In-Situ Measurement and Monitoring of Internal Stress in Organic Coatings

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Abstract

This paper presents the results of an investigation which utilized embedded miniature fibre optic strain gauges for the in-situ measurement and monitoring of the internal coating stress of different types of organic coating systems under varying relative humidity conditions at ambient temperature. As far as the author is aware, this is a novel usage of fibre optic sensors and is not reported in the open literature. Four overcoating systems commonly used for bridge structures in the USA were investigated: (1) a poly silicone alkyd, (2) an acrylic, (3) a moisture-cured urethane, and (4) an epoxy. The alkyd and epoxy coating systems developed relatively low positive internal stresses when the RH was in the 40 to 45% range. However, as the ambient RH increased, the internal stresses became less positive, becoming zero or slightly negative. Both the acrylic and urethane systems developed relatively high negative internal stresses during the curing stage when the relative humidity (RH) was in the 40-45% range. However, as the ambient RH increased to higher values the internal stress reduced significantly to almost zero or very low negative values. The practical significance of these results is that an epoxy system would be compatible as an overcoat material for alkyd systems under different RH conditions. With an acrylic or a urethane system as the overcoat material, coating disbondment and/or cracking may occur depending on the RH conditions particularly if the RH is in the 40-45% range.

Keywords: Organic coatings, Internal stress, In-situ stress measurement, Fibre-optic strain gauge

Introduction

When an organic coating is applied directly on a substrate or as an overcoat on an existing coating, it is subject to different types of internal stresses as it cures and ages over time in a given environment [1,2,3,4]. These stresses primarily include: (a) Residual Cure Stress (RCS) developed during the curing process, (b) thermal stress due to variation or cycling of

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the ambient temperature, and (c) hygroscopic stress induced as a result of the ambient humidity or moisture uptake by the coating. Structure vibration can impart additional stress on the coating system.

If the internal coating stress exceeds the adhesive strength of the coating then disbondment of the coating from the substrate can occur. In the case of an overcoat system if the internal stress of the overcoat exceeds or equals the adhesive strength of the undercoat then premature failures from lifting and/or intercoat disbonding may result [4]. By way of example, consider the overcoating of an alkyd primer with an epoxy or an acrylic polyurethane system. The residual cure stress in a common epoxy at 200 μm dry film thickness (DFT) has been found to range from 4.6 to 6.7 MPa at room temperature [5], while the hygrothermal stress for acrylic polyurethane has been determined to range from 0.3 MPa at 40°C to 2.8 MPa at 22°C [6]. The pull-off (adhesive) strength of an alkyd primer is reported to be around 2 MPa (see Table 1 [7] which shows the adhesive strengths of some common industrial coating systems).

The internal stress values of the above epoxy and urethane systems each exceed the adhesion value of the alkyd primer. Hence, if either paint is applied as an overcoat to an alkyd system, failure may result. Another coating property which can impact internal stress is the glass transition temperature (T_g). A material's T_g is defined [8] as the temperature at which there is an increase in the thermal expansion coefficient. As a coating weathers, the T_g becomes elevated and internal stress can increase [6]. Consequently, using an overcoat with a T_g lower than the weathered coating generally minimizes intercoat stress through increased flexibility, decreased hardness, decreased cohesion, and decreased tensile strength (9).

Overcoating failures are often observed on bridges in the USA when large sections of the coating system (including the existing paint) disbond from the bridge substrate [10]. This typically occurs within a few months to a few years after an overcoating project and particularly after a winter season. It has been postulated that this disbondment is associated with the stresses imparted due to thermal cycling of the coated steel substrate, internal coating stresses of the overcoat system and structure vibration. Figure 1 shows an example of a failed overcoating project. Figure 1 adapted from Ref [3] illustrates the effect of aging on oil paint systems. Aging tends to make the paint become brittle, induce internal stress and makes it vulnerable to cracking and delamination.

