Damping of Flexible Structures with PEO Coating

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Abstract: This paper deals with the study of damping as a possible measure for mitigating fatigue. It involves the experimental characterisation of thin aluminium alloy cantilever beams as representatives of flexible structures. The beams are treated with Plasma Electrolytic Oxidation (PEO) to produce dense, polycrystalline alumina coatings on the surface. These coated beams are then subjected to dynamic testing to assess the level of damping introduced by the coatings. This measurement of damping sheds light on the role of the microstructure of the coating in damping and how to optimize damping from the PEO process. Higher level of damping is desirable as it attenuates the level of stress in the substrate, leading to higher fatigue life. Simple numerical and experimental method shows that PEO coatings can be a viable method of damping.

1 Introduction

High cycle fatigue has been a prevalent problem in flexible vibrating systems. In the aerospace industry for example, high cycle fatigue is probably the dominant mode of failure for forced vibration of aero-engines. With the drive within the industry to create lighter and thinner structures, the vibration response of these systems will become larger, leading to higher stresses. This is further compounded by the fact that the resonant frequencies for these applications are usually quite high. In order to mitigate these effects, structural redesign and/or damping treatments are usually applied. The discussion of the various solutions available is beyond the scope of this paper. In this paper, focus is emphasised on the role of damping, alumina ceramic coatings in particular. Although the damping properties of some ceramic coatings have been studied in the past, there is still a wide variety of unexplored combinations of material and deposition methods to create these coatings. The Plasma Electrolytic Oxidation (PEO) deposition technique is an example [1]. The aim of this paper is to provide preliminary results on the damping qualities of alumina PEO coatings, which will give clues on how other coating materials based on this deposition technique might behave. The paper is divided into 5 sections. Section 2 gives a brief description on the PEO process. Section 3 details the mixed numerical-experimental technique used to measure the damping of coated beams. Section 4 discusses the procedure to extract the material properties of the coatings itself. The paper concludes in Section 5 with some suggestions for future work.

2 Plasma Electrolytic Oxidation

Plasma electrolytic oxidation is a form of Electrolytic Plasma Processing (EPP) used to form oxide ceramic coatings on a variety of materials including aluminium. The basic principle of EPP is to process at a sufficiently high potential and current density to cause electrical discharges which produce a near surface plasma and result in either oxide layer formation on or dissolution of the anode. A comprehensive review of plasma electrolysis that covers the majority of developments in this field can be found in this publication [1].

Studies of oxide films produced by EPP on aluminium alloys have produced a number of observations. The oxide layer formed shows three distinct regions; a porous surface layer generally amorphous to x-rays; a dense, polycrystalline layer of alumina formed under high temperature and a thin interfacial film comprising complex alloyed phases. The amorphous phase has a network of cracks and pores, which could lead to dissipation of energy when there is friction along these cracks. This is the motivation for using PEO alumina as a damping treatment. It should also be noted that this treatment method does not require a bond coat in comparison to other deposition methods like Atmospheric Plasma Sprayed (APS) and Physical Vapour Deposition (PVD) [2, 3]. Further information on PEO can be found in literature [1].

3 Mixed Numerical-Experiment Work

In order to understand the relationship between the settings for PEO and damping coatings, 6 nominally identical aluminum alloy (Al 2014) beams were machined out of a single plate. The chemical composition of the beams is given in Table 1. These beams are a simplified representation of thin flexible structures and are given a designated identification of T1, T2 and so on up to T6. The specifications of the beams are given in Figure 1, where the root of the beam has a fillet to reduce the stress concentration within that region.

Table 1 : Chemical composition of alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
0.01	0.08	4.82	0.35	0.23	0.01	0.04	Balance

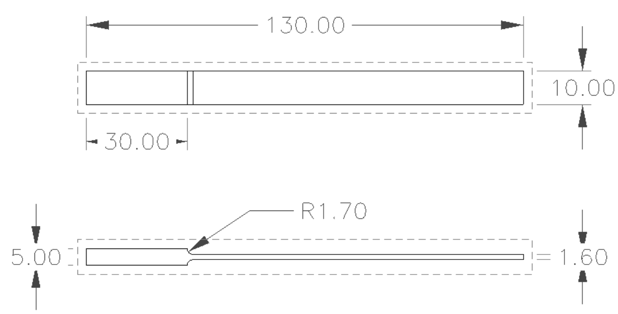

Figure 1 : Specification of the geometry of the beams. Dimensions are given in millimetres.

