Electrospark alloying of titanium alloy aircraft engine parts

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Abstract. The study objective is to improve the performance of titanium alloy parts used in aircraft jet engines with electrospark alloying. The technology can be used for hardening compressor rotary vanes and rod ball joints, protecting compressor blade leading edges from erosion. We studied the alloyed layer formation process and determined the layer structure and composition. The study presents experimental findings of the Ti alloy electrospark alloying as certain substances were introduced into the interelectrode gap. We also assessed the relationship between the electrospark alloying process variables and the alloyed layer surface finish.

1. Introduction

Ti alloy parts are extensively used in aircraft jet engines. However, titanium and its alloys have extremely low anti-friction and wear resistance properties. The reason is that during a contact interaction (friction, fretting), titanium intensively absorbs oxygen from the air. It leads to the formation of solid-state solutions that harden the contact area. As a result, the metal breaks away, and its surface adhesion to long molecular chain hydrocarbons is reduced.

Ti alloys have poor anti-friction and wear resistance properties. It is difficult to improve them by alloying with other metals. Electrospark surface alloying (ESA) [1] can be used to improve the Ti alloy parts performance under contact loads. The proposed process can be used for hardening compressor rotary vanes and rod ball joints, protecting compressor blade leading edges from erosion.

ESA can extensively control the surface layer composition and properties. It is a general-purpose, highly capable technology. Local alloying leads to reduced energy consumption, and no extra heating of the hardened parts. The deposited layer thickness range is 10 to 150 μm. The R₉₀₅ surface roughness is between 1.5 and 10 μm. The electrodes can be made of various metals to deposit wear-resistant coatings made of W, Ti, Cr, Ta, Mo, Hf, Zr, Nb, V; Ti, Zr, Ta borides; heat-resistant intermetallic compounds, Ni and Co high-temperature alloys; Au, Ag, Pt, Pd, Rh precious metals [2].

The paper presents the results of our comprehensive research intended to assure the deposition of high-quality alloyed layers on Ti alloy parts.
2. Materials and research methods
The samples were Ti alloy aircraft jet engine parts. A state-of-the-art ELFA-731 electrospark alloying machine commonly used by domestic manufacturers served as a testbench for applying multicomponent and multilayer coatings. The machine is computer numerical controlled (figure 1).

![ELFA-731 electrospark alloying machine](image1)

Figure 1. ELFA-731 electrospark alloying machine.

Figure 2 shows the machine arrangement. For electrospark alloying, alloying electrode 1 is fed into two mutually transverse directions relative to the workpiece to be hardened. The workpiece is attached to table 2 machine. For the X-axis feed, the gantry 3 is moved. For the Y-axis feed, the carriage 4 is moved. As surfaces of revolution are treated (cylindrical, tapered, shaped parts, etc.), the workpiece is held by the chunk of the tooling 5, and rotation around the Z-axis is enabled. The movements and feed rates are computer numerical programmed.

![ELFA-731 machine arrangement](image2)

Figure 2. ELFA-731 machine arrangement.

We used an independent impulse generator. It generates unipolar square-wave impulses. The impulse duration $T_i$ is 3-20 $\mu$s, the duty cycle $g$ is 10, 5, the short-circuit current $I_{cs}$ is 6.4-16 A for the output voltage $U_o = 90$ V. To improve the electro-erosion efficiency, a capacitor bank ($C = 0.1$ to 1.0 $\mu$F) is connected in parallel to the interelectrode gap.

3. Results and discussion

3.1 Alloysed layer formation
We used the Ti alloy parts electrospark alloying with ELFA-731 to identify the alloyed layer formation details.

The amount of the material transferred to the surface to be hardened usually varies directly with the period of alloying (figure 3). In this particular case, we considered the specific mass transfer $m$ for the alloying period per unit of surface $t_e$ up to 8 min/cm$^2$. In real life, the $t_e$ value commonly used for
electrospark hardening of Ti alloy parts is such that the \( m = f(t_e) \) relation can be assumed to be linear, so we can estimate the mass transfer with this assumption [3]. Figure 3 demonstrates a significant effect of the alloying electrode on the mass transfer rate for Ti alloy parts electrospark alloying. It is impossible to identify a one-fits-all criterion to unambiguously describe the mass transfer as a function of physical, chemical, and mechanical properties of the electrode materials, and the hardening conditions [4].

![Figure 3](image)

**Figure 3.** Specific alloying time vs. mass transfer: 1: base metal: VT23 Ti alloy; alloying metal: VK6-M; 2: base metal: VT23; alloying metal: tantalum.

