

Development of Algorithm for Calculating the Remaining Life of Thermal Spray Coating

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Abstract

In today's world, the product lifecycle monitoring technology has become widely used as it enables collection of data bulk and online processing. Therefore, it ensures the efficient use of monitored products and cost saving due to prevention of accidents, failures and other consequences. These investigations also involved thermal spray coatings. The previous papers mostly dealt with the investigations of the mechanical properties of coatings and addressed the spraying modes to improve them. This paper describes the operating principle of the software to calculate the remaining life of thermal spray coatings based on the knowledge about their accumulation and degradation limits. It used the results of 4-point bending tests at different loads as data. During the cycling tests the rate of plastic deformation accumulation was calculated, the math model was made, and the software is based on this model. As a result of these complex studies on 4-point bending, software was developed with an algorithm for calculating the residual life of the gas-thermal coating. It allows you to predict the performance of coatings depending on the calculation of various loads.

Keywords

Plastic Deformation, Residual Life, Thermal Barrier Coating

Introduction

Investigations of thermal spray coatings are widely spread due to the extensive use of these coatings in various manufacturing sectors, mainly in aircraft engine production, oil and gas industry and machine building. Thermal spray coatings are used for thermal protection, corrosion protection, reinforcement and other functions. In the aircraft industry the coatings are used for blades, atomizers of combustion chambers, jackets of gas turbine engines, 85% of the components have protection coatings [1]. The components with thermal spray coatings operate at a temperature of about 1000 degrees. That's why there is a great need for these investigations, but the existing methods for determining mechanical properties provide little information, for example, they do not take into account the stresses embedded during plasma spraying. However, these stresses affect adhesive and cohesive bonds in multilayered coatings, increase along with a thickness, and influence the bond strength as well as some other properties [2-5].

Rationale

The scope of this paper included the development of software with the algorithm for calculating the remaining life of a thermal spray coating. The material was zirconium dioxide partially stabilized with yttrium ($ZrO_2 - 6-8Y_2O_3$), with an optimum coating thickness of 0.25-0.45 mm. These coatings are widely used in the components of gas turbine engines and provide essential thermal protection. Software is required as there is a need for monitoring the lifecycle of components with thermal spray coatings. It helps to minimize costs in the overhaul period or predict the component replacement to prevent accidents, failures. The software contains a lot of experimental data to predict the performance of thermal spray coatings provided the correct model is used. That's why, this solution is of vital importance.

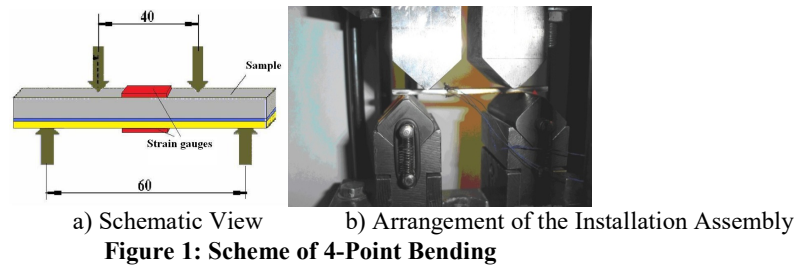
Problem Statement

The objective of this paper was to calculate the accumulation of plastic deformations at various loads under 4-point bending, define the limit values of coating deformation and make a math model. Besides, the project is complicated by high-temperature application of coatings. The tests provided the data on the effects of high temperature, but in the math model this data should be correct and take into account high-cycle loads.

Methods

A theoretical basis for calculation of remaining life of thermal spray coatings is a process of accumulation of plastic deformations from various exposures to coatings. Besides, in the coating there are internal stresses embedded during plasma spraying [6-10]. Many papers are devoted to this subjects, as well as investigations of base metal/coatings systems [11-15]. These papers make it possible to understand the processes running in the base metal, thermal spray coatings under different operating conditions [16-20].

The zirconium dioxide coatings were tested under 4-point bending to determine deformation properties (see Figure 1).



