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SURFACE REPAIR OF AIRCRAFT TITANIUM ALLOY PARTS
BY COLD SPRAYING TECHNOLOGY

Titanium alloys have the advantages of high specific strength, good corrosion resistance, high heat resistance, and low density, which is the main structural material of aerospace system components, including compressor blade, cartridge receiver, blisk, engine nacelle, thermal baffle and so on. At present, about three-quarters of titanium and titanium alloys in the world are used in the aerospace industry, including A350 for 14%, F18 for 15%, B787 for 15%, SU-37 for 18%, J-20 for 20%, FC-31 fighters for 25%, F35 for about 27%, and F22 up to 41%, etc, so it has the reputation of "space metal". However, its low wear resistance limits the further development of titanium alloy. Besides, its high manufacturing cost, if only require the occasion of surface performance can reduce the use of the substrate, and then reduced the cost. Therefore, the study of aircraft titanium alloy is of great significance, the protection of titanium alloy includes alloying technology and coating technology. Alloying technology mainly adds other elements on its basis to improve the performance, while the most popular method is coating technology, the present, there are many coating technologies, include high-speed oxygen-fuel (HVOF), HVAF, cold spraying, laser cladding, laser micro-fusion in-situ synthesized technology, micro-arc oxidation, laser melt injection (LMI), supersonic laser deposition (SLD) and supersonic plasma spray technology, surface repair titanium alloy parts by cold spraying technology are good ways to solve those problems. Because of its low process temperature, no oxidation, only plastic deformation, and repair efficiency are high, the protective coating has high bonding strength and good impact toughness. In this paper, the types and applications of aircraft titanium alloys were reviewed, the latest research results of surface repair of titanium alloys parts by cold spraying technology were reviewed, technological parameters of the cold gas dynamic spraying technology was analyzed, including powder size of particles, morphologies, critical velocity, particle compression rate, substrate preheating effects on the particle/substrate adhesion, etc.

Keywords: Titanium alloys; surface repair; cold spraying; protective coating; technological parameters.

1. Aircraft Titanium Alloys

1.1. Introduction

Titanium alloys have the advantages of low density, high specific strength and excellent corrosion resistance. So it is widely used in the field of aerospace. Ti alloys is the main structural material of aircraft parts, including compressor blade, cartridge receiver, blisk, engine nacelle, thermal baffle and so on. For instant, the titanium alloy used in the F35 for about 27%, FC-31 fighters for 25%. America's fourth-generation fighter jet, F22 engine, uses 41% [1] (table 1), it is the highest amount of titanium in use. Therefore, titanium alloy has the reputation of "space metal" [2].

There are three types of titanium alloys (table 2): α, β and (α+β) titanium alloys are widely used in aero-engines [3].

However, Titanium is easy to reactive at high temperature, great difficulty in smelting and high manufacturing cost, so it is an effective way to reduce the cost to study the repair of aircraft titanium alloys by coating technology. This paper takes aircraft Ti-6Al-4V alloy as an example, show its feasible to repair titanium alloy by cold spraying. Through the repair technology of cold spray, which brings great economic benefits. A significant cost to the department of defense of the United States supply-chain will be mitigated by Cold Spray technology [4].

| State   | Aircraft type | Service time | Mass fraction / % |
|---------|---------------|--------------|------------------|
| USA     | F/A 18E/F     | 2002         | 15               |
| USA     | F/A 22        | 2005         | 41               |
| USA     | B787          | 2011         | 15               |
| Europe  | A350          | 2013         | 14               |
| China   | FC-31         | 2016         | 25               |
| China   | J-20          | 2017         | 20               |
| USA     | F35A          | 2018         | 27               |
| Russian | SU-57         | 2019         | 18               |