Figure 4 shows the erosion rates \( \Gamma \) for alloying electrodes made of various materials. The values are experimentally measured under identical hardening conditions \( (I_c = 16 \text{ A}, g = 5, t_i = 20 \mu \text{s}, C = 1 \mu \text{F}, t_e = 8 \text{ min/cm}^2) \) according to the Palatnik criterion \( P_l = c \rho \lambda T_{pl2} \).

![Figure 4](image)

**Figure 4.** Alloying electrode erosion rate estimated with the Palatnik criterion for the VT23 Ti alloy electrospark alloying.

The identified high erosion rates of the Zr and Ti alloying electrodes are explained by the susceptibility of these materials to gas pickup when heated up by electric discharges. As a result, the electric resistance of the gas-anode interface increases, which causes excessive heat generation and mass transfer through the melted metal spreading across the surface being hardened [5]. Due to its low heat conductivity, the Zr alloying electrode heating can be so high that it ignites. Figure 5 is a photo of a VT23 Ti alloy part after electrospark alloying with a Zr electrode.

![Figure 5](image)

**Figure 5.** A VT23 Ti alloy part after electrospark alloying with a Zr electrode (×70 magnification).
We studied the effects of the alloying electrode feed rate on the erosion rate $\Gamma$. In the $v = 50$-500 mm/min electrode feed range, $\Gamma$ is virtually constant (figure 6).

![Figure 6](image)

**Figure 6.** Alloying electrode feed rate vs. electrode erosion rate for VT23 Ti alloying with vanadium.

At low feed rates, the areas adjacent to the electrode surface are heated up. It has various effects on the mass transfer rate and features for a range of electrode combinations. For Ti alloy electrospark alloying at $v < 50$ mm/min, $\Gamma$ increases. One reason is the gas pickup.

3.2. Effects of the electrospark alloying process variables on the alloyed layer surface finish

To identify the effects of the electrospark alloying process variables on the alloyed layer surface finish, we studied the VT23 Ti alloy (figure 7) at $t_e = 3.3$ min/cm$^2$. It was found that by using tantalum and adjusting the process variables it is possible to reach $R_a = 0.2$-2.0 $\mu$m surface roughness. The key variables are the short-circuit current, and the discharge capacitor capacitance. We used polished workpieces $R_a = 0.04$ $\mu$m).

![Figure 7](image)

**Figure 7.** Effects of the electrospark alloying process variables on the alloyed layer surface finish. Base metal: VT23 1: $I_c = 6.4$ A; 2: $I_c = 9.6$ A; 3: $I_c = 12.8$ A; 4: $I_c = 16$ A.

Electrospark alloying with lower intensity results in low roughness and low alloyed layer thickness. When there is no finish machining, two-pass alloying is recommended. First, the surface is hardened intensively to obtain the required thickness of the alloyed layer, and then a low-intensity mode is used to achieve low surface roughness [6]. For instance, as the VT20 Ti alloy was treated with a VK6-M
By introducing various substances into the interelectrode gap, in some cases, we can greatly intensify the anode-to-cathode mass transfer [7]. Without introducing such substances, the mass transfer in erosion-resistant materials (copper, molybdenum, tungsten, etc.) is extremely low, or non-existent.

Table 1 lists the erosion rates and the $C_t$ mass transfer rates vs. the substance spread across the hardened surface. The base metal is the VT23 Ti alloy. The electrospark alloying process variables were as follows: $I_c = 16$ A, $g = 5$, $t_i = 20$ μs, $C = 1$ μF.

| Alloying electrode | Material applied to the surface | $\Gamma \times 10^3$, mm$^3$/min | $C_t$ |
|--------------------|---------------------------------|---------------------------------|------|
| $C_r$              | No spreading                     | 9.83                            | 0.83 |
|                    | Graphite                         | 41.6                            | 1    |
|                    | Mica                             | 105.3                           | 1.07 |
|                    | MoS$_2$                          | 36                              | 1.5  |
| Cu                 | No spreading                     | 14.28                           | 1    |
|                    | Graphite                         | 16.2                            | 0.84 |
|                    | Mica                             | 80.4                            | 0.79 |
|                    | MoS$_2$                          | 11.6                            | 1.08 |
| Ta                 | No spreading                     | 6.7                             | 0.92 |
|                    | Graphite                         | 23.1                            | 1.64 |
|                    | Mica                             | 92.7                            | 1.08 |
|                    | MoS$_2$                          | 0.5                             | 4    |
| W                  | No spreading                     | 2.1                             | 1.1  |
|                    | Graphite                         | 4.2                             | 1.2  |
|                    | Mica                             | 93.1                            | 0.65 |
|                    | MoS$_2$                          | 2.5                             | 1    |