The tensile testing machine FPZ 100/1 was used as a loading device to determine the tensile, shear, flexural, compressive strength and ductility of materials. The speed of testing is continuously controlled. The small-scale deformations were measured with strain gauges 2PKB. These strain gauges were attached to the sample from the coating and base metal side, and connected to the strain indicator. Then the sample was mounted onto the fixture in the 4-point flexural loading setup in such a way as to apply tensile load to a portion of the ceramic coating between the supports. The readings of deformation were taken on a continuous basis.

In order to measure the load the module sensors were connected to the tensile testing machine FPZ 100/1 to collect load output in the range of 0 to +10 V. In order to obtain the values of deformation the sensors were connected to the strain gauges operated from a strain gauge resistance of ≈ 200 Ohm.

The hardware of the installation consists of a portable crate, two modules, two terminal boards with cable (see Table 1). The software was developed to process the data.

LTR-EU-2-5	2-slot portable LTR crate with interfaces: USB 2.0 High Speed and Ethernet
LTR 11	analog-to-digital converter (ADC), 14 bit, 400 kHz, 16/32 channels
LTR 212	strain gauge module, 4 channels
AC Cross tenzo	board for matching and connection of analogue signals to data collection device LTR212 with 1.8 m cable (terminal board with cable)
AC Cross LTR11	board for matching and connection of analogue signals to data collection device LTR11 with 1.8 m cable (terminal board with cable)

Table 1: Description of Hardware Components in Hardware-Software System

The strain gauge module (connected on the one side to the strain gauges and on the other side to the board for matching and connection of analogue signals to data collection device LTR212) conducts via the cable the strain gauge resistance signals (≈ 200 Ohm). The ADC module (connected on the one side to the tensile testing machine FPZ 1/100 and on the other side to the board for matching and connection of analogue signals to data collection device LTR11) conducts via the cable the FPZ 1/100 load output in the range of 0 and +10 V. Both matching boards are connected to the 2-slot portable LTR crate with USB 2.0 interface, which is connected with the PC and runs on the software.

The peripheral device ADC – LTR212 module for connection of the strain gauges to the special module LTR-EU-2-5 is designed for measurements using 2 strain gauge channels. Module LTR212 is a terminal board with the cable and allows for bridge and half-bridge connection of strain gauges. In order to minimize the influence of connecting line length the corresponding reference voltage outputs and inputs were connected not at the modules but at the sensor. For connection of the strain gauge signals to the modules the suitable shielded connecting lines were used.

The tests were performed in the following order: the specimens were soaked in the furnace at a temperature of 1100 °C for 1-100 hours, then subjected to 4-point bending testing in elastic (up to 400 N with unloading), elasto-plastic (up to 800 N with unloading) and plastic (up to 1200 N with unloading) regions, as well as until the coating was degraded. In addition, each loading cycle could be repeated, so it resulted in the values for the specimens subjected to high-temperature soaking with the different duration and under different test conditions. For 400 N, 800 N and 1200 N there are specific values of plastic deformation. The paper also investigated the nature of plastic deformation accumulation depending on isothermal soaking. Based on that, the math model was developed using the known algorithms for calculating stresses in coatings.

After the specimens were sprayed they were subjected to one-time and double heat treatment. One-time heat treatment means the diffusion annealing in vacuum at a temperature of 1050 C° for 4 hours to restore bulk properties of the base material. Double heat treatment means the additional oxidizing annealing in the air at a temperature of 850 C° for 2 hours to restore the stoichiometric composition of zirconium oxide in the coatings.

The signals were collected by the strain gauges during deformation of the specimens. They were transmitted in microvolts to the software, and then calibrated to micrometers to calculate absolute values. The math model for the software was based on these data.

Results and Discussion

Processing of the test results involved the calculation of average deformation accumulation rate for the thermal spray coatings. These data were uploaded to the software, and 0.25% was added to the deformation value for each 4-point bending cycle at 400 N. Likewise, 0.5% was added for each cycle at 800 N, and 0.75% - at 1200 N.

The algorithm can be understood using Table 3. It shows the following values: for example, 35 μm + 0.25% for each cycle at 400 N (without temperature exposure, HT I), 70 μm + 0.5% at 800 N, 120 μm + 0.75% for each cycle at 1200 N. The plastic deformations (Table 2) also increase by 0.25% at 400N, 0.5% at 800N and 0.75% at 1200N per each cycle. The values in the table were adjusted for the exposure to corrosive environment at 1100°C (isothermal soaking) and heat treatment.