Coating type	Typical pull-off stress
Acrylic, Direct to Metal	3.4 MPa
Alkyd Primer	2.1 MPa
Alkyd Topcoat	2.0 MPa
Alkyd, Silicone	2.0 MPa
Epoxy, Coal Tar (SSPC Paint 16)	6.9 MPa
Epoxy Polyamide	5.2 MPa
Epoxy Polyamine	5.8 MPa
Epoxy, Water Based	4.1 MPa
Epoxy, Zinc Rich	6.9 MPa
Inorganic Zinc	2.1 MPa
Urethane, Aliphatic	4.1 MPa
Urethane, Moisture Cured	4.1 MPa

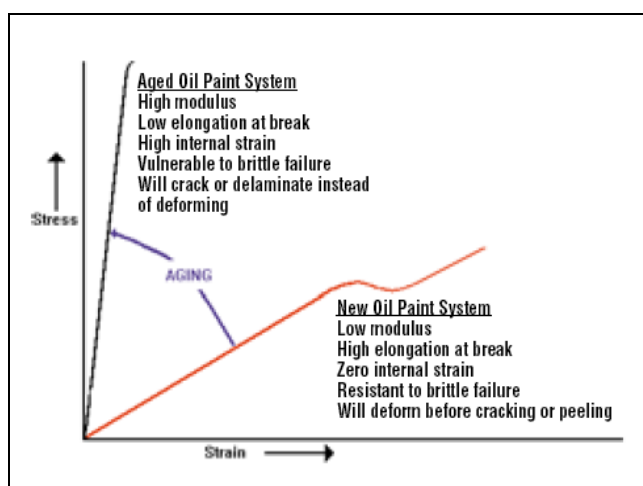Table 1: Adhesive (pull-off) strength of common industrial coating systems [7]

Figure 1: Effect of aging on oil paint systems (after [3]).

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Figure 2: Overcoating failure on a bridge structure

Given the above scenario it would be extremely useful to be able to determine the internal stresses that may develop in an overcoat system under different environmental curing conditions so that an appropriate system can be specified for a particular set of exposure conditions. Internal coating stress can be measured with a device which registers the deflection of a coated thin metal substrate induced by the stress [11,12,13]. The determination of this deflection and knowledge of the elastic properties of the substrate permit the calculation of the internal stress using the formula:

$$\sigma = \frac{DEd^3}{3\delta I^3 (d + \delta)(1 - \upsilon)},$$

Where:

σ = internal stress (MPa); D = deflection (mm)
E = substrate elastic modulus (MPa); d = substrate thickness (mm)
δ = coating thickness (mm); l = length of panel (mm)
υ = substrate Poison ratio

A negative (or contractive) stress imparts a tensile, peeling action on the undercoat and may result in subsequent coating failure. A positive (or expansive) stress puts the undercoat into compression and is not detrimental. This paper presents the results of an investigation that utilized embedded miniature fibre optic strain gauges for the in-situ

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measurement and monitoring of the internal coating stress of different types of organic coating systems under varying relative humidity conditions at ambient temperature. As far as the author is aware, this is a novel usage of fibre optic sensors and is not reported in the open literature. The operating principle of the fibre optic strain gauge is discussed in the next section followed by some experimental data in the subsequent section.

Fibre Optic Strain Gauge

The fibre optic strain gauge used for determining internal coating stress in this work is (a patented) Extrinsic Fabry-Perot Interferometer (EFPI) fibre optic sensor manufactured by Luna Innovations, Blacksburg, Virginia, USA. This device can be used to measure strain occurring on or inside materials or structures. Originally developed to measure strain inside advanced graphite/epoxy composite materials, the EFPI embedment strain gauge has been used for strain measurement with applications ranging from intelligent vehicle highway systems to acoustic emission detection. Unlike conventional strain gauges, and other types of fibre optic strain sensors, the EFPI embedment strain gauge is immune to measurement cross-sensitivity. The small size, light weight and single connection also make the EFPI Strain Gauge an attractive option for most traditional strain gauge applications. Figure 3 shows a schematic diagram of the EFPI strain gauge.
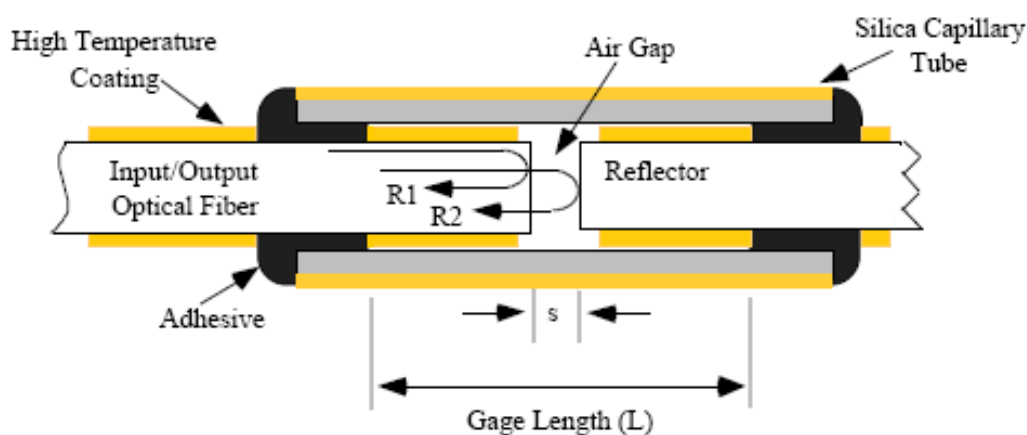