The inherent damping and the natural frequency of each of these beams are then measured using the beam resonance technique. The experiment setup of the rig, dubbed the Amplitude Dependent Damping (ADD) rig, is shown in Figure 2. It has already been used in the past to characterise other hard coating materials and is explained in greater detail in [4]. Basically, the beams are clamped at one end in a heavy block (>1000 times heavier than the beams) that sits on a thin layer of oil that minimises friction. This block is connected to an electro-dynamic shaker (Ling Dynamics Systems 455) through a rigid rod, which actually provides base excitation to the beam. The rod is buffered from the block by a force transducer (PCB type M222B) that allows the measurement of the input force to the block. The velocity of the beam is measured at 5 cm from the free tip of the beam using a Laser Doppler Vibrometer (Polytec OFV303 sensor head controlled by a Polytec OFV3001S vibrometer controller). The data acquisition and the control of the rig are provided by the SigLab Measurement 20-22A System.

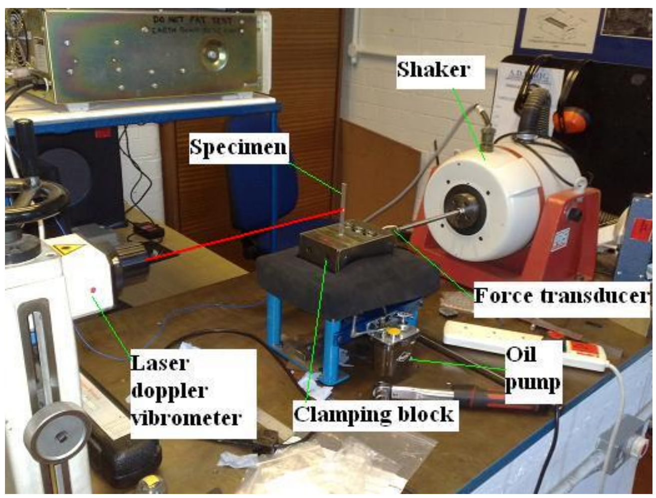

Figure 2 : Setup of the Amplitude Dependent Damping rig.

A random force input excitation is then passed through the block between 0-1kHz, with the force and velocity sampled up to 2.56 kHz. 8192 samples are acquired for each sampling window, which is filtered using a Hanning window. 20 sampling windows are then averaged in the frequency domain to construct a Frequency Response Function (FRF) of the displacement response (integrated from velocity) to the force response. The beams behave approximately linearly as the FRFs are almost invariant to the level of force excitation, with very low levels of damping. The oil layer does provide some level of energy dissipation which should vary with frequency and amplitude in theory. This is however minimal and the distortion of the FRF by it can be assumed to be negligible. A rational fraction polynomial fit [5] is then performed on the FRFs of each beam to extract the natural frequency and the loss factor of each mode of vibration. The loss factor is defined as:

$$Q^{-1} = \frac{\Delta W}{2\pi U} \tag{1}$$

where Q is the quality factor, ΔW is the amount of energy dissipated per cycle and U is the maximum energy stored per cycle. A FRF for one of the beams and the fitted rational fraction polynomial is shown in Figure 3. For the purpose of this paper, the second mode of bending (it is in fact the third mode as the real second mode is an out of plane bending) is used as the benchmark in evaluating the damping levels. Assuming all beams have an identical, exact dimension (which is not entirely true as there will be machining variations) and ignoring the inhomogeneity of the material, the Young's modulus of the beams can be extracted from a simple inverse finite element model.

