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Additive manufacturing of titanium with application of cold spray process

Technologia przyrostowa tytanu z zastosowaniem procesu natryskiwania zimnym gazem

Abstract
Cold spraying is a new technology which can be used in the area of additive manufacturing. This method is suitable for oxygen-sensitive materials, such as titanium. In this paper the microstructure and mechanical properties of cold sprayed titanium deposit were characterized.

Keywords: additive manufacturing, cold spraying, titanium

Streszczenie
Natryskiwanie zimnym gazem jest nową technologią, która może być wykorzystana również w technologiach przyrostowych. Ta metoda jest odpowiednia dla materiałów łatwo utleniających się takich jak tytan. W artykule scharakteryzowano mikrostrukturę i właściwości mechaniczne natryskanej zimnym gazem tytanowej struktury.

Słowa kluczowe: technologie przyrostowe, natryskiwanie zimnym gazem, tytan

1. Introduction

New low-cost manufacturing technologies are the base for further development for many branches of industry. Titanium with high strength to weight ratio and excellent corrosion resistance in many media including seawater is an irreplaceable material for many applications in aerospace [1, 2]. Currently used technologies for manufacturing titanium components which involve casting, forging, extrusion and machining are expensive and labor-consuming. Moreover, production process of many parts leads to significant losses of material that can reach up to 60%. Therefore, direct producing of titanium is crucial in aviation industry. Additive manufacturing technology allows for manufacturing parts of machines based on a layer by layer deposition. This process allows for producing components with complex shapes and additionally significantly lower time and cost. Recently, cold spraying has joined the group of applied additive technologies as selective laser sintering (SLS) or direct metal deposition (DMD) [3–5].

Cold gas spraying technology was developed in the mid-1980s by a team of prof. A. Papyrin at the Institute of Theoretical and Applied Mechanics in Novosibirsk. The principle of the cold gas injection process is to compress and heat the gas to 1373 K and then accelerate it to supersonic speed (2–4 Ma) in a de Laval nozzle. As the gas flows through the divergent part of the nozzle, it decomposes to a significant temperature drop, even below the ambient temperature, hence the name "cold gas spraying" [6]. The powder coating material is coaxially injected into the gas stream and reaches a velocity of 300 to 1200 m/s (Fig. 1) at the moment of impact.

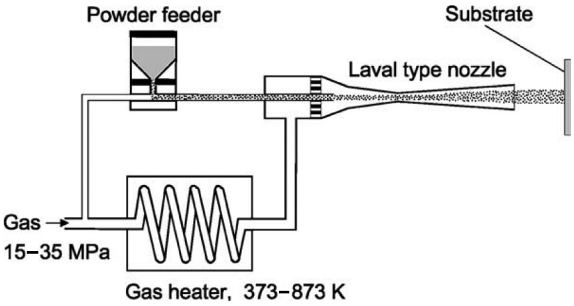

Fig. 1. Principle of cold spraying [7]

In the current operating systems for cold gas spraying, it is compressed to a pressure of 5 Pa at an output of 90 m^3/h [8, 9]. The applied powders have different granulation ranges from 1 to 50 μm. As a working gas, nitrogen, helium, air or their mixtures are used. A lower cost is the advantage of nitrogen, but if higher speeds are required, helium is used. Because of its much higher cost, it is added to nitrogen to achieve the desired velocity of the gas stream, and when used alone, systems for recovering thereof are installed.

The objective of the presented studies is to analyze the microstructure and mechanical properties of cold sprayed titanium structure for application in additive manufacturing technology.

2. Methodology

Commercially available Ti angular powder with grain size 15 ± 65 μm was used as a starting material. Titanium structure was sprayed on a flat Al 7075 aluminium alloy bar with dimensions of 400 x 30 x 5 mm. The surface of the sample was cleaned to remove contaminations and grit blasted with corundum grit with size 30. During deposition, titanium particles were accelerated in a convergent-divergent nozzle located in the gun of cold spraying system Impact Innovation 5/8 equipped with the Fanuc M-20iA robot at Kielce University of Technology (Fig. 2).