Figure 3: Schematic representation of an EFPI strain gauge

The EFPI strain gauge is fabricated by inserting two optical fibres into a silica capillary tube. The length of the strain gauge is 4 mm and the diameter can be in the range of 80 to 350 μm. Figure 4 shows the relative size of the EFPI gauge as compared to a postage stamp. The EFPI strain gauge is a reflective type fibre optic sensor meaning that the same

optical fibre serves as both input and output to the strain gauge element. During fabrication, the Input/Output and Reflector optical fibres are joined to the inside of the silica capillary tube, either with an adhesive or by directly fusing the fibres to the tube.

Figure 4: Relative size of an EFPI strain gauge.

The standard EFPI strain gauge is covered by a thin polyimide coating which is very similar to the material that is used in foil strain gauges. The polyimide greatly enhances the robustness of an EFPI strain gauge, and in embedment applications the polyimide also provides a very good stress/strain transfer interface between the silica of the sensor and host material. Gold and acrylate coated EFPI strain gauges are also available.

The distance between the Input/Output and Reflector attachment points in the silica capillary tube define the gauge length (L) of the device. Operation of the EFPI strain gauge revolves around monitoring the air gap "s" which is the distance between the Input/Output optical fibre and the Reflector (see Figure 3) with a special fibre optic signal (strain) measurement device. When a stress is applied at the surface of the base material it creates an elongation or compression of the strain gauge. An elongation of the strain gauge indicates an expansive (compressive) stress in the coating (displayed as a positive value) while a compression of the strain gauge indicates a contraction (tensile) stress in the coating (displayed as a negative value). As the strain gauge is stressed its optical properties change as signalled by changing values of "s". This change is used to determine the change

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in the gauge length, which when divided by the initial gauge length gives the strain, by the following equation:

$$\varepsilon = \frac{\Delta L}{L}$$

Where:

ε = strain; ΔL = the change in gauge length, mm
L = the original gauge length

Knowing the strain induced on a material, the stress induced along that surface can be determined. This is calculated based on the modulus of elasticity, which can be found for many materials. The stress is calculated using the following equation:

$$\sigma = \varepsilon G$$

Where:

σ = Internal stress, MPa
ε = strain
G = modulus of elasticity, MPa

Experimental Work

Four overcoating systems commonly used for bridge structures in the USA were used in the test program. These were [1] a poly silicone alkyd, [2] an acrylic, [3] a moisture-cured urethane, and [4] an epoxy. The test specimens were 1.27 cm wide by 30.5 cm long by 0.015 cm thick steel (feeler gauge) shims. The various coatings were applied on this substrate at a thickness of about 127 μm WFT (wet film thickness). This type of specimen has been found to be ideal for determining internal coating stress in the laboratory [14,15] particularly when using the deflection technique. During coating application and cure, environmental conditions (temperature and relative humidity) were monitored. These were used to ensure proper cure conditions and to determine their possible influences on coating stress.

The miniature EFPI strain gauges were oriented along the longitudinal axis of the steel shim as shown in Figure 5. The gauges were bonded to the specimen surface (after recommended surface preparation) using an M-Bond 200 adhesive (a commercially available adhesive designed for strain gauge applications).