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Titanium alloys use in aircraft [3]

| Alloy type            | Chemical composition |
|-----------------------|----------------------|
| α (near α) titanium alloy |                     |
| Pure titanium         |                       |
| Ti-3Al-2.5V           |                       |
| Ti-5Al-2.5Sn          |                       |
| Ti-8Al-1Mo-1V         |                       |
| Ti-6Al-2Sn-4Zr-2Mo-Si(O.1-0.25) |               |
| Ti-5.5Al-3.5Sn-3Zr-INb-0.25Mo-0.3Si(IMI829) | |
| Ti-5.5Al-4Sn-4Zr-0.3Mo-INb-0.5Si-0.006C(IMI834) | |
| Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-O.35Si-0.06C(IMI884) | |
| Ti-6Al-2.75Sn-4Zr-4Mo-0.45Si(Ti-1100) |               |
| β titanium alloy      |                       |
| Ti-6Al-2.75Sn-4Zr-4Mo-0.45Si(Ti-1100) |               |
| Ti-6Al-6V-2Sn         |                       |
| Ti-6Al-2Sn-2Cr-2Mo-2Cr-Si |                 |
| Ti-6Al-2Sn-2Zr-6Mo    |                       |
| Ti-5Al-2Sn-Zr-4Mo-4Cr(TC17) |                |
| (α+β) titanium alloy |                       |
| Ti-13V-11Cr-3Al       |                       |
| Ti-10V-2Fe-3Al        |                       |
| Ti-15V-3Cr-3Al-3Sn    |                       |
| Ti-15Mo-2.7Nb -3A-0.2Sn (Timetal21S) |             |
| Ti- 3Al-8V-6Cr-4Mo-4Zr(B-C) |               |

1.2. Current Coating Technology for Titanium Alloys

The defects of titanium alloy include corrosion, abrasion and oxidation at high temperature, and so on. For example, Ti-5Al-2Sn-2Zr-4Mo-4Cr presents pitting corrosion in the environment of nitric acid and raven-like corrosion pit in the environment of hydrochloric acid [5], especially in warships, where the corrosion problem is particularly serious.

Various protective coating technologies for titanium alloys have emerged. The repair methods of titanium alloy include HVOF [6], HVAF [6], cold spraying [7], laser cladding [8], laser micro-fusion in-situ synthesized technology [9], micro-arc oxidation [10, 11], laser melt injection (LMI) [12], chromium-free dacro technology [13], supersonic laser deposition [14] (SLD), which is a newly developed material deposition technique that synchronously combines the laser heating with cold spray (CS). And supersonic plasma spray technology [15], which are different from low plasma spray (LPPS).

For Ti-matrix coating, Hu [16] research on the wear and corrosion behavior of Ti-matrix functional gradient layer, indicated friction coefficient and wear rate decreased significantly, the value was 0.3…0.5 times of Ti600 substrate. Zhou Heng research on NiCrAl+YSZ+NiCrAl/Bentonite composite coatings with thickness of 2 mm were prepared by plasma spraying and flame spraying [17] on the surface of Ti40 alloy, Zhang [18] study the effect of TiN/Ti coating structure on equivalent plastic strain of Ti-6Al-4V titanium alloy after impact by ABAGQS, optimize the architecture parameter of TiN/Ti anti-erosion coating. Due to wear resistance of titanium alloy is poor, Cai [19] research on the micro-cracks in fretting wear of Ti-6Al-4V titanium alloy, showed that the increase of load and displacement reduced the binding effect during fretting wear.

In summary, 1) aircraft titanium alloy mainly includes three basic alloys: α, β, (α+β), among which the α titanium alloys include Ti-3Al-2.5V, Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, etc., it mainly contains elements such as Al, which can increase the tensile strength and creep stress of the alloy, reduce the density of titanium alloy and improve the specific strength; β titanium alloy include Ti-6Al-2.75Sn-4Zr-4Mo-0.45Si, Ti-6Al-6V-2Sn, Ti-6Al-2Sn-2Cr-2Mo-2Cr-Si, etc., it has a high enough stable element content to be the preferred structural material for airframes and wings; (α+β) titanium alloy include Ti-13V-11Cr-3Al, Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, etc., its maximum operating temperature is no more than 500°C, and its welding performance and heat resistance are lower than α titanium alloy; 2) surface coating technology for repair of titanium alloys is an effective method, while the basic coating technology includes thermal spraying technology, such as HVOF (Porosity: 1.6…2 %), cold spraying technology (Porosity < 0.5 %), Plasma spraying technology (Porosity: 5 %), Arc spray (Porosity: 10…20 %), etc. Comparative analysis of porosity, cold spraying technology has obvious advantages over other technologies.

