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RESEARCH ON WEAR RESISTANCE COATING OF AIRCRAFT TITANIUM ALLOY PARTS BY COLD SPRAYING TECHNOLOGY

Titanium alloys are the main structural material of aerospace system component, about 75 % of titanium and titanium alloys are used in the aerospace industry, which have the advantages of low density, high specific strength and excellent corrosion resistance. However, its low wear resistance limits the further application of titanium alloy. Therefore, it is of great significance to the surface protection of titanium alloy. Surface coating technology can solve the problems of titanium alloy wear. Currently, there are many coating technologies to solve the problems of wear and corrosion, including the cold spraying (CS), high velocity oxy-fuel (HVOF), the thermo-chemical treatment, the gas phase deposition, the laser melted; the plasma spray coating, the double-plasma surface alloying technology, arc spray, etc. However, when thermal spraying is used to prepare anti-titanium fire coating, the tip of the blade is prone to overheating, thus affecting the performance of the blade. But cold spraying technology is due to the preparation of titanium alloy protective coating in solid state, and the coating has high bonding strength and good impact toughness, furthermore, it can deposit almost any powder materials, such as pure metals, including aluminum (Al), magnesium (Mg), titanium (Ti), nickel (Ni), cobalt (Co), niobium (Nb), tantalum (Ta), Copper (Cu), tungsten (W), etc; nonmetal such as ceramic, etc; Metallic alloys; composite coating, including Al-Zn, Ti-Al, Ni-Al, Al-Mg, Al-SiC, Al-Al₂O₃, Ti-Ti6Al4V-Al₂O₃, Ni-Zn, Ni-cBN, Ni-Zn-Al₂O₃, Ti-Ta, Al-Mg₁₇Al₁₂, Al-FeSiBNbCu, WC-Co, Cr₃C₂-NiCr, etc. It can also directly sprayed mixed powder to produce wear resistant coatings, hence, it is widely used. At present, cold-sprayed titanium alloy materials are mainly used in the field of substrate protection and repair, and the field of cold-sprayed titanium alloy additive manufacturing that has appeared in recent years is still in the stage of process and basic theoretical exploration. In order to better understand the latest status of cold spray coating of titanium alloy, in this paper, the wear resistance coating on aircraft titanium alloy parts by cold spraying technology was reviewed, produce wear resistance coating directly by cold spraying technology was analyzed.

Keywords: Titanium alloys; wear resistance; coating technology; cold spraying technology.

1. Introduction

Titanium alloys have been widely used in the fields of aerospace [1, 2], which used in the B787 for 15 %, SU-57 for 18 %, J-20 for 20 %, FC-31 fighters for 25 %, B-2 for 26 %, F35 for about 27 %, and F22 up to 41 %, etc [3]. Aircraft titanium alloys are divided into three types according to phase composition: α , β , mixed ($\alpha+\beta$), among which α include Ti-8Al-1Mo-1V [4], Ti-6Al-2Zr-1Mo-1V [5], 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 [6] include 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; ($\alpha+\beta$) include Ti-6Al-4V, Ti-6Al-2Sn-4Zr-6 Mo [7], etc.

Due to the wide application of aerotitanium alloys, some researchers began to study the surface protection and repair of titanium alloy, including the cold spraying (CS) [8], high velocity oxygen fuel (HVOF) [9]; the laser melted [10]; the plasma spray [11], the double-plasma surface alloying technology [12], etc.

On titanium alloy substrate, cold spraying technology can solve the problem of titanium alloy surface repair, wear resistance, at the same time, high temperature resistant coatings is also a popular applications by cold spraying technology, because the titanium alloy belongs to heat sensitive material, when the temperature exceeds the titanium alloy ignition point, may produce titanium fire accident [13], the adoption of flame retardant coating (with wear resistance) is one of the most effective methods to prevent titanium fire [14-16]. However, when thermal spraying, brazing and

other methods are used to prepare anti-titanium fire coating, the tip of the blade is prone to overheating, thus affecting the performance of the blade. Cold spraying process has obvious advantages in titanium alloy protective coating due to its low temperature. In this paper, only reviewed the application of cold spraying technology in wear resistance coating of titanium alloy parts.