Fig. 2. Impact Innovation 5/8 cold spray system

Nitrogen was applied as the process gas to obtain 4.3 mm thick titanium deposit. The microstructure of the Ti powder and cold sprayed coatings were analysed with the SEM Jeol JSM 7100F and SEM Quanta 3D. Phase composition of the sprayed coatings was studied using D8 Discover Bruker. Porosity of the coatings was evaluated on the base of image analysis according to ASTM-E2109. The Vickers hardness HV0.3 was measured by means of micro-hardness tester Innovatest Nexus 4000. The micromechanical testing of coatings was carried out with the use of the nanoindentation technique (Nanovea) with a Berkovitz indenter (the Olivier and Pharr methodology). Forty nine identations were carried out for titanium structure.

3. Results and discussion

3.1. Microstructure of cold sprayed Ti structures

Figures 3a and 3b show a cross-section of a cold sprayed titanium structure with different magnifications. Despite wide particle size distribution of powder, the microstructure presents a very good bonding between deformed titanium grains (Fig. 3a). Traces of boundaries between strongly deformed particles under impact with high velocity onto substrate are visible (Fig. 3b). Moreover, small pores as a result of incomplete filling of surface irregularities by particles striking surface are well seen.

a) b)

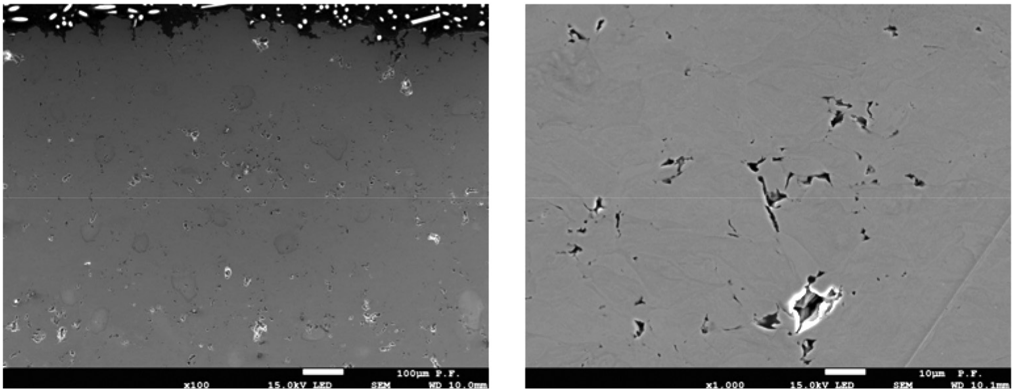

Fig. 3. Cross-section of cold sprayed titanium structure: a) 100x, b) 1000x

a) b)

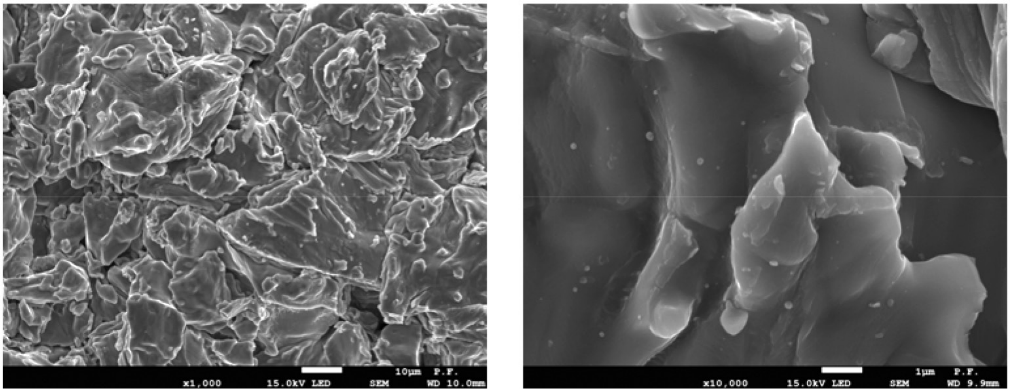

Fig. 4. Surface geometry of cold sprayed titanium structure: a) 1000x, b) 10000x

The microstructure of the surface of cold sprayed titanium structure consists of adjoining plastically deformed titanium particles which form an area with high roughness. Between deformed Ti grains, small voids are present indicating negligible porosity of coatings (Fig. 4a). The porosity of Ti structure estimated on the basis of forty images of cross-section was 2.6±0.8%. Severely flattened grains may be metallurgically bonded (Fig. 4b), which is mainly attributed to the high local temperature increase at the interface due to low thermal conductivity and resultant thermal diffusivity of titanium [10].