After testing with:	No temperature exposure		1-2 hours		10 hours		50 hours		100 hours	
	HT ^a I	HT II	HT I	HT II	HT I	HT II	HT I	HT II	HT I	HT II
400 N	2	0.5	0.2	1.2	2	2	4	4	6	6
800 N	7	1.4	3	10	5	20	10	35	20	45
1200 N	20	20	20	30	20	40	30	70	70	90

Table 2: Plastic Deformation (Residual Stresses) after Unloading at 0 N, μm

^a HT - heat treatment

It was found that the coating degraded after its total plastic deformation reached 250 μm . That's why 250 μm was taken as a limit value for coating deformation per a strain gauge length of 20 mm. This limit value was specified as a service life.

During testing with:	No temperature exposure		1-2 hours		10 hours		50 hours		100 hours	
	HT ^a I	HT II	HT I	HT II	HT I	HT II	HT I	HT II	HT I	HT II
400 N	35	35	45	45	50	50	50	60	50	70
800 N	70	70	95	115	100	125	105	140	110	150
1200 N	120	120	150	170	160	180	180	215	200	240

Table 3: Maximum Test Deformation Values, μm

^a HT - heat treatment

In order to determine the remaining life the formula was developed where the remaining life is conditionally designated as $\$$. The maximum coating deformation $\%$ is conditionally, for example, 210 μm . The total coating life $\#$ is constant and equal to 250 μm . The formula is as follows: $\$ = (\# - \%) * 100\% / \# = ((250 \mu\text{m} - 210 \mu\text{m}) * 100\%) / 250 \mu\text{m}$. Therefore, "250 - 210 = 40 μm " results in 16%, which is the remaining coating life, in %.

During the simulation of experiments using the software the degradation of the coatings occurs in two cases: a) Max mode was selected, and maximum deformation exceeds 250 μm immediately; b) plastic deformation + maximum deformation > 250 μm , whichever is the earlier. In case of coating degradation there is no remaining coating life and 0% is displayed.

The nature of plastic deformation accumulation varies according to the loads applied to the coating – 400 N, 800 N, 1200 N or their alternation. Besides, each type of load corresponds to the operating conditions of the coating on the actual part. It allows an engineer (after simulated experiments to calculate the remaining life of thermal spray coating) to make conclusions about advantages of selected spraying and heat treatment method. A load of 400 N applied to the coating is equivalent to the operating conditions of a coated gas turbine engine component in the regular flight mode, and the experimental sample itself can withstand max. 205000 such cycles. For 800 N and 1200 N this figure is significantly lower.

Conclusion

Based on the results of comprehensive 4-point bending investigations, the software with the algorithm for calculation the remaining life of thermal spray coatings was designed to predict its durability depending on loads on the coating.

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References

- [1] A.A. Inozemtsev, V.L. Sandratskij, "Gazo turbinnye dvigateli" [Gas turbine engines]. Perm (Russia), Aviadvigatel Publ., 2006. 1204 p.
- [2] E.A. Budovskikh, V.E. Gromov, D.A. Romanov, "The Formation Mechanism Providing High Adhesion Properties of an Electric-Explosive Coating on a Metal Basis", Doklady Physics, 2013, Vol. 58. – № 3. –P. 82–84
- [3] M. Beghini, L. Bertini, F. Frendo, "Measurement of Coatings' Elastic Properties by Mechanical Methods: Part 1. Consideration on Experimental Errors", Experimental Mechanics, volume 41, No. 4, December, pp. 293-304.