2. Cold spraying technology

For the wear resistance of the titanium alloy substrate surface, cold spray technology [17-23] has obvious advantages over thermal spray technology. Mainly manifested in:

1) the low temperature process of the cold spray process is suitable for titanium alloy heat-sensitive materials;

2) high deposition efficiency;

3) low porosity; etc, as shown in Table 1.

Because of the advantages of cold spraying [25], researchers [26, 27] pay attention to it. Wong [28] indicate that high deposition efficiency (100 %) for titanium and copper. Cold spraying technology can deposit almost any powder materials, including pure metals such as Al [29], Mg [30], Ti, Zn, Cu, Ni, Ag, Co,

Fe, Nb [31], Ta [32]; nonmetal such as ceramic, etc.; Metallic alloys; composite coating, etc. It can also directly sprayed mixed powder to produce wear resistant coatings, chen [33] research that Cu-Al₂O₃-Graphite Solid-Lubricating coatings deposited by cold spraying. Result show the Cu-based solid-lubricating coating with 10 % Al₂O₃ and 10 % cu-coated graphite exhibited the lowest friction coefficient of 0.29.

3. Wear-resistant coating by CS

3.1. Deposited onto titanium alloy substrate

Titanium alloy has poor surface wear resistance [34], but it is very expensive and require long delivery periods, which require repair such as wear, impact damage during service. Zhang researcher [35] have studied the wear resistance characteristics of titanium alloy, cold spraying technology stands out among many other technologies because of its low oxidation. And the deposit of Ti and titanium alloy coatings by cold spray technology may also protect substrate materials from wear especially in aggressive environment [36].

Table 1

Comparative analysis of some thermal spray coating deposition techniques with CS [24]

Process	Cold spray	HVOF	Plasma	Arc spray
Bonding mechanism	Mechanical/chemical	Mechanical	Metallurgical	Metallurgical
Maximum thickness	0.05-10mm	<1.5mm	<0.5mm	0.1mm
Surface finish	<1μm	1.3-2μm Ra	13μm Ra	2μm Ra
Deposition rate	1-10kg/h	1-5kg/h	2-7kg/h	5-60kg/h
Deposition efficiency	>95 %	50-70 %	30-60 %	35-65 %
Wear resistance	50mm ³	27mm ³	10mm ³	6mm ³
Bond strength	30-40Mpa	30-70Mpa	30-55Mpa	20-30Mpa
Corrosion rate	0.25mpy	3.5mpy	1mpy	2mpy
Porosity	0.15 %	1.6-2 %	5 %	10-20 %
Oxygen content	0.25 %	3 %	9 %	5-15 %
Gas consumption	85 %	45 %	15 %	60 %
Power consumption	5-15kw	1-2kw	30-100kw	5-10kw
Powder feed rate	25-75kg/h	25kg/h	15kg/h	125-150kg/h
Spray velocity	At least 500m/s	750m/s	500-700m/s	800m/s
Feedstock	Metals, polymers and composites	Metals and ceramics	Metals and ceramics	Metals and ceramics
Typical application	Friction, impact, Abrasion and corrosion	Friction, Abrasion and corrosion	Friction, impact, Abrasion and corrosion	Friction, impact, Abrasion and corrosion

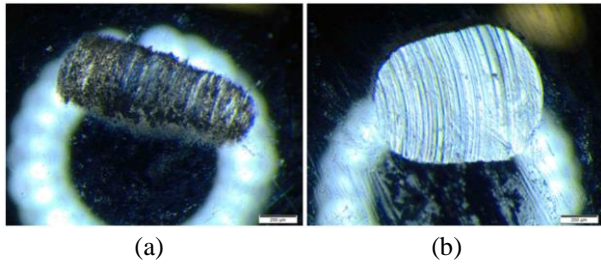


Fig. 1. Optical microscope images showing wear morphologies of counter steel balls tested against [37]: a – Ti64 substrate; b – Ti coating with a thickness of about 6200 μm