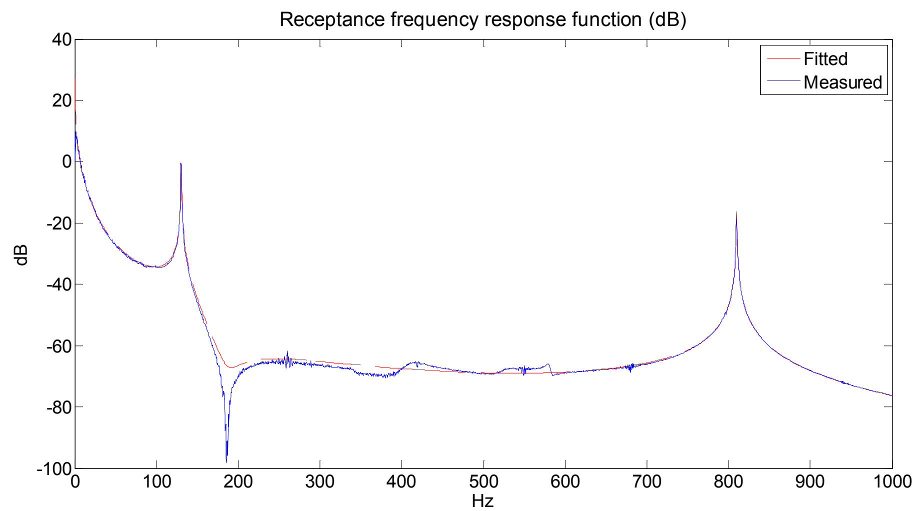

Figure 3 : The FRF measured from the ADD rig and the rational fraction polynomial fit for sample T1.

The finite element model of the untreated beams consists of 1188 quadratic continuous 3D brick elements with 20 nodes and calculated with reduced integration. The mesh and subsequent post-processing is conducted using the commercial software ABAQUS [6]. A bisection algorithm is used to optimise the Young's Modulus of the beams so that the calculated natural frequency matches the experimental measurements to within 0.01%. The natural frequencies, Young's Modulus and loss factor of each beam is shown in Table 2.

Table 2 : Properties of the untreated beams

	T1	T2	T3	T4	T5	T6
Natural Frequency (Hz)	809.92	779.74	789.34	771.92	772.46	785.55
Young's Modulus (GPa)	67.36	62.44	63.98	61.19	61.28	63.90

Loss factor	9.66e-4	6.16e-4	6.77e-4	7.49e-4	6.28e-4	6.99e-4

Each of the beams is then treated in various ways using a combination of PEO and/or shot peening in an attempt to increase the levels of damping in each beam. The treatment performed on each beam is given in Table 3.

Table 3 : Treatment on each individual beam. The intervals are a measure of the variation of coating thickness along the beam

Sample ID	Treatment type	PEO treatment time	Pulsed reversed current mode frequency (kHz)	Mean average current density(A dm^{-2})
T1	Shot peened	-	-	-
T2	Shot peened with coating thickness of 73.1±5.8 µm.	60 min	2	12
T3	Coating thickness of 71.7±5.6 µm.	60 min	2	12
T4	Coating thickness of 83.1±15 µm.	50 min	0.2	15
T5	Coating thickness of 122.5±18.1 µm.	60 min	0.02	15
T6	Untreated	-	-	-

Specimen T2 and T3 basically has the same treatment with the exception that T2 has been shot peened prior to the coating process.

Due to the fact that the material is nonlinear, the Young's Modulus and the loss factor of the beam are possibly dependent on the amplitude and the frequency of excitation. Therefore, the random excitation test mentioned previously is repeated to give an approximate value for each of the treated beams. The natural frequency of each of these beams for a particular level of vibration response is then measured from a stepped sine test covering a region of around 2Hz around the natural frequency found from the random excitation tests. The beams are then excited at resonance in order to achieve a high level of strain. After reaching steady state, the shaker is switched off and the beam response is allowed to decay. The velocity is then sampled at a rate of 25.6 kHz to enable the extraction of features later on without complications.