- [4] M. Beghini, G. Benamati, L. Bertini, F. Frenzo, "Measurement of Coatings' Elastic Properties by Mechanical Methods: Part 2. Application to Thermal Barrier Coatings", *Experimental Mechanics*, 2001, vol. 41, No. 4, pp. 305-311.
- [5] C.C. Berndt, A. Kucuk, C.G. Dambra, "Influence of plasma spray parameters on behavior of yttrium stabilized zirconium the cracking coatings", *Practical failure analysis*, 2001.Vol. 1- P. 55-64.
- [6] A. Saifutdinov, S. Fadeev, I. Fayrushin, "Some numerical simulation results of the dynamic temperature distribution in dc plasma torch "Thermoplasma 50-01"", *Journal of Physics: Conf. Series* 927, 2017, 012047
- [7] A.I. Saifutdinov, I.I. Fairushin and N.F. Kashapov 2016 *JETP Lett.* 104 180–185
- [8] M.A. Popova, V.P. Kuznetsov, V.P. Lesnikov, N.A. Popov, I.P. Konakova, "The structure and mechanical properties of single-crystal nickel alloys with Re and Ru after high-temperature holds", *Materials Science & Engineering A* 642, 2015, P. 304–308
- [9] ASTM C158-02 (2007), "Standard test methods for strength of glass by flexure (Determination of Modulus of Rupture)" [Electronical resource], ASTM. URL: www.astm.org/Standards/C158.htm
- [10] V.P. Kuznetsov, V.P. Lesnikov, M.S. Khadyev, I.P. Konakova, N.A. Popov, "Structural and phase transformations in single- crystal alloy ZHS36-VI [001] after holding in the range of 1050-1300 °C", *Metal Science and Heat Treatment*, 2012, 1(54), pp. 90-95
- [11] D.S. Terent'ev, L.I. Shevtsova, Mali V.I., A.A. Bataev, I.A. Bataev, V.S. Lozhkin, "Structure and properties of composite materials «aluminum- nicelaluminide» produced by the SPS method", *The 8 International Forum on Strategic Technology, IFOST 2013 proseedng*, 2013, p p. 187 - 189.
- [12] G. Xia, Z. Chen, A.I. Saifutdinov, S. Eliseev, Y. Hu, A.A. Kudryavtsev, "Longer Microwave Plasma Jet With Different Discharge Performances Originated by Plasma Surface Interactions", *IEEE Transactions on Plasma Science*, 2014, 10 (42), pp. 2768 – 2769.
- [13] R. Taylor, J. R. Brandon, and P. Morrel, "Microstructure, composition and property relationships of plasma-sprayed thermal barrier coatings," *Surf. Coat. Techn.* 1992. 50, 141-149
- [14] T. W. Clyne and S. C. Gill, "Residual stresses in thermal spray coatings and their effect on interfacial adhesion: a review of recent work," *J. Therm. Spray Techn.* 1996. 5, 401-418
- [15] A. Kucuk, C. C. Berndt, U. Senturk, et al., "Influence of plasma spray parameters on mechanical properties of yttria stabilized zirconia coatings. I: Four point bend test," *Mater. Sci. Eng.*, 2000. A 284, pp. 29-40; II: Acoustic emission response," *Mater. Sci. Eng.* 2000, A 284, pp. 41-50.
- [16] A.T. Ilinkova, A.I. Sayfutdinov, A.R. Ibragimov, L.N. Shafigullin, "Investigation of mechanical properties of thermal coatings obtained during plasma spraying of powder zirconium dioxide", *Journal of Physics: Conference Series: Volume 789, Issue 1, 10 February 2017, Article number 012022*
- [17] N.V. Romanova, T.M. Kokina, G.R. Shafigullina, A.R. Ibragimov, L.N. Shafigullin, "Thermal studies of polymeric foams, used in engineering", *Journal of Engineering and Applied Sciences*
- [18] R. S. Lima, C. R. Lima, and C. C. Berndt, "Deformation of plasma sprayed thermal barrier coatings," *J. Eng. Gas Turbin. Power*, 2000, No 122, pp. 387-392.
- [19] T. A. Il'inkova, A. R. Ibragimov, I. R. Bakirov, and T. N. Mel'nikova, "Method of determining the residual stresses and the energy characteristics of gas-thermal coatings," *RF Patent 2499244, Bull. Izobret.*, 2013, No. 32
- [20] A. M. Akhmetgareeva, A. T. Tagirov, I. M. Ganiev, et al., "Method of quality control of heat treatment of thermal barrier coatings," *RF Patent 2576543, Bull. Izobret.*, 2016, No. 7