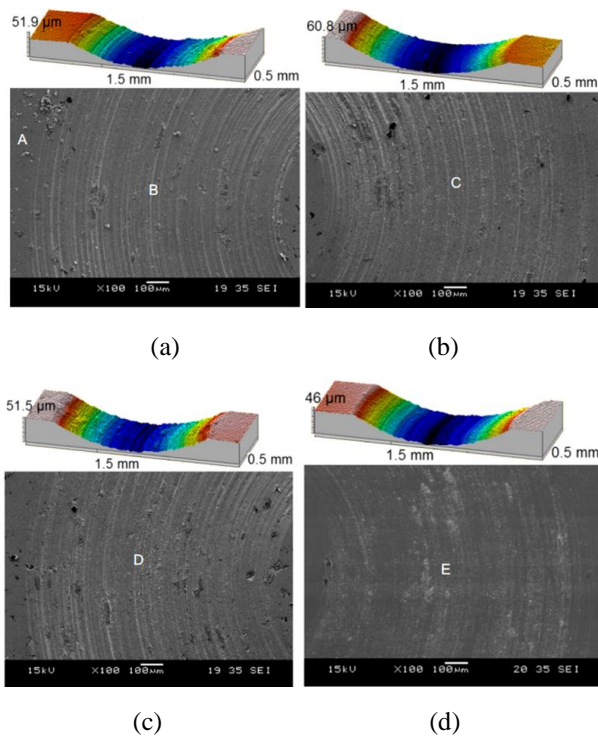


Fig. 2. Wear topographies (above) and morphologies (below) of Ti-6Al-4V deposit tested under the same condition: a – surface of the first layer; b – surface of the second layer; c – surface of the third layer; d – cross section [38]

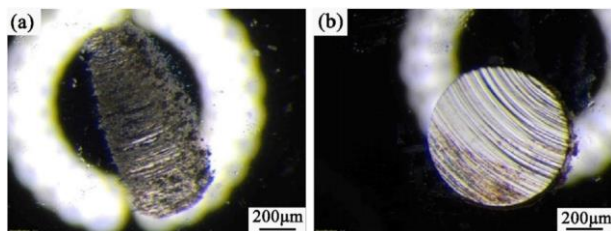


Fig. 3. Wear microtopography of 100Cr6 steel balls rubbed on Ti-6Al-4V deposits: a – without treatment; b – treatment with laser of powder 200W [41]

Khun [37] research that Ti coating on Ti-6Al-4V substrate. The average friction coefficients of the Ti coatings with thicknesses of about 100, 700, 1000, and

6200 μm are about 0.72, 0.74, 0.71, and 0.61, which shows that the Ti-6Al-4V substrate has a larger wear track than the Ti coatings (fig. 1), confirming that the Ti coatings have the higher wear resistance. Fig. 2 shows the wear topographies and morphologies of the Ti-6Al-4V coating deposits on the Ti-6Al-4V substrate [38], which is very obvious about abrasive particles in the process of wear.

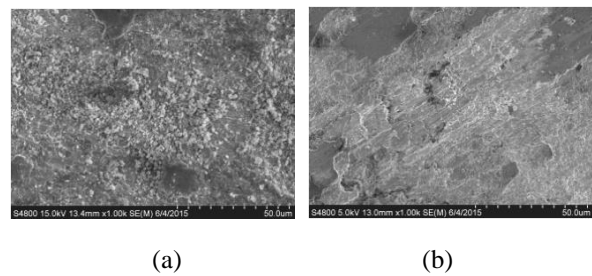


Fig. 4. The morphology of Ni-cBN coatings prepared by different size cBN [39]: a – Ni-cBN(6.2 μm); b – Ni-cBN(10 μm)

Ning [39] prepared Ni-cBN composite coating on Ti-6Al-1.5Cr-2.5Mo-0.5Fe-0.3Si substrate by low-pressure cold spraying. The results showed that the binding strength (58MPa \pm 8MPa) of Ni-cBN composite coating prepared by larger size cBN (10 μm) was significantly higher than that of the coating prepared by smaller size cBN (6.2 μm) (20MPa \pm 1MPa), resulting in more severe wear in Fig. 4a than in Fig. 4b.