We applied the G-1 grade graphite, MoS$_2$ powder, and ground mica (KAl$_2$[Si$_3$AlO$_10$][OH]$_2$) to the surface. The data show that the application of various materials on the surface have different effects on the mass transfer rate [8]. For example, with mica, the mass transfer rate can be increased tenfold, and more. There are several explanations for such a substantial increase: the alloying electrode is extra heated as the gas-anode interface resistance increases due to the deposition of chemical substances on the electrode surface; the substances dissociated and ionized by the electric discharges chemically destroy the electrode materials (mostly the anode). The compositions formed have lower electric erosion resistance than the original anode material. Substances introduced into the interelectrode gap improve the electric discharge treatment efficiency by reducing the ionization potential extra heat is generated through the decomposition of the introduced substances and chemical reactions in the interelectrode gap. The substance efficiency depends on the factors listed above. Note that the processes in the interelectrode gap are controlled by the amount of the substance introduced. The amount depends on the application technique.

Let us consider several electrospark alloying applications for various materials. The technology produces high-quality, anti-friction coatings made of metals and alloys (copper, zinc, cadmium, silver, bronze, brass, etc.) For instance, copper coatings are of special interest as they enable selective transfer and better scoring resistance. Compounds with alkali metals (K, Na, Li), and base or acid groups (OH, SO$_3$, SO$_4$, CO$_3$, MnO$_4$, B$_2$O$_3$, Br, J) in the interelectrode gap facilitate the formation of high-quality
copper coatings on steel, nickel, and titanium alloys. Salts and bases of other metals (CaCO₃, CuSO₄ and others) do not facilitate copper coating deposition. Possibly, the presence of alkali metals leads to the chemical destruction of the alloying oxygen. For instance, such compounds as KCuO₂, Na₃CuO₂ can be formed. The eroded material is exposed to pyrolysis when heated by the electric discharges. Provided that there is a reducing atmosphere around the cathode, a fine-grade coating is deposited on it. When oxygen-containing salts are applied, as a rule, the anode erosion prevails, and the coating almost completely consists of copper. When the salts contain halogens (KBr, KJ), the anode and cathode erosion rates are comparable, and an alloyed layer is formed (bronze containing the substrate metal). With this technology, we manufactured high-quality coatings on Ti alloys covered with KBr. The Cu and Ti bromides after decomposition form a bronze, golden color coating with high wear-resistance and excellent anti-friction properties [9]. Electrospark alloying with graphite applied to the hardened surface is an efficient way of making bronze coatings on steel parts. Bronze alloying electrodes are used. The coating properties depend on the alloying elements. For instance, BrO₁₀S₁₀ (US analog: C93700), BrB₂ (US analog: C17200), BrAZHMTS₁₀-3-1.5 (EU analog: CuAl₁₀Fe₃Mn₂), BrVB₂₃NTS (composition: BaSb₃Ni₃Zn₃Pb₂₀P0.₂) bronze grades were used to make anti-friction coatings on SHKH₁₅ (US analog: 52100), 30KHGSA (US analog: 14331), 13KH₁₁N₂V₂MF (US analog: 420) steel grade substrates. The microhardness values of the coatings are: $H_m = 1650$ MPa (BrO₁₀S₁₀), $H_m = 5320$ MPa (BrB₂), $H_m = 3670$ MPa (BrAZHMTS₁₀-3-1.5), $H_m = 2140$ MPa (BrVB₂₃NTS). Graphite intensifies the transfer of bronze to the steel part surface. Some graphite burns out in the electric discharges liberating extra heat. Another portion of the graphite remains in the coating as inclusions that improve its anti-friction performance.

We detected the max transfer rate for BrB₂ bronze electrospark alloying ($I_c = 246.4 \times 10^3$ mm³/min). It can be attributed to beryllium oxidation, a sharp rise of electric resistance and subsequent extra heat generation at the anode. The surface finish in this case is rough.

For BrO₁₀S₁₀ bronze that forms uniform, continuous, soft coating with low substrate erosion, the transfer rate $I_c$ is $118 \times 10^3$ mm³/min (at the most intense electrospark alloying mode supported by ELFA-731). Bronze-graphite coatings can be deposited on Ti alloys as well. In this case, the applied graphite powder should also contain 10-20% of an alkali metal composition (e.g., mica.) Otherwise, the bronze transfer is low, and no anti-friction coating is formed.