2. Surface Repair of Aviation Titanium Alloys by Cold Spray

Cold spraying technology for surface repair has great advantages: first of all, the parts do not need to preheat, and the heat in the repair process is small; Secondly, the repair efficiency is high (> 95 %) and the speed is fast. The final coating has high bonding strength and good impact toughness. Unlike thermal spray, cold spray is capable of producing dense and thick coatings exhibiting extremely low porosity
(≤ 0.5 %), while avoiding oxidation, phase transformations and adverse residual stresses for a wide selection of metals, cermets, and other material mixtures. Cold spraying technology will become a hot trend in remanufacturing and repairing parts.

In view of the aircraft titanium alloy variety, in this paper, the feasibility of cold spraying repair technology was discussed with the classic aviation Ti-6Al-4V titanium alloy.

2.1. Cold Gas Dynamic Spray (CGDS)

Cold Gas Dynamic Spray (CGDS) was first developed by Papyrin [20] et al. in the mid-1980s at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Science in Novosibirsk while working with tracer particles in supersonic wind tunnels [21]. Major innovative development began in the 1950s by Rochevill, using a gas flow at a velocity higher than those obtained with the existing methods at that time. The flow of gas through a nozzle called the De Laval Nozzle produces a uniform thin coating [22 - 24]. The deposition during CGDS can be summarised into the molecular attraction between the surface deposit of the particles and the substrates and in-built deposit growth. At a supersonic velocity, particles impact and plastically deform on the substrate. The deformation process results in adhesion to the surface [25 - 30]. Compared with thermal spraying, since cold spraying is carried out at a lower temperature, the driving force for phase transformation is small, solid particles are not easy to oxidize, and the phenomenon of grain growth is not easy to occur. Because of the advantages of cold spraying [31], some researchers [32 - 39] begin to study it. Wong [40] indicate that high deposition efficiency, values as high as 100% for titanium and copper.

Powder (table 3) that can be used for cold spraying technology include pure metals such as Al, Zn, Cu, Ni, Ti, Ag, Co, Fe, Nb, super alloy and high hardness ceramic of metallic coatings, ceramic coatings and organic coatings [41 - 43]. These coatings can not only be used to repair defective parts, but also can be made by rapid near-net molding. Based on the cold spray technology for aluminum and magnesium alloy repair has become mature [44 - 48], the application of aircraft as shown in the fig. 1, fig. 2 and fig. 3.

2.2. Repair Process of Ti Alloy parts with Cold Spray

Cold spraying is a very good method to repair titanium alloy, which heat effect of the parts is small, compared with other thermal repair has a great advantage, especially for heat sensitive materials [49].

Jin Lei [50] utilize Ti-6Al-4V, Ti and Al$_2$O$_3$ mixed powder on the damaged surface of Ti-6Al-4V titanium alloy thin wall plate to get the repair coating by cold sprayed. The repair coating has good characteristics.

| Powder types         | Powders Chemical composition                      |
|----------------------|---------------------------------------------------|
| Pure metal coating   | Aluminum, Magnesium, Copper, Titanium, Zinc, Nickel, silver, tantalum, molybdenum, etc. |
| Nonmetal coating     | Ceramic, etc.                                     |
| Alloy coating        | Al alloy, Mg alloy, Cu alloy, Ti alloy, Zn alloy, Ni alloy, Ag alloy, etc. |
| Composite coating    | Al-Zn, W-Cu, Al-Ti, Al-Ni, Al-Cu, Al-Fe, Al-SiC, Al-TiN, Al-Al2O3, Al-Mg17Al12, Al-FeSiBnBcu, WC-Co, Cr3C2-NiCr, etc. |

Fig. 1. AMAD Housing  
Fig. 2. ADG Housing  
(a)  
(b)  
Fig. 3. Cold spray repair steyr engine channel corrosion area [53]: a – before the repair; b – after the repair

Ogawa [51] used Al and its alloy coating to repair parts in the space shuttle solid-fuel rocket boosters and aircraft structures. The United States army research laboratory [52] also used cold spraying technology to repair the magnesium alloy crankcase shell of the helicopter.

Jean-Louis [54] Pelletier provided simulation about Ti-6Al-4V coating onto Ti-6Al-4V substrate using low pressure cold spray, simulated damage repair was successfully, and the coating quality is no major effect. This phenomenon associated to the high-velocity of the particles hitting the substrate and non-recovery of...
the dislocations. Such strain hardening increases with the degree of particle deformation. So Ti-6Al-4V alloy parts could be repaired efficiently by producing Ti-6Al-4V coating on a machined flat surface or with a 10 to 1 slope (6 degrees) or less. As fig. 4 and fig. 5 show, the interface between the coating and the substrate is very tight. The black dark area are the coating porosities [55], porosity is found to be 2.69 ± 0.28 %.

