PAPER • OPEN ACCESS

The use of experimental bending tests to more accurate numerical description of TBC damage process

To cite this article: T Sadowski and P Golewski 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **123** 012017

View the article online for updates and enhancements.

The use of experimental bending tests to more accurate numerical description of TBC damage process

T Sadowski, P Golewski

Faculty of Civil Engineering and Architecture, Lublin University of Technology Lublin, Poland

E-mail: sadowski.t@gmail.com

Abstract. Thermal barrier coatings (TBCs) have been extensively used in aircraft engines to protect critical engine parts such as blades and combustion chambers, which are exposed to high temperatures and corrosive environment. The blades of turbine engines are additionally exposed to high mechanical loads. These loads are created by the high rotational speed of the rotor (30 000 rot/min), causing the tensile and bending stresses. Therefore, experimental testing of coated samples is necessary in order to determine strength properties of TBCs. Beam samples with dimensions 50x10x2 mm were used in those studies. The TBC system consisted of 150 μm thick bond coat (NiCoCrAlY) and 300 μm thick top coat (YSZ) made by APS (air plasma spray) process. Samples were tested by three-point bending test with various loads. After bending tests, the samples were subjected to microscopic observation to determine the quantity of cracks and their depth.The above mentioned results were used to build numerical model and calibrate material data in Abaqus program. Brittle cracking damage model was applied for the TBC layer, which allows to remove elements after reaching criterion. Surface based cohesive behavior was used to model the delamination which may occur at the boundary between bond coat and top coat.

1. Introduction

The novel materials are different types of composites obtained as mixtures of various phases and further subjected to specific technological process in the manufacturing, e.g. [1, 2]. The materials engineering allows for designing of almost arbitrary internal structure of the composites, particularly important for industrial demands, e.g. 2-phase ceramic materials [3-9]. A very important example are functionally graded materials, possessing gradation of the material properties, (e.g. [10-20]), for possible applications in thermal barrier coating (TBC) of engines critical parts.

The study of TBC protective coatings is a very complex and difficult issue. The mere fact, that the protective coating is applied on the turbine blades with complex shapes, makes the stress and strain fields are non uniform [21, 22] in comparison to simple layered TBC structure. In addition, the blades also have internal cooling channels, which introduce variable stiffness of the substrate and are a source of thermal stresses formation. Therefore, it is necessary to strive for their most optimal distribution, also taking into account the cooling efficiency ratio [23].

In addition to thermal loads, turbine blades are also carry the considerable mechanical loads. As a result of not overlapping the direction of centrifugal force with the centers of gravity of blade cross - sections, tends to form a complex stress state caused mainly by stretching and bending. Such a complex case was analyzed at work [24].

A very important issue that will have an influence on the durability and strength of protective layer are environmental loads. Due to the fact that the TC layer (top coat) is porous it does not constitute a barrier to oxygen contained in the exhaust gas. Therefore, during blade operation, it comes to gradual increase of TGO (thermally grown oxide) layer on the interface between TC and BC (bond coat). The growth process of this layer and microscopic measurements are presented in [25].

The difficulty, that always appears during TBC coating research is the strain measure. The reason for this is that, the coating thickness is about 0,5mm, and would be difficult to use eg. tensometric gauges. Therefore, in this paper, a solution to solve this problem by using optical displacement measurement system Aramis was proposed.

## 2. Description of test method

The method presented in this work consisted of three steps: bending test with strain observation by Aramis system, microscopic observations and damage model calibration in Abaqus program.

Experimental studies were carried out on the MTS 25kN testing machine. Due to the small sample sizes b x h x w (10mmx2mmx50mm) previously designed handle was used for the bending test, which allows to adjust the supports and conduct research for different loads.