3.2. Phase composition

XRD analysis (Fig. 5) showed that the titanium powder and sprayed structure did not contain additional phases in the form of oxides or nitrides which can be formed in high temperature of the spraying stream.

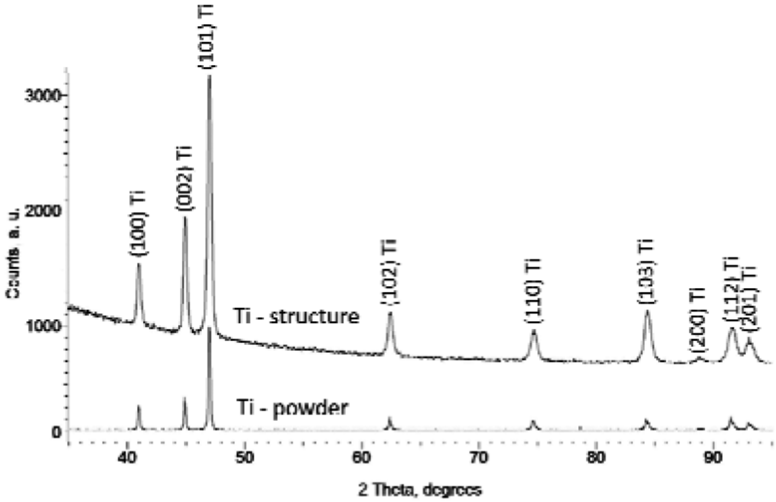

Fig. 5. XRD patterns of Ti powder and cold sprayed

3.3. Mechanical properties

The distributions of the nanomechanical properties were plotted as histogram distributions and maps of surface where each hardness and Young's modulus result was shown on the charts with the same dimensions and locations as in the investigated areas. Histograms and probability distributions of the hardness and Young's modulus of all cold sprayed titanium coatings are shown in Fig. 6.