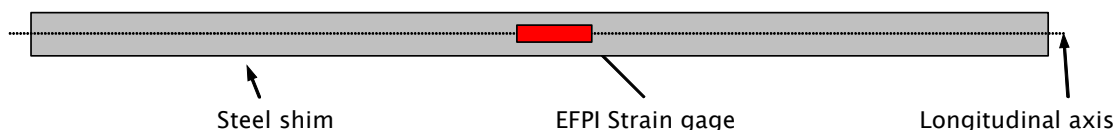Steel shim   EFPI Strain gage   Longitudinal axis

Figure 5: Placement of EFPI strain gauge on coated steel shim.

Following attachment of the strain gauge and complete cure of the adhesive, each coating was brush-applied over the entire length of the shim material and allowed to cure. The coated specimens remained exposed to ambient laboratory conditions for periods up to about 1000 hours. No attempts were made to control either the temperature or the relative humidity (%RH) in the room; i.e. ambient conditions were allowed to prevail. It was noted that though the room temperature remained more or less constant to within a few degrees of 20°C, the ambient relative humidity (%RH) changed from around 40% to over 65%. Throughout the cure and exposure period, measurements of the strain were recorded to determine internal coating stress as a composite function of time, temperature and %RH.

Results

The internal coating stress measured and monitored for each of the coating systems: alkyd, acrylic, urethane and epoxy as a composite function of time, temperature and %RH are presented in Figures 6, 7, 8 and 9 respectively.
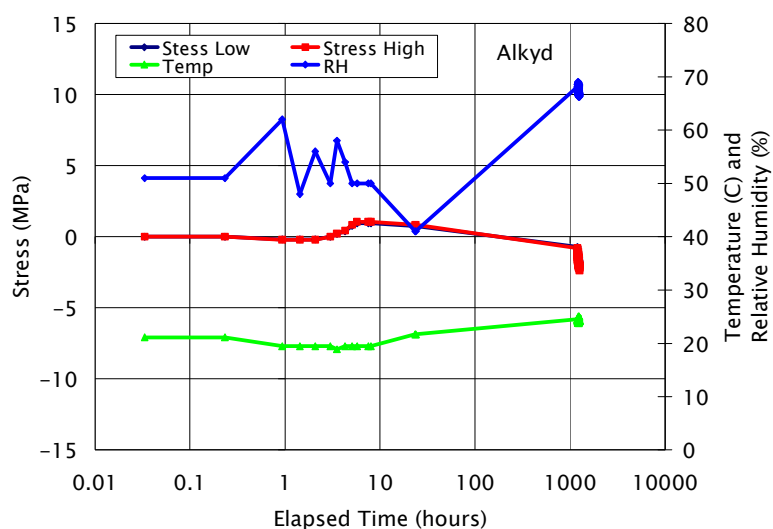
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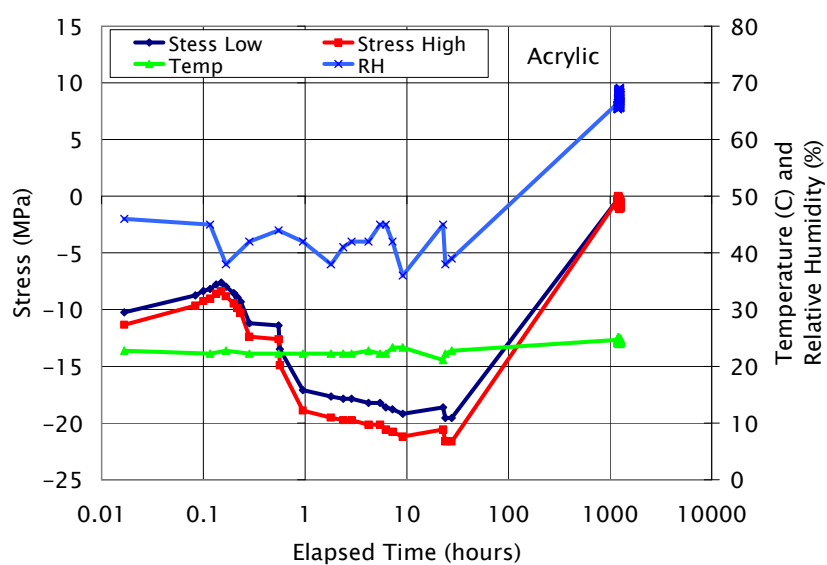Figure 6: Internal coating stress measurement in an alkyd system.