The decay envelope and the instantaneous phase (this allows the extraction of the instantaneous frequency which is simply the derivative of the instantaneous phase) of the velocity can be extracted from the Hilbert Transform [7], assuming that the signal has a monocomponent frequency. An initial inspection of the instantaneous frequencies shows that there is a periodic occurrence of a discontinuity of the data (refer to Figure 4). This manifests itself in the decay envelope as well. This is caused by the memory buffer problem of the data acquisition system which prevents it from acquiring a continuous signal beyond a sampling window. The discontinuities are then pruned based on a threshold on the derivatives of the instantaneous frequencies.

Utilising the FREEVIB method devised by Feldman [8] and assuming the corresponding single-of-degree system can be represented by a mass-spring-viscous damper, the instantaneous natural frequency and the loss factor of the system can be extracted for a particular level of strain. A plot of the loss factor of the system in terms of the level of displacement (integrated from velocity) at the measurement point is shown on Figure 5. The natural frequencies of the treated beams (apart from T1 which is approximately constant with displacement) is shown in Figure 6.

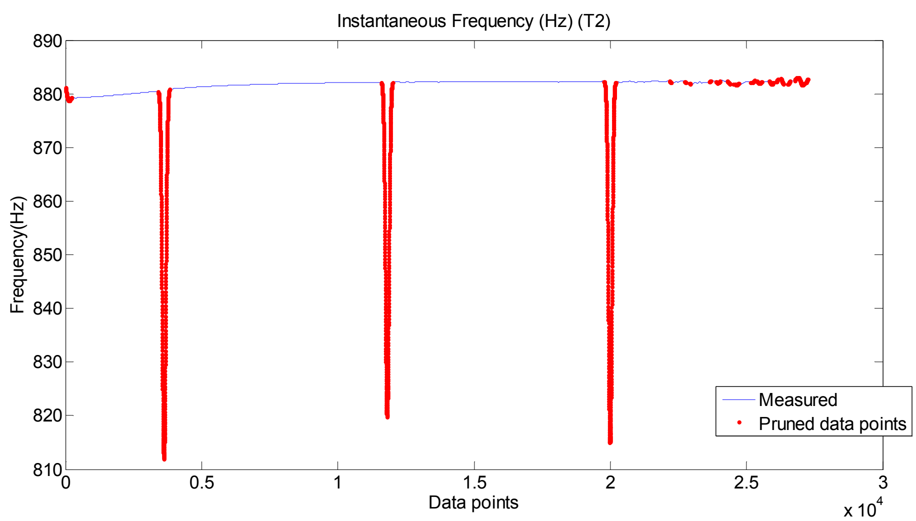

Figure 4 : The instantaneous frequency of sample T2.

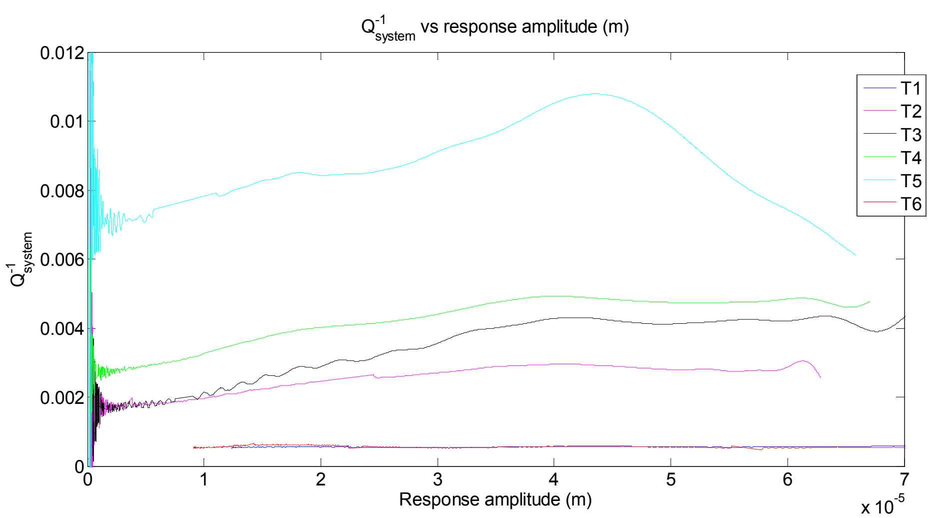

Figure 5 : The system loss factor of the beams.

