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Resonance bending fatigue testing with simultaneous damping measurement and its application on layered coatings

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ABSTRACT

The use of specimen loss factor as fatigue damage indicator of Hastelloy-X substrates with different surface treatments was investigated together with other fatigue damage indicators, namely resonance frequency and crack mouth length. The tested surface treatments included grit-blasting and plasma spraying of NiCoCrAlY bond coat and yttria stabilized zirconia (YSZ) top coat. The loss factors of fatigue test specimens were measured repeatedly during the resonance bending fatigue test using the conventional free decay method. The analysis of the damping spectra, i.e. the model describing the relation of loss factor to maximum macroscopic specimen strain ε_{yy} was drafted. The model is based on the combination of defect models developed by Göken and Riehemann (2004) and classical dislocation model of Granato and Lücke (1956). It appears, that the damping spectra can be well approximated as a combination of two defect peaks (C_1 and C_2) and one dislocation peak (D_1). The low strain defect peak (peak C_1) is sensitive to the presence of fatigue cracks. The second defect peak (peak C_2) can be attributed to the remaining substrate and coating defects such as embedded grit particles, coating porosity, surface roughness and sliding in the sample clamping area. The fatigue damage detection using the C_1 peak magnitude was performed and its results were related to the crack length obtained by digital image correlation (DIC) method. In the crack initiation stage I., the C_1 peak height shows different behavior than the resonance frequency and therefore provides new information. The underlying processes causing C_1 peak changes need to be found yet, however. In the crack growth stage II., both resonance frequency and peak height C_1 correlate with the measured fatigue crack size.

1. Introduction

The wide spread industrial use of various surface treatment techniques such as grit-blasting or thermally sprayed coatings calls for the estimation of the fatigue resistance of surface treated parts. The applied fatigue testing methods are usually based on bending of flat specimens [3–9] or rotating beam bending of round cross-section specimens [10–16]. Uniaxial fatigue testing was also used by several authors [17–21]. The published fatigue data show important influence of thermally sprayed coating on fatigue properties. Both increase and decrease of fatigue life were observed, depending on the particular coatings and substrates tested.

For the deeper understanding of the experimental fatigue data, the processes taking place both in substrate and coating during fatigue must be described. These rather complex processes include material property changes, crack initiation and crack growth. In bulk materials, some of these processes may be observed directly during the fatigue test. Optical crack observation methods, fatigue fuses, brittle paints or penetration test can be used to detect fatigue crack initiation and describe its growth. Sample stiffness or stress–strain response can be evaluated to assess material property changes. Fatigue degradation of material can be monitored by potential drop methods or magnetic methods, by eddy currents etc. The set of suitable experimental methods is however significantly reduced when it comes to samples with surface covered by thermally sprayed coatings. Moreover the above methods are often not selective enough to separate the effect of the coating and substrate. Therefore new methods are being developed to overcome these difficulties such as in-situ monitoring of resonance frequency [9,22], and magnetic methods [23,24]. In this paper, the damping spectra measurement and evaluation is attempted in this

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Table 1
List of tested samples and the corresponding fatigue lives Nf. H and h denote substrate and coating thickness.

Symbol & sample	Treatment	N_f (cycles)
○ P	As received Hastelloy X sheet, $H = 4.8$ mm	377,673
● GB	Grit blasted using HVAF gun	2,021,914
○ APSBC	APS NiCoCrAlY bond coat on GB substrate, $h = 225$ μm, Amperit 827.843 powder	381,063
● APSBCTC	APS BC + YSZ top coat, $h = 225 + 250$ μm, AMDRY 365-2 powder	517,554

search for fatigue damage detection methods suitable to samples with protective thermally sprayed coatings and surface treatments in general. This work is based on preliminary studies on damping measurement [25] and digital image correlation (DIC) based crack detection [26]. A new method of damping spectra evaluation is presented and the DIC crack detection method is enhanced by introduction of strain field discontinuity into the DIC process. The applicability of the above methods is demonstrated on samples included in our previous fatigue study of samples with thermal barrier coatings (TBC) [27].

The specimen damping may be an important source of information on damage processes [28]. In its traditional form, i.e. if it is estimated from free decay curves [1,28,29], the damping is obtained as a function of strain or deflection forming a damping spectrum. This spectrum reflects damping caused by sample clamping, fatigue cracks and other defects in the substrate and coating and by dislocation movement. The spectrum is then a sum of contributions of each specific damping mechanism:

$$\eta = \eta_{cracks} + \eta_{clamp} + \eta_{defects} + \eta_{disloc}$$

Peaks generated by fatigue cracks were already described by Göken and Riehemann [1]. In their paper, the material is modelled as a set of two parallel springs of stiffness E_i and E_r. The spring E_i has a frictional grip characterized by critical stress or strain ε_c. During the tension part of the loading cycle, when the critical stress of the grip is reached, the grip disconnects and the energy stored in spring E_i is dissipated. Then, during the compression part, the initial status of the system is restored and spring E_i is loaded again. This discrete model is transformed into continuous one by assumption of existence of many cracks with lognormal distribution of critical strain ε_c in the sample. The model describing this *crack peak* shape as a function of maximum macroscopic strain ε_{yy} on the surface of bending beam specimen is proportional to:

$$\eta_{cracks}(\varepsilon_{yy}, \varepsilon_m, \gamma) \approx \frac{1}{\pi \varepsilon_{yy}^2} \left(erf \left(\frac{log\left(\frac{\varepsilon_m}{\varepsilon_{yy}}\right) + 3(log(\gamma))^2}{\sqrt{2} log(\gamma)} \right) - 1 \right) \qquad (1)$$

In the following text, this model is normalized so that $max\ (\eta_{cracks}(\varepsilon_{yy})) = 1$. In this model, ε_m and γ are the mean and the geometrical standard deviation of the assumed critical strain distribution.

The dislocation damping can be described by a established vibrating string model of Granato and Lücke [2]. This model assumes the unpinning of dislocations loops from point defects as a result of strain field. The peak height normalized strain dependent form of this *dislocation peak* can be simplified based on [30] as:

$$\eta_{disloc}(\varepsilon_{yy}, \varepsilon_D) \approx \frac{1}{\varepsilon_{yy}} e^{\left(-\frac{\varepsilon_D}{\varepsilon_{yy}}\right)}, \qquad (2)$$

where ε_D is the position parameter. Again, we use the normalized form $max\ (\eta_{disloc}(\varepsilon_{yy})) = 1$ in this paper.

The nature of remaining two types of damping, i.e. η_{clamp} and $\eta_{defects}$ can be considered of similar nature to the crack induced damping and modelled as the crack peaks. Based on this simple approach each damping spectra can be modelled as sum of three crack peaks given by Eq. (1) and one dislocation peak given by Eq. (2).

2. Materials and methods

2.1. Samples

The conventional TBC coatings sprayed by atmospheric plasma torch on Hastelloy-X substrates were tested in this study. Samples P, GB, APSBC and APSBCTC correspond to subsequent stages of the coating process and are described in Table 1. Substrates were laser-cut from cold rolled Hastelloy X sheet (thickness $H = 4.8$ mm) into dimensions according to Table 1. During grit-blasting and spraying, samples were mounted in a rotational sample holder (carousel) and blasted and fully coated from both sides. The grit-blasting was done with alumina grit using M3 HVAF torch (Uniquecoat Technologies, LLC, USA) set in the grit-blasting regime. The spraying was performed using F4-MB torch (Sulzer Metco, Switzerland). For further information on the coating properties please see [27].

2.2. Resonance bending fatigue test

Fatigue bending test was selected for this study as it offers increased sensitivity on the specimen surface properties. In bending methods such as rotating beam or cantilever beam, the deformation is highest at the surface and the stiffness of the sample significantly depends on the stiffness of the layer just below its surface.

From the bending methods, the resonance bending ($R = -1$) fatigue test of flat unnotched specimens already proved itself as an efficient way for testing surface treated materials. By utilizing resonance, the test can proceed at high loading frequency. Moreover, if the specimen is a part of the resonance circuit, remarkable sensitivity of the system resonance on specimen stiffness can be achieved [31]. The in-house developed fatigue test device "SF-Test" (Surface Fatigue–Test, see Fig. 2) benefits from the above mentioned advantages. This device was continuously improved and used to conduct several hundreds of fatigue tests of surface treated samples in the past few years [7–9,24,32–34]. The basic principle and new modifications of this device are briefly described here.

The schematic drawing of the device is in Fig. 1 the actual photograph is in Fig. 2. The specimen excitation is controlled by the *A_gen* and *f_gen* variables, corresponding to excitation coil signal amplitude and frequency. The sample free end deflection $u(t)$ is measured by the fast laser triangulation distance sensor OADM12I60 (Baumer A.G. Frauenfeld, Switzerland) and the parameters of its harmonic motion (A, f, C) are discriminated by the IEEE1057 standard. This techniques significantly increases the precision of discriminated parameters as the whole recorded waveform is analyzed. The analysis of the coil current signal $I(t)$ is performed as well. The phase shift θ between the u and I signals is also evaluated. In contrast to other similar fatigue tests [31,35], the real time phase shift technique is used to keep the loading frequency equivalent to the resonance frequency for the whole duration of the fatigue test. The phase shift technique updates the loading frequency, *f_gen* based on phase shift θ between the loading current I and specimen deflection u approximately 10 times per every second so that $\theta = 90°$. This ensures, that the specimen vibrates at its first resonance frequency f_r and its