### 3.4 Experimental Studies of the Coating Performance

VT₂₃ Ti alloy was electrospark alloyed. The process variables were $I_c = 16$ A; $g = 5$; $t_i = 5$ μs; $C = 20$ μF; $v = 200$ mm/min; $t_c = 6.4$ min/cm². We express tested the relation between the alloying electrode metal and the coating wear resistance. It was found that tantalum, tungsten, nickel, TiC electrospark alloying produces the best wear resistance properties (table 2).

The strength of an alloying layer over a Ti alloy substrate is limited. To estimate the strength, we measured the number Np of sliding strokes of an artificial diamond ball penetrator till the alloyed layer is destroyed, another property that characterizes the hardened surface bearing capacity is the bearing layer thickness $h_{bl}$. It is estimated by measuring the bp width of the groove formed as the alloyed layer is broken as follows:

$$h_{bl} = \frac{b_p^2}{8R} \tag{1}$$

$h_{bl}$ depends on the alloyed layer thickness and strength. W is the wear resistance multiplier determined by the express tests (the alloyed layer is rubbed by an artificial diamond ball penetrator) as compared to the bare substrate. W, Np and $h_{bl}$ values indicate the alloyed layer bearing capacity under contact loads. For Ti alloy electrospark alloying with hard melting electrodes, the coating’s bearing capacity rises as the alloying period per unit area increases. For example, for W alloying electrodes at $t_c = 6.4$ min/cm² Np is 1690 strokes ($w = 4.3 \times 10^9$ mm³/N); for $t_c = 12.8$ min/cm² it rises to 6900 strokes ($w = 2.3 \times 10^9$ mm³/N), while for $t_c = 19.2$ min/cm² it exceeds 300000 strokes, and the wear resistance is very high ($w = 4.2 \times 10^{11}$ mm³/N). Note that increasing $t_c$ for electrospark alloying on steel substrates

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does not lead to better bearing capacity [10]. For electrospark alloying of Ti alloys, higher \( t_e \) values increase the gas pickup in the surface layer and improve the bearing capacity. Higher \( t_e \) reduces the process efficiency. This is unacceptable in most cases. To increase efficiency while maintaining the high bearing capacity of the alloyed layer it is advisable to introduce some substances into the interelectrode gap. These substances intensify the mass transfer and facilitate the formation of high-strength compositions [11]. As indicated in table 3, electrospark alloying with a BN layer applied drastically increases the surface layer bearing capacity (for an aluminium alloying electrode and a VT23 alloy substrate.) To further increase the alloyed layer strength, a two-layer KH20N8O (Nichrome), Al (BN) system is applied.

### Table 2. Alloying electrode material vs. wear resistance for VT23 Ti alloy.

| Alloying electrode | \( H_{\text{avg}} \) (MPa) | Np | W |
|--------------------|-----------------|----|---|
| No electrospark alloying | 3860 | — | 1.0 |
| Aluminium | 4770 | 45 | 1.3 |
| Vanadium | 4150 | 63 | 3 |
| Tungsten | 4890 | 1690 | 90.7 |
| VK6-M alloy (DIN analog: HG1110) | 4800 | 670 | 24.4 |
| Cobalt | Molybdenum | 4970 | 750 | 20.5 |
| Nickel | 4850 | 1020 | 35.5 |
| Niobium | 4850 | 1320 | 111.4 |
| Tantalum | 5170 | 890 | 43.8 |
| Titanium | 4200 | 870 | 134.5 |
| TSK10 alloy (DIN analog: HS345) | 4280 | 1040 | 60.9 |
| TiC | Chromium | 4020 | 580 | 90.7 |
| WC | 4280 | 2330 | 195 |
| 3980 | 1980 | 60 |
| 6520 | 2690 | 75 |