Due to the fact the Aramis system was used, side surfaces of the samples had to be first carefully sanded and polished (Figure 1).
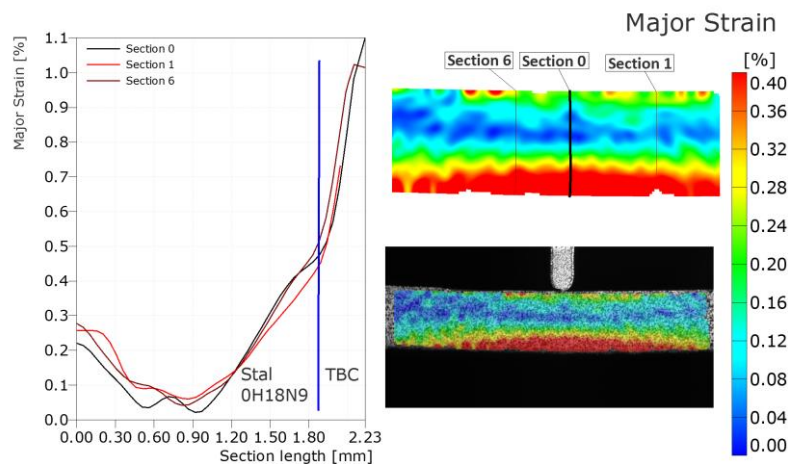

Figure 1. Samples preparation
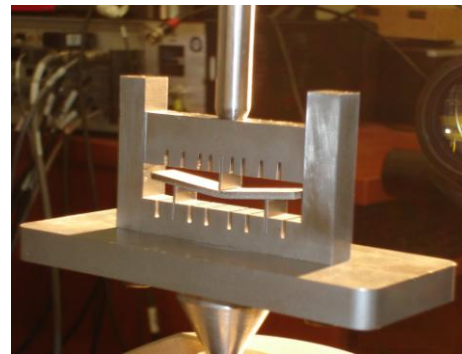
Figure 2. Bending test

The three point bending test was carried out in a static way (Figure 2). During the test, both the force, displacement and strains of the side surface of the sample with TBC layer were registered. The research was carried out for 10 load levels from 50N to 500N with the increment of 50N.


Figure 3. The results from Aramis system

A high noise occurred for small loads from 50N to 250N and in strain fields it was difficult to distinguish the individual layers: substrate and TBC. From 300N to 400N a clear distinction of individual layers already occurred, but just at the edge there were still areas where the system could not determine the correct values. The best effect was obtained for the largest load. In Figure 3 we can clearly read the position of the neutral axis, and the maximum strain values. Making cross - sections (section 0, 1 and 6), we can read the values for both the BC and TC layers.

3. FEM model description

The numerical model was built with elements of type CPS4R (A 4-node bilinear plane stress quarrilateral, reduced integration, hourglass control). For a beam model 12500 elements were used and for a single support 289. The substrate was made from stainless steel OH18N9 with 2mm thickness (Figure 4) for which a separate strength tests were carried out. The following values were assumed for the substrate: E = 200 GPa, n = 0.3, R_e = 190 MPa, R_m = 700 MPa, A = 0.45.
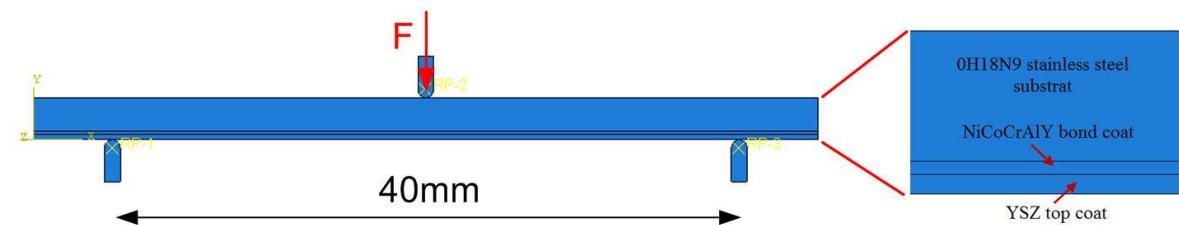
Figure 4. Boundary conditions and structure of FEM model.

