing the content and quality of process gas according to previously described succession, additionally, with decrease of heat amount transferred into the work piece, we may observe the following positive technological effects: a certain increase in the height of deposited bead, approximately by 0.5 mm per layer; a decrease in the total bead volume by approximately 35%, mostly due to a decrease in the side reinforcements of deposited bead from 2.5—3.5 mm up to 1.0—1.5 mm per side. This generally results into higher multilayer MPWD process productivity and lower labor input, and moreover, lower labor input and technical difficulty of further mechanical processing of multilayer bead. The mentioned technological effect takes an essential part in creating positive image of MPWD process for Ukrainian GTE refurbishment industry.

Recent publications [26—27] have shown that the destructive conditions under high-temperature 1000 °C tensile strength test on ZhS32 and ZhS6K MPWD-deposited metal are characterized with ultimate tensile strength $\sigma_в$ = 345—385 MPa

Table 3. **Energy Parameters of Two-Layer MPWD on “Base-Deposited Metal” Weld Joint Samples of ZhS6U-ZhS6K System Depending on Shielding Gas Type with UPNS-304M2/M3 Welding Machine**

δ, mm	Shield gas	I_{RMS}, A	q_i, W	v, m/h	Q_Σ/L, J/mm	$[Q_\Sigma/L]_\Sigma$, J/mm
5 (layer 1)	Ar	25.84	425.45	0.987	1552	3553
5 (layer 2)	Ar	26.66	425.15	0.765	2001	
5 (layer 1)	90% Ar + 10% H_2	25.87	402.36	1.375	1054	2145
5 (layer 2)	90% Ar + 10% H_2	27.14	431.24	1.422	1091	

Note: I_{RMS} is the effective welding current; q_i is the micro-plasma arc effective heat power; v is the welding speed; Q_Σ/L is the heat input considering heating efficiency; $[Q_\Sigma/L]_\Sigma$ is the total heat input sum considering heating efficiency

Table 4. **Nozzle Sash Edges Multilayer MPWD Process Energy Parameters Depending on Shielding Gas Quality and Type. Thin Base Width ≈4 mm; ChS40 Deposited Metal**

Argon process gas	H, mm	Deposited layers number	V_D, cm³	I_{RMS}, A	q_i, W	Q_Σ/L, J/mm	$[Q_\Sigma/L]_\Sigma$, J/mm	v, m/h	p, mm
First Grade	5	3	≈8	22.3	431.4	750.8	2252.5	2.068	2.5–3.5
Highest Grade	5	2	≈6	19.8	328.2	528.2	1056.3	2.237	1.5–2.5
Highest Grade + shield gas 95% Ar + 5% H_2	6	2	≈5.2	20.32	350.49	380.2	760.4	3.319	1.0–1.5

Note: H is the deposited bead height; V_D is the total volume of deposited metal; I_{RMS} is the effective welding current; $[Q_\Sigma/L]_\Sigma$ is the total heat input sum given heating efficiency; p is the side reinforcement of deposited bead.

and critical deformation ε = 0.1—0.65%. The long-term practice of GTE parts refurbishment has shown that these conditions can be quite easily exceeded with an increase in the heat amount transferred into the work piece by 30—50% of optimal range of MPWD process technological parameters, thus substantially increasing the amount of defective parts during large-scale repair. Therefore, in addition to a reduction in the loss of specialized filler powder and a certain improvement in "base-deposited metal" welded joint formation conditions, in terms of decreasing the level of temporary and residual stresses and strains, respectively improving the GTE blade MPWD repair process qualitative stability, according to the authors, the technological effect of reducing the heat amount transferred into the work piece by gas type and quality optimization, which mainly appears in lesser single part deposition time, is of great importance.

CONCLUSION

1. The expediency of decreasing amount of heat transferred into the work piece during the MPWD process by the consequent optimization of process gas content and quality by the following scheme: argon First Grade GOST 10157-79 (plasma, transporting and shielding gas) → argon Highest Grade GOST 10157-79 (plasma, transporting and shielding gas) → argon Highest Grade GOST 10157-79 (plasma and transporting gas) + 95% Ar + 5% H_2 argon-hydrogen mixture → argon Highest Grade GOST 10157-79 (plasma and transporting gas) + 90% Ar + 10% H_2 argon-hydrogen mixture has been proved.

2. It has been determined that the most essential decrease in the transferred heat amount (approximately 2.0—2.2 times) is observed when the Highest Grade argon substitutes for the First Grade argon. This effect is achieved mostly because of an increase in the thin base powder deposition efficiency by lowering transferred heat amount of single-layer deposition and number of deposited metal layers.

3. The increasing effective arc heating power with the use of 95% Ar + 5% H_2 mixture is compensated by a decrease in the welding current intensity that is required to provide nickel-based super alloy MPWD process stability and the possibility of a simultaneous increase in the deposition speed. The comparative research for MPWD of sample hard-to-weld nickel-based super alloy aircraft GTE parts with 10—30 A effective welding current has shown that the switch from Highest Grade argon to argon-hydrogen mixture 90% Ar + 10% H_2 results in a decrease in the total work piece-transferred heat amount: by 15—30%, in the case of single-layer deposition and by 30—60%, in the case of multi-layer deposition. The total effect of decreasing transferred heat amount is observed as much for single weld pool, because of a decrease in the effective micro-plasma arc heating power and the required existence time, as for deposited bead as a whole.