### Table 3. Applying various substances vs. the VT23 Ti alloy bearing capacity.

| Alloying electrode (applied substance) | \( H_{\text{avg}} \) (MPa) | Np | W |
|---------------------------------------|-----------------|----|---|
| Aluminium (BN) | 4970 | 26850 | 539.2 |
| KH20N8O (BN) | 5240 | 57100 | 425.6 |
| Tantalum (BT) | 5210 | 1980 | 369.0 |
| Vanadium (BN) | 4230 | 2020 | 17.1 |
| VK6M (mica) | 5140 | 450 | 32.1 |
| Vanadium (mica) | 4210 | 44900 | 377.9 |
| Copper (mica) | 3410 | 3550 | 266.6 |
| Copper (CdJ) | 2950 | 220 | 22.7 |
| Copper (KMnO₄) | 8340 | 10400 | 476.9 |
| Copper (Na₂B₄O₇) | 6410 | 7840 | 413.9 |
| Copper (KBr) | 5250 | 11800 | 535.5 |
| Copper (KCr₂O₇) | 5750 | 9250 | 380.5 |
| Copper (NaHCO₃) | 5820 | 22400 | 734.0 |

As noted above, applying mica to the surface increases the alloying electrode mass transfer rate by ten folds. However, the hardened layer properties often degrade. This was the case for electrospark alloying with VK6-M, Ta, Mo, Cr, KH20H8O (Nichrome) electrodes. Electrospark alloying with a
vanadium electrode and a mica layer produces a high-strength, high wear-resistance coating. With the application of copper and bronze, anti-friction coatings are made.

To make anti-friction coatings, other substances (KMnO$_4$, NaHCO$_3$, KCr$_2$O$_7$) intensifying the alloying electrode to substrate mass transfer can also be used. For instance, copper electrospark alloying when the above-mentioned substances are applied results in coatings with various hardness and wear resistance properties [12]. We should emphasize the high hardness and strength of such coatings. The reason for this may be the formation of intermetallic compounds (Ti$_3$Cu) and titanium nitride. These phases were identified with X-ray analysis.

As the above-listed data show, copper and bronzes are the most efficient alloying electrode materials for Ti alloy electrospark alloying when wear resistance is to be improved. Electrospark alloying with graphite application does not produce sufficiently strong alloyed layers.

Multicomponent and multilayer alloying is an efficient way of improving the surface properties. For friction couple components, double-layer coatings are recommended. They are formed by alloying with hard, wear-resistance materials (VK6-M, T15K6, W, Ta, Mo, Cr, etc.) with subsequent deposition of an anti-friction material (copper, silver, bronze, tin, etc.). Table 4 lists the bearing capacity values of such coatings [13]. Multicomponent coatings with aluminum, chromium, nickel, molybdenum disilicide are promising for improving heat resistance and thermal stability of titanium alloys used in friction couples under elevated temperatures.

Table 4. Double-layer bearing capacity values for the VT23 Ti alloy.

| Alloying electrodes (applied substance) | Hm$_{avg}$, MPa | Np | W |
|----------------------------------------|-----------------|----|---|
| BrO10S10 (mica)                        | 3240            | 20650 | 970.3 |
| BrAZHMts10-31-0.5 (mica)               | 4297            | 4190  | 257.9 |
| BrKMts3-1 (mica)                       | 5410            | 2360  | 241.9 |
| Cr, Cu (mica)                          | 3210            | 15200 | 519.7 |
| W, Cu (mica)                           | 2970            | 15380 | 749.5 |
| Zr, Cu (mica)                          | 3620            | 29100 | 909.3 |
| VK6-M, tin                             | 1610            | 11800 | 523.3 |
| Mo, Al                                 | 4980            | 140   | 78.5 |
| Cr, Al                                 | 5690            | 250   | 42.1 |
| MoSi$_2$                                | 5410            | 1540  | 37.6 |
| KH20N8O, Al (BN)                       | 5750            | 27350 | 631.2 |
| Ni-Cr-Al-Yt                            | 6690            | 2710  | 162.6 |

The bearing capacity of such coatings at normal temperature is much lower than that of copper and bronze coatings [14]. Still, it can be significantly improved by applying BN as it was shown for the KH20N8O, Al (BN) coating. We also used a Ni-Cr-Al-Yt alloy for electrospark alloying.

As it was mentioned, electrospark alloying of Ti alloys with copper and copper alloys give the highest bearing capacity under contact loads. Electrospark alloying with bronze and brass is comprehensive. Since the alloying elements burn out, and the erosion of the alloying electrode components is selective, the coating composition differs from the initial alloying electrode composition. We obtained the best results with the BrO10S10 grade bronze. The bronze ensures stable mass transfer and excellent coating continuity. No protrusions are formed, as is the case with BrAZHMts10-3-1.5 and BrKMts3-1 bronzes. Electrospark alloying with the BrB2 bronze also produces acceptable coatings, but there may be safety issues with the exposure to hazardous beryllium contained in the alloy [15]. Electrospark alloying with brass leads to the intense formation of protrusions, so their use is limited.
4. Conclusion
Electrospark alloying is an advanced and promising process that uses erosion caused by spark discharges in a gaseous environment, and the erosion product deposition onto the cathode (the workpiece.) The cathode surface is heated and exposed to thermomechanical, hydrodynamic, and diffuse phenomena that facilitate the anode-cathode material mixing and interaction with the gaseous environment components. It ensures high adhesion between the base metal and the coating being formed.