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Fig. 4. Example of Simulated damage repair of Ti-6Al-4V with repair microstructure under optical microscope [54]

Fig. 5. Cold spray deposit, substrate and the interface, the dark areas in the coating porosities [55]

Cao Congcong [56] research on Ti-6Al-4V (fig. 6) coating were deposited by cold spray on surfaces of Ti-6Al-4V substrates, show higher micro-hardness, better bending property, smooth fractured surface characterized by brittle fracture with no phase change happened, which confirmed the feasibility of repairing titanium alloy components by cold spray technique.

Ti-6Al-4V particles deposited on Ti-6Al-4V substrate, mainly by mechanical combination, forming a dense coating (fig. 6, a). The interface between particles and particles in coating is closely bonded, and mainly combined by metallurgy, with some small pores (fig. 6, b).

As fig. 7 show, utilized the Lagrange finite element method to observe the obvious mechanical locking at the contact [57] surface between titanium particles and aluminum matrix (fig. 7). This shows that aluminum and titanium materials have good bonding characteristics by cold spraying technology.

Fig. 6. Ti-6Al-4V/Ti-6Al-4V coating [56]:
    a – coating cross-section, b – the microstructure

Fig. 7. cross-sectional OM micrographs of the cold sprayed titanium coating depositing aluminum substrate at different spray angles [57]:
    a – 90°; b – 75°; c – 60°

Base on the above analysis, it can be concluded that:
1) it has obvious advantages to repair the surface of Ti alloy parts by cold spraying technology;
2) on Ti-6Al-4V substrate, utilize Ti-6Al-4V as cold spraying coating, with an average porosity of 8 % and a hardness of up to 300 MPa. Under the condition of nitrogen temperature of 600 °C and pressure of 3 MPa, TC4 coating with a porosity of 6.46 %;
3) repair surface of Ti-6Al-4V titanium alloy can choose Ti-6Al-4V, Ti and Al materials mixture, which are mechanically combined with good bonding performance. Repair coating material composition: Ti-6Al-4V is 40 %~70 %, Ti is 29 %~50 %, Al₂O₃ is 1 %~10 %, the matrix temperature of Ti-6Al-4V titanium alloy is less than 150°C, the pressure of He work gas is 0.6~1MPa, spraying temperature is 300 °C~600 °C, spraying distance is 10~30 mm. The porosity of repair coating is 0.1 % and the hardness of repair coating reaches 1147HV₀.₁.
2.3. Cold Spraying Process Parameters of Titanium

Cold spraying process has many parameters [58], including Powder size of particles, morphologies and property. Particle size should be in the appropriate range, if too small (fig. 8), the collision energy is insufficient to form effective deposition [59]; Particle velocity and critical velocity [60]; Substrate preheating effects on the particle/substrate adhesion, fig. 9 and fig. 10 shows, as the substrate temperature increases, decrease particle compression ratio and crater depth go up [61]; Substrate surface roughness effects on particle/substrate adhesion; Substrate surface texturing effects on the particle/substrate adhesion; Effects of nozzle unit design; Characteristic of propellant gas, for instant. Adding a small amount of helium to nitrogen can increase the exit velocity of gases and particles, while avoiding the high cost of using only helium to accelerate [62].

![Fig. 8. Particle sizes and substrate of plastic strain [59]:](a) – size of 20 nm; (b) – size of 20 μm

![Fig. 9. Particle compression rate versus the initial temperature of substrate [61](a)](a)

![Fig. 10. Crater depth of substrate versus the initial temperature of substrate [61](a)](a)

The most important Cold spraying process parameters of titanium are critical velocity and temperature (table 4). critical velocity can be calculated by numerical simulation [63]. Beyond the limit of critical velocity, a further increase in particle velocity results in a decrease in deposit porosity.

Han [64] research on morphology characteristics of Ti-6Al-4V particles colliding with the Ti-6Al-4V substrate at different temperature and velocity (fig. 11), showed that both thickness and density of the coatings prepared increase as gas pressure increases.

