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Mechanical characterization of protective coatings for offshore wind turbine towers and transition pieces

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Abstract—**Marine coatings develop residual stresses in all stages of their lifetime; excessive residual stresses affect adhesion and can compromise the integrity of both the coating system and substrate. The mechanical properties of three epoxy-based paint systems for offshore wind turbine towers and transition pieces were determined by dynamic mechanical analysis in 3-point bending mode. The coatings were airless sprayed onto steel substrates and cured. A mathematical model using composite beam stress analysis was developed to determine the Young's modulus of the coatings. The results show that the mechanical properties of the coatings depend on the film thickness. The composite modulus and Young's modulus of the coatings decrease when the coating thickness increases. Understanding the mechanical properties of marine coatings, and the factors which influence them, could lead to further improvements in the coating and corrosion protection of offshore structures in general.**

Keywords—DMA; 3-point bending; paint; wind turbines

I. INTRODUCTION

Epoxy-based marine coatings are widely used in the protection of metallic materials from corrosion; this is due to their high efficiency in seawater [1]. Epoxy coatings are thermoset polymers that can be cured at room temperature by amines, which react with the terminal epoxy groups. They generally outperform other resins in terms of mechanical properties and resistance to environment degradation. Epoxy resins possess a highly cross-linked structure which is responsible for their good mechanical properties. However, their structure is also responsible for their brittle behavior [2, 3]. They are film formers that consist of a linear chain molecule with a reactive epoxy group at each end. Different types of epoxies differ both in the length of the molecular chain between the epoxy groups and their detailed structure [4].

Epoxy paints cure by chemical reaction between components in the paint. To ensure that the ingredients in the paint won't react with each other, they are separated into two or more containers and mixed before application. These paint systems are denominated "two-pack systems" and the product is a cross-linked polymer [5].

Regardless of the mechanism of film formation, whether it's solvent evaporation, coalescence, chemical reaction, or a combination of these, coatings tend to contract. If the coating's contraction is prevented by the adhesion to the substrate and/or mobility of macromolecular segments is hindered, a tensile stress will develop within the coating [6].

The stress phenomenon in organic coatings and its effect on coating failure (delamination and/or cracking) has been the subject of numerous studies [7, 8]. Organic coatings experience stress due to some or all of the following causes: film formation, cyclic temperature and relative humidity changes, the stresses developed are identified as internal, thermal, and hygroscopic respectively. Whatever the nature of the cause, the stress developed will rise when the movements provoked by these processes are prevented by coating adhesion to the substrate and/or stiffness of the polymer segments [7].

During film formation, as the paint film gradually changes from liquid to solid and the solvent diffuses through the coating, the coating is mainly reduced in size parallel to the surface as a consequence of its adhesion to the substrate. Consequently, the internal stress developed is mainly in the plane parallel to the substrate. The gradual molecular change in the coating over time, termed "aging" also contributes to the internal stresses in the film. Surface tension and internal stresses contribute to the formation of a flat and uniform film [2, 6, 9].

Coating films always have some degree of internal stresses, and they are almost always tensile in nature. Moreover, internal stresses always affect the mechanical properties of the coating, with the exception of high compressive internal stresses. It is important for the internal stresses to be small in comparison with the adhesive and cohesive forces that maintain the

integrity of the coating. In general, internal stresses reduce the capacity of the coating to accommodate additional hygrothermal (thermal and hygroscopic) stresses, which are tensile in nature, during the component's lifetime. Failure due to internal stresses can be observed in the form of peeling or cracking. Peeling corresponds to the cases in where the internal stresses are greater than the film's adhesive strength. On the other hand, cracking is observed when the internal stresses are larger than the cohesive strength of the film. Hence, the nature of the failure will depend on the mechanical properties of the coating film. Generally, the tensile and compressive stresses affecting adhesion and cohesion will depend on film formation and service conditions, coating chemistry, composition, curing mechanism, age, thickness, among others [9, 10].

Paint systems applied on steel for protective and decorative purposes must be mechanically robust to maintain their integrity during the component's service life. The paint must be sufficiently ductile during application to coat complex profiles and resist cracking and delamination [11, 12].

Understanding of the mechanical properties and behavior of coatings is of paramount importance. However, there is very little information available on basic mechanical properties such as the Young's modulus of epoxy coatings, which is often assumed to be 3- 3.5GPa and constant regardless of coating thickness. Accurate knowledge of this property is crucial for the determination of the internal stresses affecting the coatings due to film formation. Properties such as the Young's modulus and residual stresses are essential for the appropriate modelling of the mechanical behavior of the multilayer system constituted by the substrate and paint scheme [11, 13, 14].