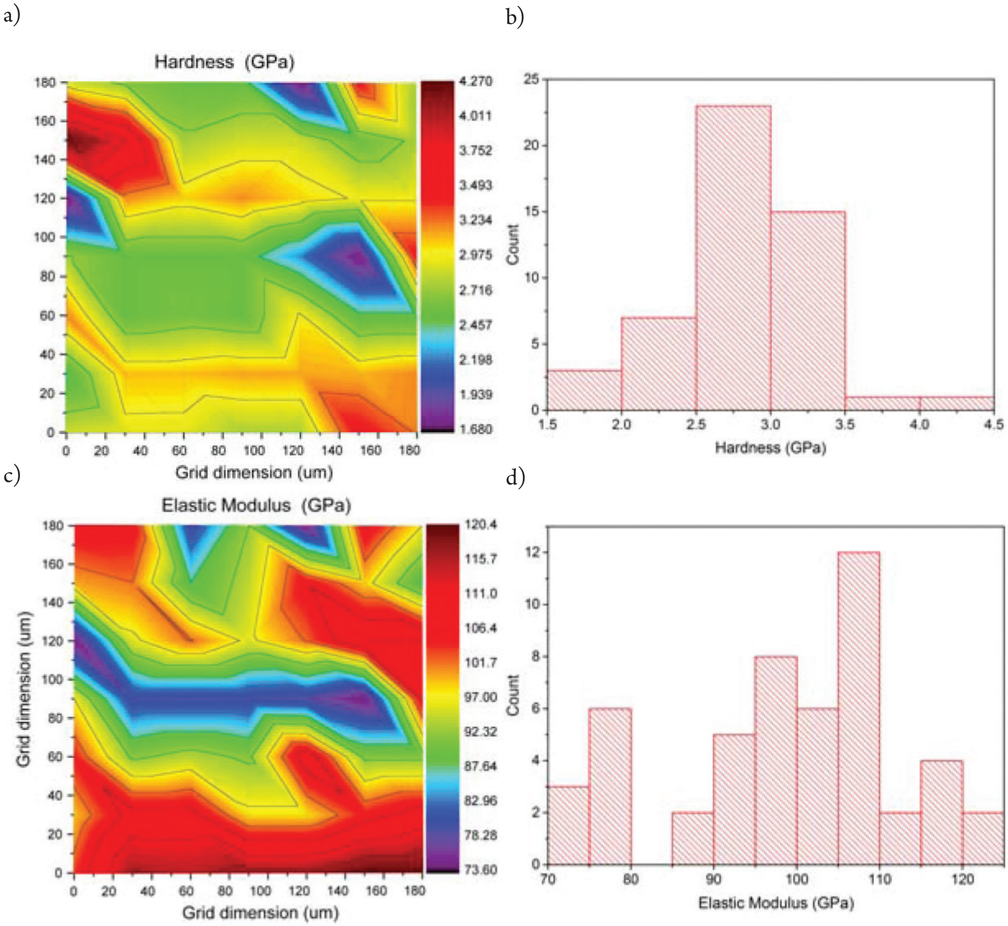

Fig. 6. Distribution of Ti structure coating: a) hardness map, b) hardness histogram and probability, c) Young's modulus map, d) Young's modulus histogram and probability

The nanoindentation tests showed the distribution of mechanical properties (hardness and Young's modulus) related to different areas of titanium structure. Mechanical properties and porosity of cold spayed titanium coatings are presented in Table 1.

Table 1. Properties of cold sprayed Ti structure

Property of Ti structure	**H (GPa)**	**ΔH (GPa)**	**E (GPa)**	**ΔE (GPa)**
	2.8	0.5	98.8	12.9

4. Conclusions

Microstructures of titanium deposits present a very good bonding between deformed titanium grains and negligible porosity. Severely flattened grains may be metallurgically bonded, which results from high local temperature at the interface. XRD analysis revealed that the titanium powder and sprayed structure did not contain additional phases. The nanoindentation tests showed the distribution of mechanical properties (hardness and Young's modulus) related to different areas of a titanium structure.

Acknowledgments

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References

[1] Hussain T., McCartney D. G., Shipway P. H., Marrocco T., *Corrosion Behavior of Cold Sprayed Titanium Coatings and Free Standing Deposits,* J. of Thermal Spray Technology, 260, Volume 20(1-2), January 2011.

[2] Cinca N., Barbosa M., Dosta S., Guilemany J.M., *Study of Ti deposition onto Al alloy by cold gas spraying,* Surface & Coatings Technology, 205, 2010, 1096–1102.

[3] Raoelison R.N., Verdy Ch., Liao H., *Cold gas dynamic spray additive manufacturing today: Deposit possibilities, technological solutions and viable applications*, Materials and Design, 133, 2017, 266–287.

[4] Villafuerte J., *Considering Cold Sprayfor Additive Manufacturing,* Advanced Materials & Processes 50, May 2014, 50–52.

[5] Blochet Q., Delloro F., N'Guyen F., Jeulin D., Borit F., Jeandin M., *Effect of the Cold-Sprayed Aluminum Coating-Substrate Interface Morphology on Bond Strength for Aircraft Repair Application,* J. of Thermal Spray Technology, 26, 2017, 671–686.

[6] Papyrin A., *Cold Spraying,* Elsewier Ltd. 2007.

[7] Stoltenhoff T., Voyer M., Kreye H., *Cold Spraying – State of the art and applicability,* Proceedings of the ITSC 2002, Essen, 366–374.

[8] Kay C. M., J. Karthikeyan, *High Pressure Cold Spray*, ASM International 2016.

[9] Assadi H., Kreye H., Gartner F., Klassen T., *Cold spraying e A materials perspective,* Acta Materialia, 116, 2016, 382–407.

[10] Bae G., Kumar S., Yoon S., Kicheol K., Na H., Kim H., Lee C., *Bonding features and associated mechanisms in kinetic sprayed titanium coatings,* Acta Materialia, 57, 2009, 5654–5666.

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