Cold spraying technology can also be used in combination with other technologies to produce wear resistant coatings. Zhang [40] utilized cold spraying technology to prepare the TiAl gradient coating on the surface of titanium alloy by controlling the mixing ratio of aluminum and titanium powder, and treated the coating surface with chemical technology to achieve the dual purpose of wear resistance and insulation, the hardness value reached 600HV.

The wear resistance of laser treated (fig. 3b) Ti-6Al-4V deposit is better than that of the untreated (fig.3a) Ti6Al4V deposit by laser technology [41]. Li sprayed H13 powder on the surface of titanium alloy to form an H13 coating with a thickness of 50~105 μm , and then used laser cladding technology to fuse cobalt metal powder on the surface of H13 (Fig. 5). Bonding strength of coating and matrix is up to 55MPa. Coating thickness is 4.1mm, hardness reaches 1117.21HV_{0.2}, porosity is 0.61 %, and friction coefficient is 0.18 [42].

From the analysis above, different coating materials can be selected for different titanium alloy substrates. Such as Ti-6Al-4V substrate, the average friction coefficients of Ti coatings with thicknesses of 6200 μm are best, up to 0.61; Ti substrate, microhardness of the SiC composite coating was

increased to (125 ± 17.75) $HV_{0.3}$; Ti-6Al-1.5Cr-2.5Mo-0.5Fe-0.3Si substrate, binding strength of Ni-cBN composite coating reached $(58 \text{MPa} \pm 8 \text{MPa})$. However, Most studies focus on Ti-6Al-4V matrix materials, and more other titanium alloy matrix materials need to be studied.

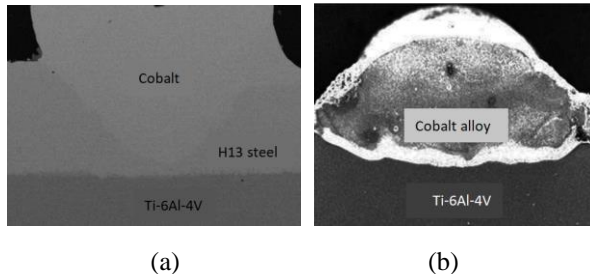


Fig. 5. Scanning electron microscope [42]:
a – CS+Cladding technology; b – Only Cladding technology

3.2. Preparation of wear-resistant coating by CS

Wear – resistant coating can be produced directly by cold spaying technology. Fig. 6 shows the friction coefficients of Ti6Al4V deposits produced with nitrogen and helium [43]. Obviously, under the same conditions, the friction coefficient of helium gas is lower than that of nitrogen gas, indicating that the friction performance of helium gas as propellant is better.

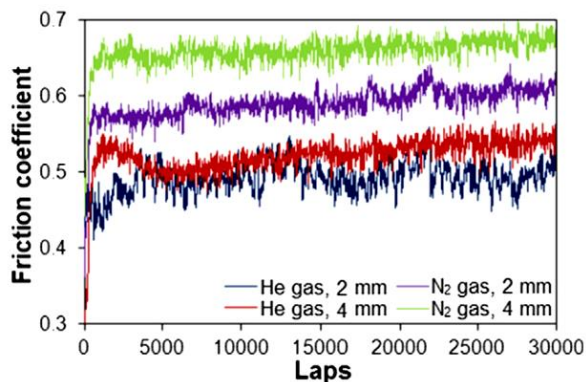


Fig. 6. Friction coefficients of Ti-6Al-4V deposits as a function of wear lap. Note that friction coefficients were tested against a 100Cr6 steel ball of 6mm in diameter in circular paths for 30,000 laps at a sliding speed of 3 cm/s under a normal load of 1N [43]

Through investigation, WC-Co is a potential wear resistant coating material of titanium alloy substrate, because of its superior wear resistance properties. Wang [44] studied the cold spraying coating experiments of three materials (fig. 7): micron WC-12Co, nanometer WC-17Co and WC-23Co, and made a comparative

analysis with 316L stainless steel, indicating that WC-Co coating has excellent wear resistance.