4. It has been determined, that using 90% Ar + + 10% H_2 mixture in ZhS32 nickel-based super alloy MPWD allows up to 2 additional filler powder re-usage cycles due to limitation of an increase in the total work piece-transferred heat amount approximately 1.5—2 times. This lowers expensive filler powder consumption by 20—30%, therefore we may predict a positive economic effect due to increased consumption efficiency of expensive filler powder, which is approximately estimated as 2...3 times in terms of purchase costs.

REFERENCES

1. Paton, B. E., Gvozdetskiy, V. S., Dudko, D. A. (1979). *Micro-plasma welding*. Kyiv [in Russian].
2. Gvozdetskiy, V. S. (1974). Welding arc contraction. *Automatic welding*, 2, 1—4 [in Russian].
3. Peychev, G. I. (2005). Repair of operation-worn cast turbine blades bandage shelve constructive elements made of JS-type alloys. *Aircraft and space technic and technology*, 9(25), 221—223 [in Russian].

4. Yushchenko, K. A., Savchenko, V. S., Yarovitsyn, O. V., Nakonechny, A. A., Nastenko, G. F., Zamkovoj, V. E., Belozertsev, O. S., Andrejchenko, N. V. (2010). Development of the technology for repair microplasma powder cladding of flange platform faces of aircraft engine high-pressure turbine blades. *The Paton Welding Journal,* 8, 25—29.
5. Yushchenko, K. A.,Yarovytsyn, O. V. Technological advancement of refurbishment process for the aircraft GTE blade's upper bangade shelf. *Complex target program of NAS Ukraine «Operation resource and safety problems of buildings and machine constructions», article digest on results achieved in 2010—2012. Paton EWI NAS Ukraine*, Kyiv. 506—509 [In Ukrainian].
6. Yushchenko, K. A., Yarovytsyn, O. V., Fomakin, O. O. (2016). Development of JS32 micro-plasma powder deposition technology for gas-cooled aircraft high-pressure turbine blade. *Complex target program of NAS Ukraine «Operation resource and safety problems of buildings and machinery constructions», article digest. Paton EWI NAS Ukraine*, Kyiv. 696—701 [In Ukrainian].
7. Zhemanyuk, P. D., Petrik, I. A., Chigilejchik, S. L. (2015). Experience of introduction of the technology of reconditioning microplasma powder surfacing at repair of high-pressure turbine blades in batch production. *The Paton Welding Journal*, 8, 43—46. https://doi.org/10.15407/tpwj2015.08.08.
8. Sims, C. T. (1987). *Super alloys II: High-Temperature Materials for Aerospace and Industrial Power.* (Eds. C. T. Sims, N. S. Stoloff and W. C. Hagel). New York: John Wiley & Sons.
9. Sorokin, L. I. (1999). Strain and cracks during welding and thermal processing of nickel super alloys. *Welding manufacturing*, 12, 11—17 [in Russian].
10. Du Pont, John N. (2009) *Welding metallurgy and weld ability of nickel-base alloys* (Eds. John N. Du Pont, John C. Lippold, Samuel D. Kisser). New Jersey.
11. Gladkiy, P. V. (2007). *Plasma cladding* (Eds. Gladky P. V., Perepliotchikov E. F., Ryabtsev I. A.) Kyiv [in Russian].
12. Yarovitsyn, A. V. (2015). Energy approach in analysis of microplasma powder surfacing modes. *The Paton Welding Journal*, 5—6, 14—21. https://doi.org/10.15407/tpwj2015.06.03.
13. Yushchenko, K. A., Yarovitsyn, A. V., Chervyakov, N.O. (2017). Effect of energy parameters of microplasma powder surfacing modes on susceptibility of nickel alloy ZhS32 to crack formation. *The Paton Welding Journal*, 2, 3—7. https://doi.org/10.15407/as2017.02.01.
14. Yushchenko, K. A., Yarovitsyn, A. V., Yakovchuk, D. B., Fomakin, A. A., Mazurak, V. E. (2013). Some techniques for reducing filler powder losses in microplasma cladding. *The Paton Welding Journal*, 11, 32—38.
15. Yarovitsyn, A. V., Yushchenko, K. A., Nakonechny, A. A., Petrik, L. A. (2009). Peculiarities of low-amperage argon-arc and microplasma powder cladding on narrow substrate. *The Paton Welding Journal*, 6, 37—42.
16. Demyantsevich, V. P., Mykhailov, N. P. (1973). Research on micro-plasma arc heat distribution under condition of heated spot center displaced from the welded joint axis. *Welding manufacturing*, 6, 1—3.
17. Peremylovskiy, I. A., Geychenko, V. S., Frumin, I. I. (1976). Cladding refurbishment of aircraft engine turbine blades. *Automatic welding*, 5, 54—56.
18. Petryk, I. A., Peremylovsky, I. A. (2001). Future development of strengthening technology for superalloy blade's bandage shelves. *Technological systems*, 3, 90—92.
19. Bronstein, I. N., Semendyaiev, K. A. (1967). *Mathematics reference book (for engineers and technical university students, 11thed.)*. Moscow.
20. Demyantsevich, V. P., Mikhailov, N. P. (1973). Interaction of microplasma arc with the heated work piece. *Welding manufacturing*, 8, 2—4.
21. Renderos, M., Griffit, F., Lamikiz, A., Njrregaray, A., Sainter, N. (2016). Ni-based reconditioning and reuse for LMD-process. *Physics Procedia,* 83, 769—777. https://doi.org/10.1016/j.phpro.2016.08.079.
22. Petroic, V., Niňerola, R. (2015). Powder recyclability in electron beam melting for aeronautical use. *Aircraft Engineering and Aerospace Technology*, 87(2), 147—155. https://doi.org/10.1108/AEAT-11-2013-0212.
23. Yushchenko, K. A., Yarovitsyn, A. V., Khrushchov, G. D., Fomakin, A. A., Olejnik, Yu. V. (2015). Analysis of process of bead shaping in cladding on narrow substrate. *The Paton Welding Journal*, 9, 20—27. https://doi.org/10.15407/tpwj2015.09.03.
24. *Technical Conditions TU 1-92-177-91.* Vacuum-melted cast super alloy measured charge billet. 5th edit. [in Russian].
25. *DSTUGOST 10157:2019.*Liquid and gas argon. Technical conditions (GOST 10157-2016, IDT).
26. Yarovytsyn, O. V. (2020). About the deformation ability of overlay metal of nickel-base difficult to weld high temperature strength alloys with γ′-phase strengthening high content. *Metaloznavstvo ta obrobka metalliv*, 26(94), 38—48. https://doi.org/10.15407/mom2020.02.038 [in Ukrainian].