First of all, data within the low displacement regime is scattered, discontinuous and should be neglected. This is due to the low level of Signal-to-Noise ratio within these levels. All the beams which have been treated with PEO also showed increased levels of damping. It can be seen that shot peening on its own has a negligible effect on the damping levels. It does however; lower the natural frequency of the beam very slightly. This is to be expected as the compressive residual stresses of shot peening has the opposite effect of tension forces (which increases stiffness). When shot peening is combined together with the coating, it actually reduces the level of damping, as can be seen in the difference between T2 and T3 in Figure 5.

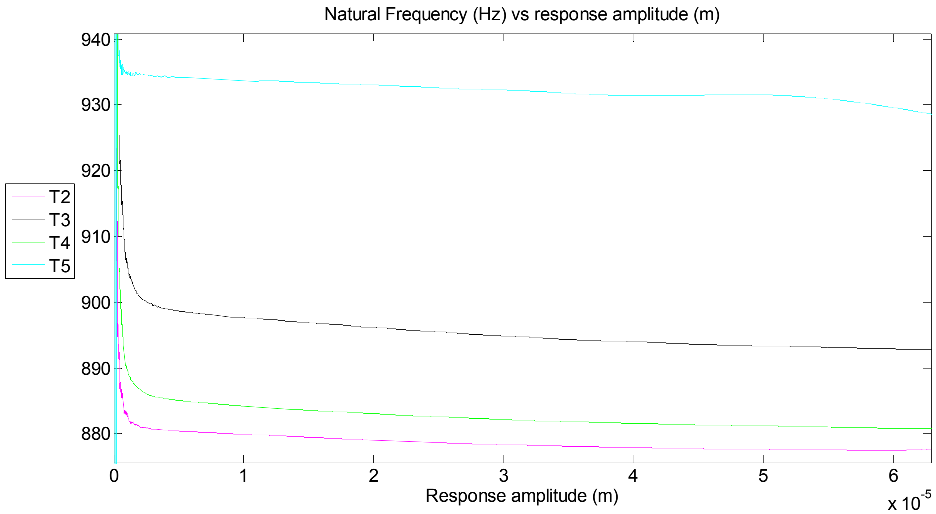

Figure 6 : The natural frequencies of the beams.

The thickness of the coating also seems to have a large effect on damping, with the thickest coated specimen with the highest level of damping, which peaks at a certain displacement amplitude. The damping level reduces in sequence as the thickness of the coating reduces.

The damping levels measured by the decay method for the untreated beam is also slightly lower compared to the measurements extracted from the forced excitation. This can be explained by the fact that energy dissipation caused by the oil layer, the clamping block and the rod is effectively cut down when shaker is switched off. The level of damping measured on T6 based on the free decay method will be used as the baseline damping of all the aluminium alloy substrate in the subsequent section.

It can also be seen that the natural frequencies of the beams seem to be decreasing slightly with increasing amplitude. This suggests that there is some form of strain softening, which could possibly be caused by the fact that the material in the coating can move more freely when the friction between the cracks are overcome and/or other nonlinearities from geometry.

It must be noted that the microstructure of the different coating thicknesses could be very different in terms of phase composition and is not expected to be linearly scaled with thickness. This difference in microstructures accounts for the difference in properties, rather than the fact that the coatings are just of different thicknesses. All the tests were also done with one specimen for each treatment, so there might be variations to the material properties when performed with the same treatment for different beams.

4 Damping Properties of Alumina Coating

The experiment in the previous section enables the measurement of the natural frequencies and the loss factors of the treated beams. It is however more informative to deconvolute the properties of the coating from the substrate. The approach to this deconvolution technique is simply to repeat the inverse finite element method based on data mentioned in the previous section.