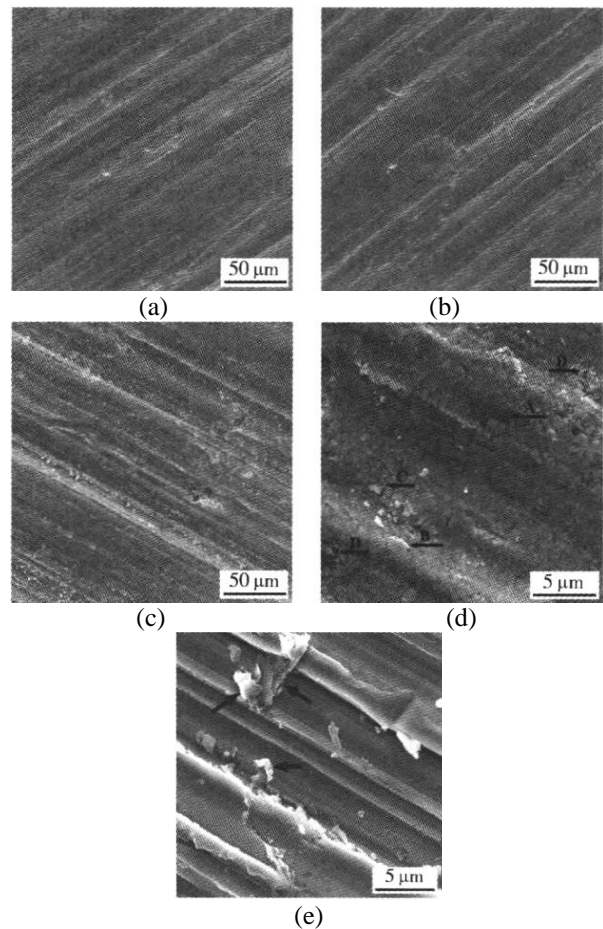


Fig. 7. Worn surface morphologies of cold sprayed multiple dimensional WC-Co coating and 316L stainless steel [44]: a – WC-12Co; b – WC-10Co-4Cr; c – WC-17Co; d – WC-17Co; e – 316L

Further research the nanometer WC-Co coating was prepared by cold spraying technology [45], and conducted the wear resistance experiment on three materials (Fig. 8): WC-12Co, WC-17Co and WC-23Co. It showed that the microhardness of WC-17Co was the highest, about $1500HV_{0.3}$, and wear resistance of coating was the best, which was 11 times that of 316L stainless steel.

Conclusions and prospects

Titanium alloy is a heat-sensitive material, which has poor resistance to abrasive wear for rotating or rubbing aerospace components. Cold spraying technology is suitable for the surface of titanium alloy wear resistant coating.

1. There are few studies on the wear resistance characteristics of titanium alloy substrates using cold spray technology. At present, most researchers only

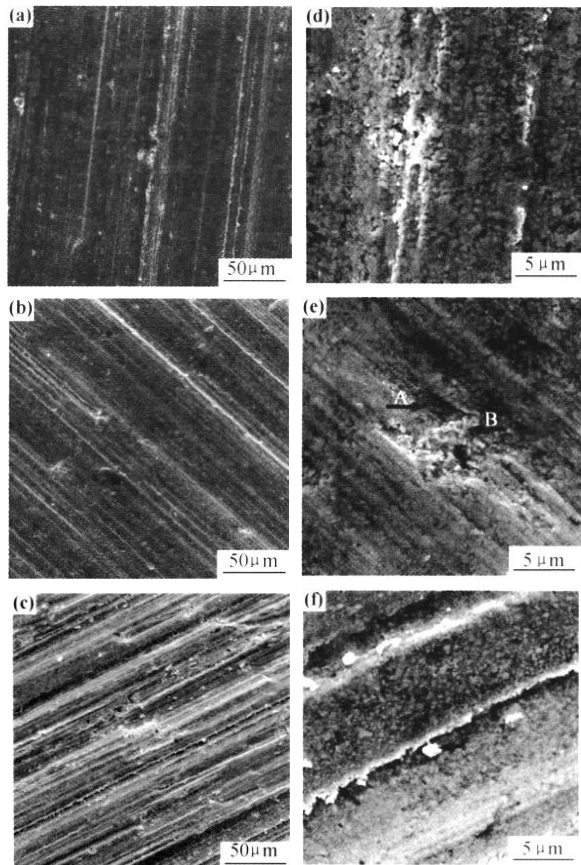


Fig. 8. Wear morphologies of the cold sprayed WC-Co coatings [45]: a – micrometer WC-12Co; b – nanometer WC-17Co; c – nanometer WC-23Co; d – micrometer WC-12Co; e – nanometer WC-17Co; f – nanometer WC-23Co