Till recently, the adoption rate of electrospark alloying was low due to insufficient machine performance. As new machines with microprocessor NC controllers, efficient impulse generators and servo drives emerged, the electrospark alloying process became much more capable and usable [16].

Ti alloys are relative soft substrates. It affects the total bearing capacity of the alloyed layer. Besides, they have a low resistance to electric erosion, so the alloyed layer is formed with a significant Ti alloy transfer to the alloying electrode that reduces the electrode erosion. For hard melting electrodes (W, Ta, Mo, etc.) the erosion is negligible.

Our studies and hands-on experience indicate that erosion and mass transfer properties should be considered for the specific electric erosion conditions. The mass transfer can be controlled by changing the process variables. We failed to identify any generalized relations to forecast the mass transfer in various materials.

Till recently, the available sources that deal with the physical and chemical aspects of electrospark alloying did not extensively cover the effects of substances introduced into the interelectrode gap on the hardened layer formation and the anode-to-cathode mass transfer. Still, it is known that grease on the surface (fat, various particles) greatly intensifies the electric discharge process, and improve its stability [17]. The electrospark alloying efficiency (effective impulse rate, heat generation) can be improved by introducing low ionic potential substances. A highly important aspect is the chemical synthesis of new substances from the introduced material and the electrode material to obtain specially hardened layer features such as anti-friction properties. The substance efficiency depends on its chemical interaction with the electrode surface. It is also important that the substance does not form compounds that reduce the hardened layer performance.

We also identified that the surface roughness can be controlled by adjusting the electrospark alloying process variables. It was found that reduced electrospark machine intensity leads to better quality, but thinner coatings.

The study produced experimental data and empirical electrode mass transfer rate vs. electrospark alloying process variable curves for Ti workpieces. The amount of the material transferred to the surface to be hardened usually varies directly with the period of alloying. In the $\nu = 100-500$ mm/min electrode feed range, $\Gamma$ is virtually constant. For $\nu < 50$ mm/min $\Gamma$ is either reduced or increased depending on the material of the electrodes. At low feed rates, the areas adjacent to the electrode surface are heated up. It has various effects on the mass transfer rate and features for a range of electrode combinations.

We investigated possible methods of increasing the alloying material transfer by introducing the substances that intensify the erosion into the interelectrode gap. We revealed the physical and chemical processes behind it. It was found that the surface layer can be additionally alloyed by applying an extra layer of some substance. In this respect, carbon, nitrogen, boron, silicon compositions, and some metals are of special interest for making carbide, nitride, boride, silicide hardening phases. BN, AlSi, BC, disperse metal powders are very promising. Electrospark alloying with introducing various substances and powders into the interelectrode gap form multicomponent and multilayer coatings with high bearing capacity suitable for a range of operating conditions.

The surface condition after electrospark hardening was estimated. The effects of electrospark alloying time and process variables on the surface finish and the material distribution in the surface layer were identified. When there is no finish machining, two-pass alloying is recommended. First, the surface is hardened intensively to obtain the required thickness of the alloyed layer, and then a low-intensity mode is used to achieve low surface roughness and better surface quality.
The $R_a$ value tends to decrease as the surface roughness increases. When the surface roughness is up to $R_a = 6 \mu m$ $\Gamma$ changes only slightly. For higher $R_a$ values, the alloying electrode erosion rate reduces greatly.

Our tests proved that electrospark alloying can improve the performance of titanium alloy parts. It is shown that multicomponent and multilayer alloying is an efficient way of improving the friction couple surface properties. It is recommended to use double-layer coatings for friction couple components [18]. They are formed by alloying with hard, wear-resistance materials (VK6-M, Ti5K6, W, Ta, Mo, Cr, etc.) with subsequent deposition of an anti-friction material (copper, silver, bronze, tin, etc.) Electrospark alloying with introducing various substances and powders into the interelectrode gap form multicomponent and multilayer coatings with high bearing capacity suitable for a range of operating conditions.

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