27. Yushchenko, K. A., Zviagintseva, G. V., Yarovytsyn, O. V., Chervyakov, N. O., Khrushchov, H. D., Volosatov, I. R. (2019). New Approaches in Evaluation of Mechanical Characteristics and Microstructure of Restored Parts of GTE from Nickel Heat-Resistant Alloys. *Metallofizika I Noveishie Tekhnologii,* 10(41), 1345—1364. https://doi.org/10.15407/mfint.41.10.1345 [in Ukrainian].

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РОЗШИРЕННЯ ТЕХНОЛОГІЧНИХ МОЖЛИВОСТЕЙ ПРОЦЕСУ БАГАТОШАРОВОГО МІКРОПЛАЗМОВОГО ПОРОШКОВОГО НАПЛАВЛЕННЯ ШЛЯХОМ ОПТИМІЗАЦІЇ ЯКОСТІ ТА СКЛАДУ ТЕХНОЛОГІЧНИХ ГАЗІВ

Вступ. Освоєння технології багатошарового мікроплазмового порошкового наплавлення (МПН) для відновлення деталей авіаційних газотурбінних двигунів із нікелевих жароміцних сплавів (НЖС) є актуальним питанням вітчизняної авіаційної промисловості.

Проблематика. При відновленні наплавленням або наступних термічних обробках після тривалого напрацювання в деталях авіаційних газотурбінних двигунів (ГТД) з НЖС із високим вмістом зміцнюючої γ'-фази може виникати підвищена схильність до утворення тріщин. Пошук шляхів оптимізації технології наплавлення виявив необхідність детального вивчення корисного технологічного ефекту від раціонального вибору якості та складу технологічних газів.

Мета. Дослідження впливу складу технологічних газів на теплові характеристики джерела тепла, кількість тепло вкладень у виріб та умови формування наплавленого металу.

Матеріали й методи. Порівняльні дослідження теплових характеристик мікроплазмової (плазмотрон ППС04, установка УПНС-304М) та аргонової (джерело живлення ВСВУ-315) дуг залежно від величини зварювального струму, складу та якості технологічних газів проводилися згідно методик проточного калориметрування, а порівняльну оцінку складових загальних тепловкладень у виріб — шляхом реєстрації параметрів режиму зварювання на базі АЦП mDAQ-14.

Результати. Порівняльні дослідження при наплавленні модельних деталей показали, що склад та якість технологічних газів можуть суттєво впливати (до 2,5 разів) на кількість тепловкладень у виріб, та, відповідно, на можливість забезпечення технологічної міцності зварного з’єднання «основний—наплавлений метал».

Висновки. Виявлено резерви та обґрунтовано доцільність оптимізації промислового процесу МПН за складовими тепловкладень у виріб, технологічної міцності зварного з’єднання «основний—наплавлений метал» та витрат присадного порошку шляхом підвищення якості аргону (плазмоутворюючий та транспортуючий гази) за вмістом домішок інших атмосферних газів та переходу до використання аргоноводневої суміші 90% Ar + 10% H_2 як захисного газу замість аргону.

Ключові слова: мікроплазмове порошкове наплавлення, нікелеві жароміцні сплави, технологічний газ, зварюваність, технологічна міцність, кількість тепловкладень у виріб, ефективність використання присадного порошку.