focus on Ti-6Al-4V alloy, and further research is needed for other titanium alloys. Such as the abrasive resistance of Ti-6Al-4V coating was sprayed onto Ti-6Al-4V substrate by CS is better than Ti coating, the main reason is that the porosity of the titanium coating is larger than that of Ti-6Al-4V, hence, reducing porosity is the future research focus of cold spray wear resistant coatings. In addition, the combination of cold spray technology and other technologies, post-treatment of cold spraying process, are also the future trend to be solved. for example, on Ti-6Al-1.5Cr-2.5Mo-0.5Fe-0.3Si substrate, deposited Ni-cBN composite coating, used the 10 μ m size of cBN, the bonding strength is (58 \pm 8MPa) after 600 $^{\circ}$ C heat treatment conditions;

2. Cermet not only has the toughness, high thermal conductivity and good thermal stability of metal, but also has the characteristics of high temperature resistance, corrosion resistance and wear resistance of ceramics. Cermets are widely used in rockets, missiles, supersonic aircraft shells, and flame nozzles in combustion chambers. The WC-Co in this article is a

typical cermet material with a very good surface wear-resistant material, for example, wear-resistant coating of WC-Co is directly prepared, microhardness of WC-17Co is the highest, about 1500HV_{0.3}, and wear-resistant performance of coating is the best, which is 11 times that of 316L stainless steel, however, the porosity of the WC-Co coating directly prepared by cold spraying technology is about 1.2 %, hence, how to reduce the porosity and use it to spray on the titanium alloy surface to obtain the best physical properties is the content of further research.

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ДОСЛІДЖЕННЯ ЗНОСОСТІЙКОГО ПОКРИТТЯ ДЕТАЛЕЙ ІЗ ТИТАНОВОГО СПЛАВУ ЛІТАКІВ НА ОСНОВІ ТЕХНОЛОГІЇ ХОЛОДНОГО НАПИЛЕННЯ

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Титанові сплави є основним структурним матеріалом компонента аерокосмічної системи, в аерокосмічній галузі використовується близько 75 % титанових та титанових сплавів, які мають переваги низької щільності, високої питомої міцності та відмінної стійкості до корозії, однак, її низькі межі зносостійкості подальше застосування сплаву титану. Тому він має велике значення для захисту поверхні титанового сплаву. Технологія поверхневого покриття може вирішити проблеми зносу титанових сплавів. В даний час існує безліч технологій нанесення покриттів, включаючи холодне напилення (CS), високошвидкісне окиснене паливо (HVOF), термохімічну обробку, осадження газової фази, розплавлення лазера; покриття плазмовим розпиленням, технологія подвійного плазмового поверхневого легування, дугове розпилення тощо, але технологія холодної напилення обумовлена підготовкою захисного покриття з титанового сплаву в твердому стані, а покриття має високу міцність скріплення та хорошу ударну в'язкість. осаджують майже будь-які порошкові матеріали, такі як чисті метали, включаючи алюміній (Al), магній (Mg), титан (Ti), нікель (Ni), кобальт (Co), ніобій (Nb), тантал (Ta), мідь (Cu), вольфрам (W) тощо; неметал, наприклад кераміка тощо; Металеві сплави; композитне