The material data for bond coat (BC) and top coat (TC) were partially taken from the literature and confirmed in our own tests using microhardness testing. The samples were made by air plasma spraying method (APS) by PZL Rzeszów and the same covering was applied also on guide turbine blades of PZL 10W engine. In order to make the numerical model closer to reality, the material model for ceramic coating also includes damage by using brittle cracking model. This is a fuzzy type model representing discontinuities in the brittle material. Therefore, a single crack is not tracked like in the case of X-FEM method [26]. Crack initiation is based on a simple Rankine hypothesis, which assumes that a crack arises when the maximum tensile stresses reach the tensile strength σ_t^I.
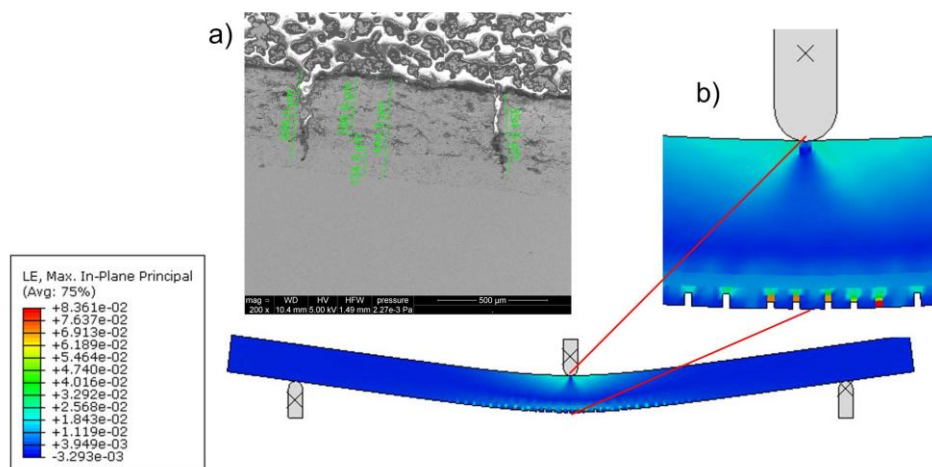
Figure 5. Damage of TBC coating:
a) results from microscopic observations, b) FEM simulation

Additionally, the brittle cracking model requires also the definition of damage evolution. The following criteria are used to describe the damage evolution: stress - strain criterion, fracture energy criterion and displacement criterion. Figure 5 summarizes two results: a) the experimental test and b) FEM simulation. Microscopic observations were carried out on Quanta FEG scanning electron microscope of FEI company. The coating thickness (TC) was about 300μm, and the thickness of bond coat 150μm, these values were also adopted in the simulation. In Figure 5a there is also visible the folding of the individual layers. It should also be pointed out that the crack does not always occur only in the ceramic coating (TC) and may also propagate to the bond coat (BC). Therefore, further works in research and FEA simulations are needed in order to describe the damage process in as much detail as possible, including delamination with application of the cohesive model, e.g. [27-33] . The example has confirmed that it is possible to use strain measurements of Aramis system and microscopic observations for a better description of damage in Abaqus program.

4. Conlusions

In this paper three - point bending tests were performed using an innovative method of system Aramis application for strain measurement in TBC layer. The tests were performed for 10 load levels from 100N to 500N with increments of 50N. For each load level microscopic observations were carried out in search of places where a crack or delaminating occurred. The results of deformation and damage information allowed for more detailed description of brittle cracking model for TBC in Abaqus program.