The geometry and mesh of the beams T2, T3, T4 and T5 are generated in finite element with the same element type, though with a reduce element count of 864 elements. Since PEO actually takes away material from the substrate to form the coating, the geometry of all the treated beams is different. It is estimated that the alumina coating is composed of approximately 50-66% of the substrate material. In order to facilitate simulation, the thickness of all the individual beams is assumed to be reduced by 60% of its coating thickness. A layer of elements is then added on each of the beams to represent the coating by using FELLA [9], a proprietary software developed in the University of Sheffield.

Since the levels of damping involved are quite far away from the level of critical damping, it can be safely assumed that the mode shapes of the beams are the same with or without the presence of damping. This is the basis of the Modal Strain Energy method [10]. This assumption allows the loss factor of the coating to be extracted via the following formulation:

$$Q_{coating}^{-1} = \frac{\left(U_{substrate} + U_{coating}\right)}{U_{coating}} Q_{system}^{-1} - \frac{U_{substrate}}{U_{coating}} Q_{substrate}^{-1} \tag{2}$$

where $Q_{coating}^{-1}$, $Q_{substrate}^{-1}$ and Q_{system}^{-1} denotes the loss factors of the coating, the substrate (approximately constant as extracted in the previous section) and the system (which is the overall coated beam). $U_{coating}$ and $U_{substrate}$ are the maximum strain energy of the coating and the substrate respectively. The second term on the right-hand-side of Equation (2) is basically a correction factor to eliminate the damping present in the substrate.

Damping properties are usually given in terms of the strain level on the material. In a fully coated material however, the strain fields are non-uniform and vary depending on the mode of vibration (refer to Figure 7). Due to the absence of this information at this point, the damping of the coatings is described in terms of the displacement at the measurement point. 5 equidistant displacement levels are then selected for each of the coated specimen in order to extract the level of damping at each of these points.

The Young's modulus of the coatings are optimised so that it matches the measurements from the experiments for the 5 specified levels of displacement. Equation (2) is the utilised at each of these level of displacement to extract the loss factor of the coatings. Figure 8 shows loss factor of the coating for 5 levels of displacement while Figure 9 shows the Young's modulus of the coating for the displacement levels.

The loss factors are at a comparable level to some previous studies on PVD based ceramics (Zirconia based ceramics) [2]. The Young's modulus of the coatings is however much higher compared to the ceramics studied in [2]. Atmospheric Plasma Sprayed ceramics based on Zirconia based ceramics [2] and a titanium-alumina blend [11] however, have a much higher damping loss factor (nearly double). It is noted though, that the loss modulus (which is the product of loss factor and the storage modulus) is almost comparable as the Young's modulus of those other coatings are lower (approximately half). As energy dissipation for a specific level of strain is proportional to the loss modulus, the overall damping performance of the different coating treatments might be similar, though it is difficult to compare accurately at the moment due to the difference in strain distribution.

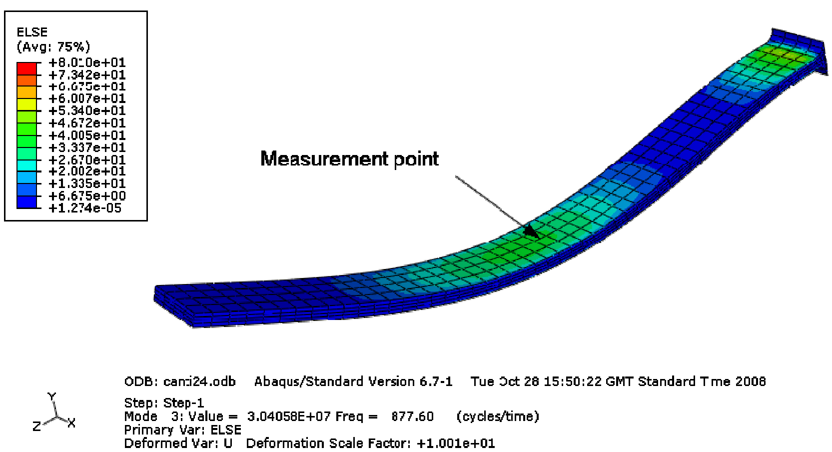

Figure 7 : The elastic strain energy fields of the coated beam T2 for the second in-plane mode of vibration.