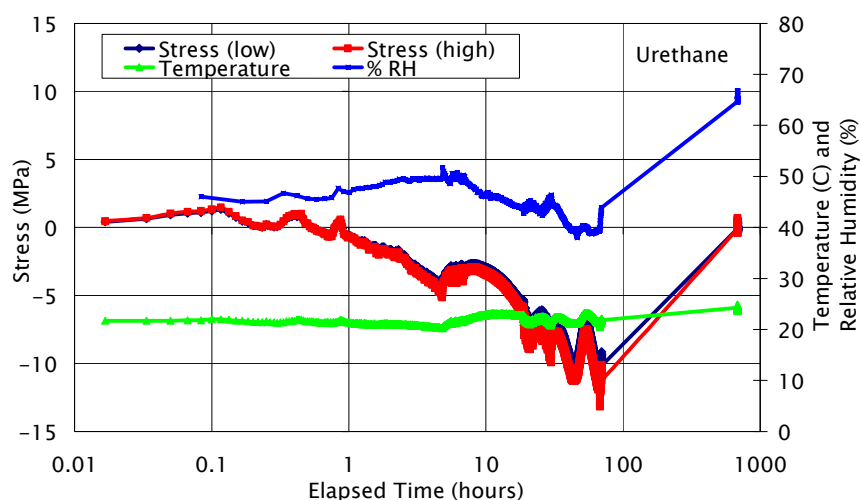Figure 7: Internal coating stress measurement in an acrylic system

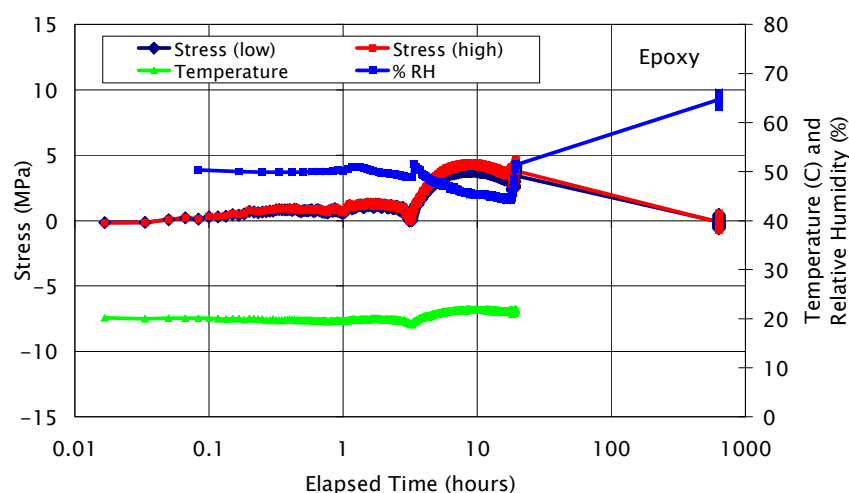Figure 8: Internal coating stress measurement in a urethane system.

Figure 9: Internal coating stress measurement in an epoxy system.

It is important to note the difference in stress patterns displayed by the different types of coating systems depending on the ambient relative humidity. Specific observations are as follows:

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- The **alkyd system** did not show any noticeable internal stress development for the first several hours but then showed slight positive values in the range of 1 to 2 MPa over the next 10 hours or so followed by a drift towards zero during the next 150 hours. The stress value started to become negative after about 200 hours of exposure and attained a value of about –2 MPa after 1050 hours. During the exposure period the %RH fluctuated between 40 to 68%.

- The **acrylic system** showed relatively high negative stress values, ~10 MPa soon after coating application. As the coating cured over the next 48 hours or so, the stress became even more negative reaching a value of approximately –20 MPa. The stress then started to move steadily towards the positive direction reaching a value of about –1 MPa by end of the exposure period of 1050 hours. The %RH, which was hovering around 40% during the first 48 hours, increased gradually to a value of about 68% by the end of the experiment. It may be noted that there seemed to be a direct linear relationship between the stress pattern and the RH particularly after the first 48 hours. Thus, as the RH increased from 40 to 68%, the internal stress level changed towards less negative values. The slopes of the two parameters were in the same positive direction.