According to the analysis in fig. 11, particles of 700 m/s and 800 m/s have a very strong plastic deformation, and with the increase of particle velocity, the plastic deformation does not increase significantly, indicating that Ti-6Al-4V particles have effective deposition above 700 m/s.

Table 4

| Partical | Substrate | Propellant gas | Particle diameter | Temperature (°C) | Pressure (Mpa) | Nozzle throat diameter (mm) | Nozzle length | Ref. |
|----------|-----------|----------------|------------------|-----------------|---------------|-----------------------------|---------------|------|
| Ti       | Ti        | N2             | 29μm             | 300-800         | 3.4           | -                           | -             | [69] |
| Ti       | Ti        | N2             | 16-22μm          | 600             | 2.4           | -                           | -             | [70] |
| Ti       | Ti        | He             | 16μm             | 600             | 1.5           | -                           | -             | [71] |
| Ti       | Ti6A14V   | He             | 5-29μm           | 260             | 1.6           | 3.8                         | 90mm          | [71] |
Fig. 11. Morphologies of the Ti-6Al-4V after colliding at different speeds [64]:
a – 500 m/s; b – 600 m/s; c – 700 m/s; d – 800 m/s

Yang [65] studied various concepts and calculation methods of critical velocity. For example, the recovery coefficient (fig. 12) determines the critical velocity.

Article [66] estimate the critical velocity by this method to be 690 m/s for angular titanium powder. Schmidt [67] reported a critical velocity of around 750 m/s for a 25 μm titanium particle. Wong [68] measured the critical velocity of spherical titanium powder between 505-610 m/s.

![Fringe levels](image)

Fig. 12. The velocity range of coating formed by particle being bonded on substrate:
a – Ti/Ti; b – Ti/Al [65]

The temperature parameters of Ti and Ti-6Al-4V are as follows table 4, for different conditions such as particle, substrate, particle diameter, propeller gas, pressure, nozzle throat diameter, etc., the suitable temperature is also different, which ranges from 260°C to 800°C.

### 3. Conclusions

Surface repair of aircraft titanium alloy parts by cold spraying technology has obvious advantages.

1. Types of powder materials for aircraft titanium alloy include Ti-6Al-4V, Ti, Al, Al₂O₃, steel, etc.
2. Cold spraying technology can be sprayed on almost any material, including Al, Zn, Cu, Ni, Ti, Ag, Co, Fe, Nb, super alloy and high hardness ceramic of metallic coatings, ceramic coatings and organic coatings.
3. Hardness of Ti-6Al-4V substrate is high, and porosity of cold spraying coating is usually more than 1%. If Ti-6Al-4V is used as spraying material, the porosity is only 6.46 %, but mixing Ti-6Al-4V (60 %), Ti (33 %) and Al₂O₃ (7 %), the porosity can reach 0.1 %
and the hardness of repair coating reaches 1147HV30, which solves the problem that the mechanical properties of coating are affected by the large porosity.

4. Development of special software and procedures for technological parameters optimization can provide serious reserve of implementation of different material mixtures as well as regulation of energy of cold spraying process for formation of special predicted physical-mechanical parameters of a coating-substrate complex. As the preheating of the matrix increases, the compression ratio of the particles decreases. Ti-6Al-4V alloy needs more than 700m/s to be effectively deposited. The critical velocity of titanium deposition on the titanium substrate and the aluminum substrate are 650 m/s~900 m/s and 630 m/s ~ 800 m/s.

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РЕМОНТ ПОВЕРХОНЬ АВІАЦІЙНИХ ДЕТАЛЕЙ З ТИТАНОВИХ СПЛАВІВ
ХОЛОДНИМ ГАЗОДИНАМІЧНИМ НАПИЛЮВАННЯМ