The increasing number of studies of the stress phenomena experienced by organic coating films resides in the strong evidence relating it to coating degradation. Modern coating systems such as thermosets are more susceptible to experiencing high stresses than traditional coatings such as alkyd paints [6]. Additionally, epoxy paints do not usually self-support to form uniform free films to determine the mechanical properties as neat films. The complications associated with the production of homogeneous free films for mechanical testing are considered to contribute to the lack of information regarding the mechanical properties of paint. Therefore it is convenient to apply them onto a flexible substrate to determine their mechanical properties as a system so then the properties of the neat coatings can be determined by the application of a mathematical model. Dynamic mechanical analysis (DMA) presents a means for calculating thermomechanical properties by studying the storage and loss modulus as a function of temperature, frequency or time. Graphical representation of moduli and tan δ (the ratio between storage and loss modulus) in terms of these variables can be used to determine functional properties, effectiveness of the curing processes and damping behavior under specific conditions [15].

II. EXPERIMENTAL

A. Materials

Three epoxy-based transition piece and tower coatings, presented in Table 1, were selected to perform a comparative study of their mechanical properties. The coatings were airless-sprayed onto steel substrates (50mm x 8.5mm x 0.23 mm) to produce bi-layer composite samples. The substrates were previously sanded and etched to promote adhesion to the coating. Additionally, thick films were airless-sprayed onto silicone coated paper to produce free films.

The samples were post-cured to establish a baseline that can be reproduced; the post cure temperature was chosen below the glass transition temperature (T_g) of the paints to avoid stress relaxation. The cure schedule consisted of 3 days at room temperature followed by 4 days at 50˚C.

B. Dynamic mechanical analysis

The dynamic mechanical analysis was performed in a DMA 8000 manufactured by PerkinElmer. The samples were mounted in the 3-point bending mode of the DMA presented in Fig 1. The tests were conducting with a static load of 1N, strain amplitude of 50μm, frequency oscillation of 1Hz and a temperature ramp from 25 to 45˚C at 2˚C/min.

C. Intetrnal stresses

To determine the stress in a mono-layer coating system, Corcoran's equation was applied [6]. This equation considers that the stress (S) develops in two directions:

$$S = \frac{4dE_s t^3}{3l^2 t_c(t_s + t_c)(1 - v_s)} + \frac{4dE_c(t_s + t_c)}{l^2(1 - v_s)}$$

(1)

Where l is length of the sample [m], d is the deflection in the middle of the substrate [m], E_s is the elastic modulus of the substrate [Pa], E_c is the elastic modulus of the coating [Pa], v_s is the Poisson's ratio of the substrate, t_s is the thickness of the substrate [m], and t_c is the thickness of the coating [m].

TABLE I.   CHARACTERISTICS OF THE COATING SYSTEMS

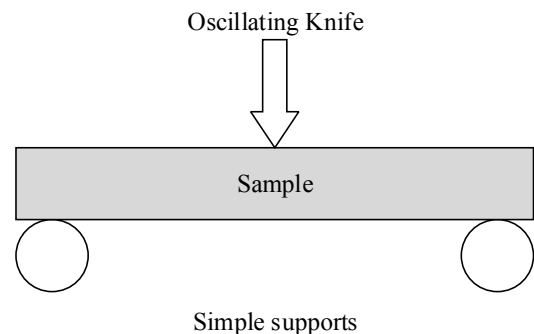| Coating	Volume solids, VS [%]	Dry to touch [h, ˚C]
A	70±1	2 (20 ˚C)
B	79±1	8-10 (10 ˚C)
C	74±1	1.5 (20 ˚C)

Fig 1 Representation of the 3-point bending mode

III. YOUNG'S MODULUS: MATHEMATICAL MODEL

The mechanical response of the coated and uncoated substrates in 3-point bending and the geometrical parameters of the samples were analyzed using composite beam stress analysis. The model provided the Young's modulus of the coatings and was developed assuming that the materials in the coated system are elastic, homogeneous and isotropic. Moreover, it was assumed that the coating and the substrate have the same deformation [16]. Fig 2 shows the cross sectional area of the coated substrates. The location of the neutral axis (y) of a bi-layer beam is calculated by (2):

$$y = \frac{E_c t_c^2 + 2t_c t_s E_s + E_s t_s^2}{2E_c t_c + 2E_s t_s} \tag{2}$$

Assuming that the beams were subject to pure bending with no shear, the beams were simply supported and loaded with a concentrated load applied in the middle of the span. The bending stiffness of the bi-layer system can be determined by (3):

$$BS_{sample} = \frac{48}{L^3}(E_c I_c + E_s I_s) \tag{3}$$

where BS_{sample} is the bending stiffness of the sample [N/m], L is the span length [m], I_c is the moment of inertia of the coating [m^4] and I_s is the moment of inertia of the substrate [m^4].