покриття, включаючи Al-Zn, Ti-Al, Ni-Al, Al-Mg, Al-SiC, Al-Al₂O₃, Ti-Ti₆Al₄V-Al₂O₃, Ni-Zn, Ni-cBN, Ni-Zn-Al₂O₃, Ti-Ta, Al-Mg17Al12, Al-FeSiBNbCu, WC-Co, Cr₃C₂-NiCr тощо. Він також може безпосередньо розпорошувати змішаний порошок для отримання зносостійких покриттів, тому широко застосовується. В даний час матеріали з титанових сплавів в основному застосовуються в галузі захисту та ремонту підкладки, а сфера виготовлення добавок з титанового сплаву з холодним напиленням, що з'явилася в останні роки, ще знаходиться на стадії процесу та базових теоретичних розвідок, і не було жодних успішних випадків конструкцій деталей з аерокосмічного та аерокосмічного титанового сплаву, але титановий сплав має низьку зносостійкість поверхні, і це було дуже дорого, тому він потребує ремонту, такого як зношування, пошкодження ударами під час експлуатації. У цій роботі було розглянуто, покриття зносостійкості на деталях із сплаву літака з титанового металу методом холодного напилення, проаналізовано виробництво покриття зносостійкості безпосередньо методом холодного напилення.

Ключові слова: титанові сплави; зносостійкий; технологій нанесення покриттів; холодне напилювання.

ИССЛЕДОВАНИЕ ИЗНОСОСТОЙКОГО ПОКРЫТИЯ АВИАЦИОННЫХ ДЕТАЛЕЙ ИЗ ТИТАНОВОГО СПЛАВА ПО ТЕХНОЛОГИИ ХОЛОДНОГО НАПЫЛЕНИЯ

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Титановые сплавы являются основным конструкционным материалом компонента аэрокосмической системы, около 75 % титана и титановых сплавов используются в аэрокосмической промышленности, которые обладают преимуществами низкой плотности, высокой удельной прочности и отличной коррозионной стойкости, однако имеют низкие пределы износостойкости дальнейшего применения титанового сплава. Следовательно, это имеет большое значение для защиты поверхности титанового сплава. Технология покрытия поверхности может решить проблемы износа титановых сплавов. В настоящее время существует множество технологий нанесения покрытий, в том числе холодное распыление (CS), высокоскоростное кислородно-топливное (HVOF), термохимическая обработка, осаждение в газовой фазе, расплавленный лазер; покрытие плазменным напылением, технология двойного плазменного легирования поверхности, дуговое напыление и т. д., но технология холодного напыления обусловлена подготовкой защитного покрытия из титанового сплава в твердом состоянии, и покрытие имеет высокую прочность сцепления и хорошую ударную вязкость, оно может осаждать практически любые порошковые материалы, такие как чистые металлы, включающее алюминий (Al), магний (Mg), титан (Ti), никель (Ni), кобальт (Co), ниобий (Nb), тантал (Ta), медь (Cu), вольфрам (W) и т. д.; неметалл, такой как керамика и т. д.; Металлические сплавы; композитное покрытие, включающее Al-Zn, Ti-Al, Ni-Al, Al-Mg, Al-SiC, Al-Al₂O₃, Ti-Ti₆Al₄V-Al₂O₃, Ni-Zn, Ni-cBN, Ni-Zn-Al₂O₃, Ti-Ta, Al-Mg17Al12, Al-FeSiBNbCu, WC-Co, Cr₃C₂-NiCr и т. д. Он также может непосредственно распылять смешанный порошок для получения износостойких покрытий, поэтому он широко используется. В настоящее время материалы из титанового сплава с холодным напылением в основном используются в области защиты и ремонта подложки, а область производства присадок с холодным напылением из титанового сплава, появившаяся в последние годы, все еще находится на стадии процесса и базовых теоретических исследований, и не было успешных случаев использования аэрокосмических и аэрокосмических деталей из конструкционных титановых сплавов, но титановый сплав имеет низкую износостойкость поверхности, и это было очень дорого, поэтому он требует ремонта, такого как износ, ударное повреждение во время эксплуатации. В этой статье обзор было рассмотрено износостойкое покрытие деталей авиационного титанового сплава по технологии холодного распыления, проанализировано получение износостойкого покрытия непосредственно по технологии холодного распыления.

Ключевые слова: титановые сплавы; износостойкий; технологий нанесения покрытий; холодное напыление.

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