- The stress level for the **urethane system** started off slightly positive soon after coating application. However, after about 1 hour, the stress steadily became more negative and reached a value in the range of –12 to –14 MPa after around 90 hours of exposure. Similar to the acrylic system, the stress level then started to become less negative, becoming almost zero by the end of the experiment. The RH hovered around 40–45% during the first 100 hours and then gradually increased to ~65% by the end of the exposure period. Here also a direct relationship between the stress pattern and change in %RH could be seen which was similar to the acrylic system.

- The **epoxy system** started off with zero stress values at the outset and then developed slightly positive values, <1 MPa over the next 5–6 hours. This was followed by a noticeable increase during the next 40 hours or so to around 3 to 4 MPa. The stress level then steadily became less positive reaching almost zero at the end of the experiment. The RH was around 45–50% during the first 48 hours and then gradually increased to ~65%. The variation of %RH and coating stress had an inverse relationship, somewhat similar to the alkyd system (i.e. as the RH increased from 45 to 65%, the stress level changed towards less positive values). The slopes of the two parameters

were in opposite directions; thus, the RH parameter in the positive direction, and the stress parameter in the negative direction.

Discussion

The use of embedded miniature EFPI fibre optic strain gauges provide an accurate and elegant way of in-situ measurement and monitoring of internal stresses developed in various types of organic coating systems. These stresses may be generated due to one or a combination of different factors such as curing, environmental variations in RH and/or temperature, aging, structure vibration, etc. The use of EFPI strain gauges for measuring internal coating stress is not cited in the open literature and can be considered to be a novel usage of this technology.

The data from the present study indicates that the alkyd and epoxy coating systems behave somewhat similarly during curing and environmental exposure. Both systems develop relatively low positive internal stresses when the RH is in the 40 to 45% range. However, as the ambient RH increases, the internal stresses tend to become less positive becoming zero or slightly negative.

The acrylic and urethane systems showed similar behaviour during curing and exposure. Both systems developed relatively high negative internal stresses during the curing stage when the RH was in the 40-45% range. However, as the RH increased to higher values, the internal stress reduced significantly to almost zero or very low negative values.

As mentioned earlier, positive stress values indicate expansive or compressive forces and are not detrimental to coating performance. However, when the internal stress shows negative values it signifies that the coating is under tensile stress. If this tensile stress exceeds the adhesive strength of the coating then disbondment of the coating from the substrate may occur. In the case of an overcoat system if the internal stress of the overcoat exceeds or equals the adhesive strength of the undercoat then premature failures from lifting and/or intercoat disbonding may result [4].

From a practical standpoint the results from the present study show that an epoxy system would be compatible as an overcoat material for alkyd systems under different RH conditions. If an acrylic or a urethane system is chosen as the overcoat material for an existing alkyd system, then coating disbondment and/or cracking may occur depending on the RH conditions particularly if the RH is in the 40-45% range.

Conclusions

1. The use of embedded miniature EFPI fibre optic strain gauges provide an accurate and elegant way of in-situ measurement and monitoring of the internal coating stress of different types of organic coating systems under varying relative humidity conditions at ambient temperature. This use of EFPI strain gauges for measuring internal coating stress is believed to be a novel usage of this technology.

2. The nature and magnitude of internal stress has an important bearing on coating performance. A positive stress value indicates compressive forces and is not detrimental to coating performance. When the internal stress shows negative values it signifies that the coating is under tensile stress. If this tensile stress exceeds the adhesive strength of the coating then disbondment of the coating from the substrate can occur. In the case of an overcoat system if the internal stress of the overcoat exceeds or equals the adhesive strength of the undercoat then premature failures from lifting and/or intercoat disbonding may result.

3. The alkyd and epoxy coating systems investigated behaved somewhat similarly during curing and environmental exposure. Both systems developed relatively low positive internal stresses when the RH was in the 40 to 45% range. However, as the ambient RH increased, the internal stresses became less positive, becoming zero or slightly negative.

4. Both the acrylic and urethane systems developed relatively high negative internal stresses during the curing stage when the RH was in the 40-45% range. However, as the ambient %RH increased to higher values the internal stress reduced significantly to almost zero or very low negative values.

5. The practical significance of the results from the present study is that an epoxy system would be compatible as an overcoat material for alkyd systems under different RH conditions. If an acrylic or a urethane system is chosen as the overcoat material for an existing alkyd system, then coating disbondment and/or cracking may occur depending on the RH conditions particularly if the RH is in the 40-45% range.

Acknowledgements

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