Substituting the moment of inertia of the coating and substrate into the equation for bending stiffness of the sample provides a quadratic equation for the determination of the Young's modulus of the coatings (E_c). The equation produces two roots; only one root is positive and has a physical meaning.

IV. RESULTS

In this section the mechanical properties of the coatings sprayed onto metallic substrates are discussed. This requires the measurement of the mechanical properties of the uncoated and coated substrates to determine the mechanical properties of the coatings through a mathematical model. The elastic modulus and the bending stiffness of the steel substrate were 196GPa and 1.89kN/m respectively. The theoretical value for the elastic modulus is 210GPa, which proves the dynamic mechanical analysis produces results close to those obtained by static mechanical instruments. Fig 3 shows the bending stiffness of the coated samples in terms of coating thickness. The bending stiffness is a geometry-dependent parameter and it increases with the increase of coating thickness. For epoxy coatings, the increase of stiffness also means an increase in the brittleness of the coating. The storage or elastic modulus determined by DMA is presented in Fig 4. The elastic modulus of the composite samples decreases with the increase of the coating thickness.

The mechanical response of the coated substrates in 3-point bending (at room temperature) and the geometrical parameters

of the samples have been analyzed through the application of composite beam stress analysis. The mathematical expression developed provided the Young's modulus of the three coating systems and its variation with coating thickness, as presented in Fig 5. The Young's moduli of the free film are also shown in Fig 5, the free films present Young's moduli higher than the ones produced by coatings cured restrained on steel substrates.

With knowledge of the Young's modulus of the coatings, the internal stresses produced during film formation or curing are determined and presented in Fig 6.
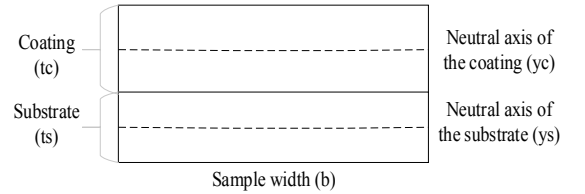

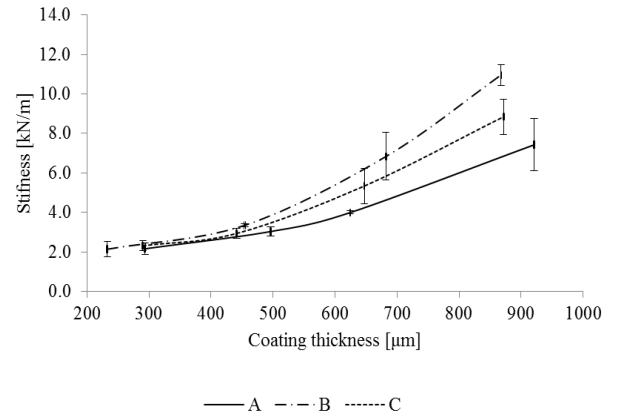Fig 2 Cross section of the composite samples

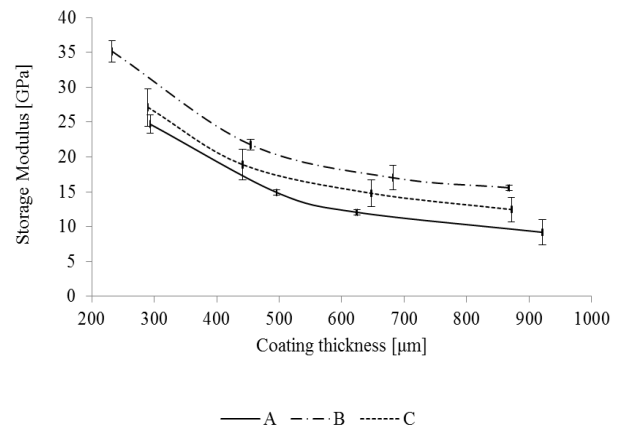Fig 3 Variation of stiffness with coating thickness