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Перевагами титанових сплавів є висока питома міцність, хороша корозійна стійкість, висока жаростійкість, низька цілісність, і використовуються в якості конструкційного матеріалу для виготовлення деталей аерокосмічної техніки, таких, як лопатки компресора, патронний приймаць, гондола двигуна, теплові перегородки і так далі. В даний час в аерокосмічній промисловості використовується близько трьох четвертей титану і титанових сплавів в світі. У процентному співвідношенні кількість деталей з титанових сплавів в літаках А350 становить 14%, F18 – 15%, B787 – 15%, Су-57 – 18%, J-20 – 20%, винищувачі FC-31 – 25%, F35 – 27%, F22 – до 41% і т. д., а даний метал має репутацію «літаючого металу». Однак його низька зносостійкість обмежує широке застосування титанових сплавів. Ще одним недоліком деталей з титанових сплавів є їх висока собівартість виробництва. Тому вивчення і розвиток технологій захисту і поліпшення аерокосмічних титанових сплавів має велике значення. В даний час використовуються металургійний спосіб підвищення зносостійкості за рахунок впливу легируючих добавок, а також технології в наплавленні, наприклад, високошвидкісне газо-плазмове напилювання (HVOF), наплавка, детонаційне, плазмове напилювання та інші. У даній роботі розглянута перспективна технологія холодного газодинамічного напилювання для ремонту і відновлення деталей з титанових сплавів. Перевагами технології в порівнянні з іншими методами нанесення покриттів є низька температура процесу, відсутність окислення і структурно-фазових перетворень в матеріалах покриття і підкладки, відносно низька собівартість отримання покриттів. Покриття мають високу міцність зчеплення з підкладкою, мікротвердість і низьку пористість. У даний статті розглянуто особливість застосування аерокосмічних титанових сплавів, наведено приклади деталей з таких сплавів, проаналізовано дефекти і причини їх виникнення. Виконано аналіз останніх робіт в області поверхневого ремонту деталей з титанових сплавів за допомогою технології холодного напилювання, проаналізовано технологічні параметри процесу формування покриттів, в тому числі розмір часток напилливаного порошку, температура частинок в процесі напилювання, пливе попереднього нагріву підкладки на адгезію міцність системи покриття/підкладка та інше.

Ключові слова: титанові сплави; відновлення поверхні; холодне напилювання; захисне покриття; технологічні параметри.

РЕМОНТ ПОВЕРХНОСТЕЙ АВІАЦІЙНИХ ДЕТАЛЕЙ З ТИТАНОВИХ СПЛАВІВ
ХОЛОДНИМ ГАЗОДИНАМІЧНИМ НАПИЛЮВАННЯМ

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Титанові сплави обладають перевагами, які включають високу удельну прочність, хорошу коррозійну стійкість, високу жаростійкість, низькую плотність, і використовуються в якості конструкційного матеріалу для виготовлення деталей аерокосмічної техніки, таких, як лопатки компресора, патронний приймаць, гондола двигуна, теплові перегородки і так далі. В даному направленні у аерокосмічній промисловості використовується близько трьох четвертей титану і титанових сплавів. В процесі виробництва літальних апаратів використовуються понад три чверті титану, і використовується в якості конструкційного матеріалу для виготовлення деталей аерокосмічної техніки, таких, як лопатки компресора, патронний приймаць, гондола двигуна, теплові перегородки і так далі. В даному направленні в аерокосмічній промисловості використовується близько трьох четвертей титану і титанових сплавів. В процесі виробництва літальних апаратів використовуються понад три чверті титану, і використовується в якості конструкційного матеріалу для виготовлення деталей аерокосмічної техніки, таких, як лопатки компресора, патронний приймаць, гондола двигуна, теплові перегородки і так далі. В даному направленні в аерокосмічній промисловості використовується близько трьох четвертей титану і титанових сплавів.
смотrena перспективная технология холодного газодинамического напыления для ремонта и восстановле-
ния деталей из титановых сплавов. Преимуществами технологии в сравнении с другими методами нанесе-
ния покрытий является низкая температура процесса, отсутствие окисления и структурно-фазовых превра-
щений в материалах покрытия и подложки, относительно низкая себестоимость получения покрытий. По-
крытия обладают высокой прочностью сцепления с подложкой, микротвердостью и низкой пористостью. В
данной статье рассмотрены области применения авиационных титановых сплавов, приведены примеры де-
тейлей из данных сплавов, проанализированы дефекты и причины их возникновения. Выполнен анализ по-
следних работ в области поверхностного ремонта деталей из титановых сплавов с помощью технологии хо-
лодного напыления, проанализированы технологические параметры процесса формирования покрытий, в
том числе размер частиц напыляемого порошка, морфология, скорость и температура частиц в процессе
напыления, влияние предварительного нагрева подложки на адгезию прочность системы покры-
тие/подложка и т.д.

**Ключевые слова:** Титановые сплавы; восстановление поверхности; холодное напыление; защитные
покрытия; технологические параметры.

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