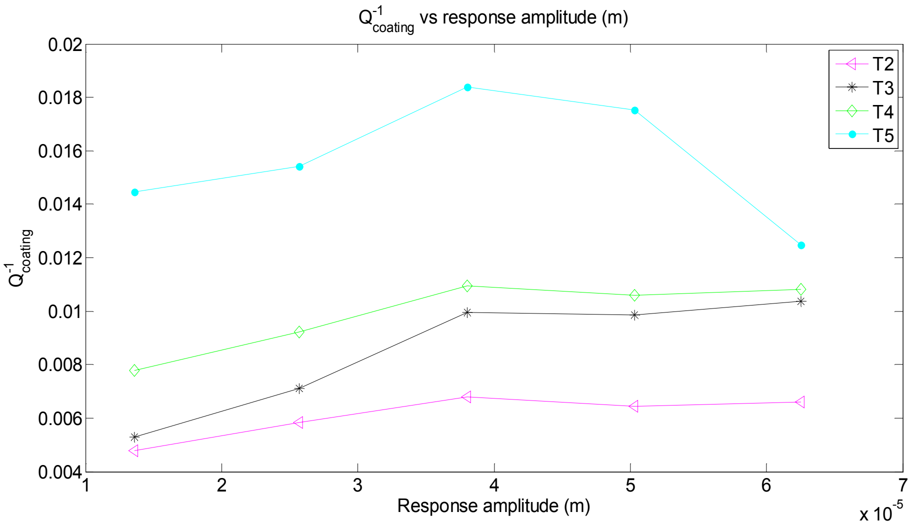

Figure 8 : The loss factor of the coatings for varying levels of displacement

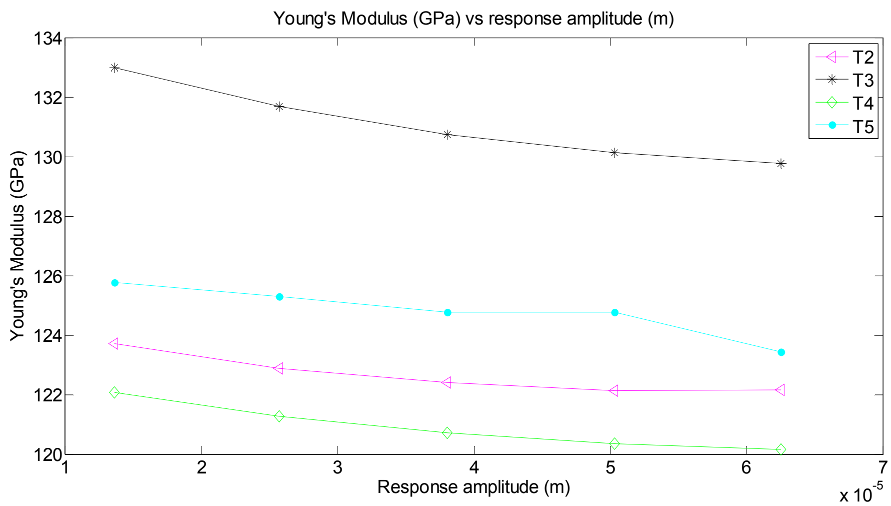

Figure 9 : The Young's modulus of the coatings for varying levels of displacement.

5 Conclusion

The damping property of PEO alumina coatings has been studied in this paper. The preliminary results are encouraging as it shows that some degree of control can be achieved in terms damping by modifying the PEO process configurations. It will be interesting to apply the same process to other alloys, notably titanium which will increase the number of potential applications especially at high temperatures. There is however more work that needs to be done, for example the fatigue testing of the coatings, studying the memory effects of the coatings, initial strain amplitude dependence and possibly frequency dependence [3]. More accurate comparisons with the other coatings in literature can also be performed by accounting for the non-uniform strain fields or recoating the beams to induce uniform strain fields.

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