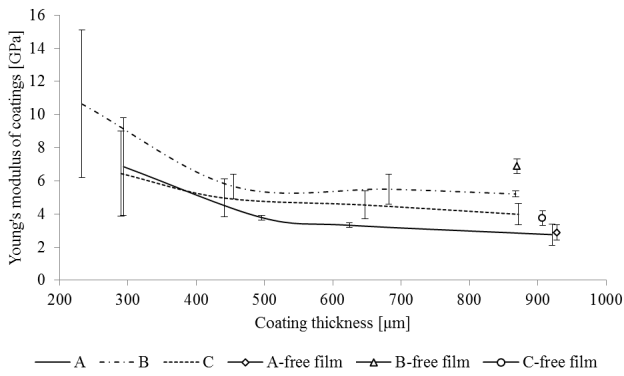Fig 4 Variation of storage modulus with coating thickness

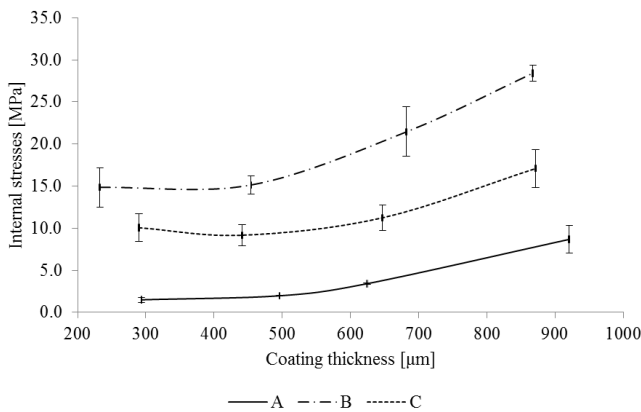Fig 5 Variation of Young's modulus of the coatings with coating thickness

Fig 6 Variation of internal stresses with coating thickness

V. DISCUSSION

The Young's modulus of the coatings decreases with the increase of coating thickness. This behavior has also been observed by Roche and Bouchet in a series of studies on thin un-filled solvent-free epoxy coatings applied onto aluminum substrates and post-cured above T_g [14, 17]. The researchers state that this behavior is due to the formation of an interface between the substrate and the coating. The study proposes that the coating's Young's moduli reach the bulk value for coatings thicker than 200-250μm, suggesting that thickness as the interphase's thickness.

However, coatings A, B, and C are solvent-borne epoxy coatings, and post cured below the glass transition temperature. In coatings post-cured below T_g, a portion of the solvent is retained in the samples and the presence of trapped solvent plays an important role on the mechanical properties of the coatings. The retained solvent is not evenly distributed and a profile is formed within the coating with a minimal concentration in the air-coating interface. Overall, solvent retention increases with the increase of coating thickness.

Retained solvent acts as a plasticizer and reduces the crosslinking density of the coating. The solvent acts as a lubricant easing the movement of the polymer chains and increasing the flexibility of the polymers [18]. Thus, the presence of retained solvent lowers the T_g, tensile strength and elastic modulus of the coatings [18, 19]. Therefore, the increase in solvent retention associated with the increase of coating

thickness also produces a reduction in the Young's modulus of the coating.

In the present study it has been stablished that for coatings A, B and C used in towers and transition pieces, the Young's moduli of the coatings decreases with the increase of film thickness and for coatings with thicknesses higher than 620 μm, the moduli reach a stable value. This value can be identified as the bulk value of the modulus for each coating. The thickness-dependent Young's modulus could also be attributed to structural changes of the cross-linked structure across the thickness of the coating.

The comparison between the Young's modulus of supported and unsupported coatings showed that when coatings are cured as free films, the Young's modulus produced is higher. This could be associated to a lower percentage of solvent retention on the free films. The presence of a steel substrate restrains the evaporation of the solvent to the air-coating interface.

DMA results are useful to perform comparative studies; it is known that there are small discrepancies between the temperature-dependent elastic moduli measured by DMA and the ones measured with a static mechanical testing machine. From all the test modes allowed by the DMA, 3-point bending mode is considered to be the most suitable for measuring the elastic modulus of materials. This bending mode eliminates the clamping effect, present on the single cantilever and dual cantilever mode, and serves as an analogous method to static mechanical test [20].

VI. CONCLUSIONS

A mathematical model which considers the 3-point bending results provides reasonable results for the Young's modulus of thick coatings with applications in offshore wind turbine towers and transition pieces. The Young's modulus of the coatings decreases with the increase of coating thickness due to the plasticizing effect of the solvent retained within the coating.