References

[1]   Gömze,L.A.; Gömze L.N. 2009 *Ěpitöanyag – J. Silicate Based and Comp. Mat*. **61** 38
[2]   Gömze,L.A.; Gömze L.N. 2013, *IOP Conf. Ser.: Mater. Sci. Eng*. 47 012033
        http://dx.doi.org/10.1088/1757-899X/47/1/012033.
[3]   Sadowski, T. 2012, *Comput. Mat. Sci*., **64**, 209
[4]   Sadowski, T.; Marsavina, L. 2011, *Comput. Mat. Sci.,* **50**, 1336
[5]   Sadowski, T.; Samborski, S. 2008, *Comput. Mat. Sci*., **43**, 75
[6]   Marsavina, L.; Sadowski, T. 2009 *Comput. Mat. Sci*. **44**, 941
[7]   Marsavina, L.; Sadowski, T. 2009 *Comput. Mat. Sci*. **45**, 693
[8]   Marsavina, L.; Sadowski, T. 2007 *Int. J. Frac*. **145**, 237
[9]   Postek, E.; Sadowski, T. 2011 *Comp. Interf*. **18**, 57
[10]   Birman, V. ; Byrd, L. V. 2000 *Appl. Mech. Rev*. **53**, 147
[11]   Sadowski, T. ; Neubrand, A. 2004 *Int. J. Fract*. **127**, 135
[12]   Ivanov, I.; Sadowski, T.; Pietras, D. 2013 Eur. *Phys. J. Special Topics* **222** 1587
[13]   Petrova, V.; Sadowski, T. 2014 *Meccanica* **49**, 2603
[14]   Sladek, J.; Sladek, V.; Zhang, Ch. 2005 *Comp. Mater. Sci*. **32**, 532
[15]   Hosseini, S.M.; Abolbashari, M.H. 2012 *Heat Transf. Eng*. **33**, 261
[16]   Sadowski, T.; Nakonieczny, K. 2008 *Comput. Mat. Sci*. **43**, 171
[17]   Sadowski, T.; Ataya, S.; Nakonieczny, K. 2009 *Comp. Mater. Sci*. **45**, 624
[18]   Nakonieczny, K. ; Sadowski, T. 2009 *Comp. Mater. Sci*. **44**, 1307
[19]   Birsan, M.; Altenbach, H.; Sadowski, T.; Eremeyev, V.; Pietras, D. 2012 *Comp. Part B* **43**, 1315
[20]   Birsan, M.; Sadowski T.; Marsavina L.; Linul E.; Pietras D. 2013 *Int. J. Sol. Str*. **50** 519
[21]   Sadowski, T.; Golewski, P. 2011 *Comp. Mat. Sci*. **50** 1326
[22]   Sadowski, T.; Golewski, P. 2012 *Def. and Diff. Forum* **326-328** 530
[23]   Sadowski, T.; Golewski, P. 2012 *Comp. Mat. Sci*. **52** 293
[24]   Sadowski, T.; Golewski, P. 2012 *Comp. Mat, Sci*. **64** 285
[25]   Sadowski, T.; Golewski, P. 2014 *Sol. St. Phenom*. **216** 128

[26]   Golewski, G. L.; Sadowski, T.; Golewski P. 2012 Comp. Mat. Sci. **62** 75
[27]   Burlayenko, V.; Sadowski, T. 2009 *Comp. Mater. Sci*. **45** 658
[28]   Burlayenko, V.; Sadowski, T. 2014 *Meccanica* **49** 2617
[29]   Sadowski, T. ; Golewski, P. ; Zarzeka-Raczkowska, E. 2011 *Comp. Mat. Sci*. **50** 1256
[30]   Burlayenko, V.; Sadowski, T. 2014 Comp. Struct. **108** 354
[31]   Sadowski, T.; Golewski, P.; Kneć, M. 2014 *Comp. Struct*. **112** 66
[32]   Sadowski, T.; Marsavina, L.; Peride, N.; Craciun, E.-M. 2009 *Comput. Mat. Sci*. **46** 687
[33]   Balawender, T.; Sadowski, T.; Golewski, P. 2011 *J. Adhes. Sci. Technol*. **25**, 2391