The dynamic mechanical analyzer allows the determination of the temperature-dependent elastic modulus of epoxy paints with the use of small amounts of materials and eliminates the need to conduct expensive tests in traditional testing machines at different temperatures.

The present analysis was developed considering room temperature properties. However, depending on the application, the mechanical response of the material at any other temperature can be used to determine the Young's modulus of the material at the given temperature, given that the material is elastic at that temperature.

Nonetheless, the results obtained are dependent on a group of input parameters and small variations in these could introduce an error to the calculations [11]. Inevitable variations from sample to sample in the thickness of the coating and the substrate produce variations on the calculated Young's modulus, which is evident on the error bars shown in Fig 5.

In general, free films in the thickness range selected for the study are difficult to produce. When left to cure unsupported, epoxy coatings curl during curing and handling is difficult, by

testing the material coated on steel substrates it can be ensured that the samples won't break while handling and meet the criteria of sufficient stiffness necessary to be tested in 3-point bending. Moreover, testing supported coatings allows accounting for the interaction between coating and substrate during mechanical testing.

REFERENCES

[1] Fredj, N., Cohendoz, S., Feagas, X., Touzain, S., Some consequences of saline solution immersion on mechanical behaviour of two marine epoxy-based coatings. Progress in Organic Coatings 2010. 69: p. 82-91.

[2] Seymour, R., Mark, H., Handbook of Organic Coatings. 1990: Elsevier.

[3] Hobbiebrunken, T., Fiedler, B., Hojo, M., Ochiai, S., Schulte, K., Microscopic yielding of CF/epoxy composites and the effect on the formation of thermal residual stresses. composites science and technology, 2005. 65: p. 1626-1635.

[4] Vicevic, M., A comparison of fatigue properties of epoxy coatings in marine environments, in School of Chemical Engineering and Advanced Materials. 2008, University of Newcastle Upon Tyne: Newcastle Upon Tyne. p. 266.

[5] Turner, G.P.A., Introduction to paint chemistry and principles of paint technology. 3rd ed. 1988: Chapman and Hall.

[6] Perera, D., Stress phenomena in organic coatings in MNL17-EB Paint and coating testing manual: 15th edition of the Gardner-Sward Handbook 2012, ASTM International.

[7] Perera, D., On adhesion and stress in organic coatings. Progress in organic coatings, 1996. 28: p. 21-23.

[8] Hare, C., The mechanical properties of coating films and their characterisation. Journal of protective coatings and linnings, 1996: p. 77-95.

[9] Hare, C., Internal Stress: Part I. Journal of protective coatings and linnings, 1996: p. 65-75.

[10] Sato, K., The internal stress of coating films. Progress in organic coatings, 1980(8): p. 143-160.

[11] Spinks, G., Liu, Z., Brown, H., Swain, M., See, H., Evans, E., Paint layer thermomechanical properties determined by in situ dynamic mechanical analysis in 3-point bending. Progress in Organic Coatings, 2004. 49: p. 95-102.

[12] Lambourne, R., Strivens, T., Paint and surface coatings theory and practice. 2nd ed. ed. 1999: William Andrew Pub.

[13] Benabdi, M., Roche, A., Mechanical properties of thin and thick coatings applied to various substrates. Part I. An elastic analysis of residual stresses within coating materials Journal of adhesion science and technology, 1997. 11(2): p. 281-299.

[14] Bouchet, J., Roche , A., Jacquelin, E., Determination of residual stresses in coated metallic substrates. Journal of adhesion science and technology, 2001. 15(3): p. 321-343.

[15] ASTM, Standard test method for plastics: dynamic mechanical properties: in flexure (three-point bending). 2015.

[16] Hibbeler, R., Mechanics of materials. 8th ed. 2011: Prentice Hall

[17] Bouchet, J., Roche, A., Hamelin, P., Internal stresses, Young's modulus and practical adhesion of organic coatings applied onto 5754 aluminium alloy. Thin solid films, 1999. 355-356: p. 270-276.

[18] Cowie, J., Polymers: chemistry and physics of modern materials 1991, Blackie and Son Ltd. .

[19] Boxall, J., von Fraunhofer, J., Concise paint technology 1st ed. 1977: Paul Elek (Scientific Books) Ltd.

[20] Deng, S., Hou, M., Ye, L., Temperature-dependent elastic moduli of epoxies measured by DMA and their correlations to mechanical testing data. Polymer testing, 2007. 26: p. 803-813.