Experimental study on the onset of swelling for thin intumescent coatings

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ABSTRACT

Intumescent coatings (also known as reactive coatings) are widely used to protect load-bearing steel structural elements during fire. Upon heating, these initially thin coatings swell to form a low density, highly insulating foamed char that insulates steel substrate. Within the context of modern fire safety engineering design of steel structural systems, thermal insulation during fire may be key for assuring that steel does not reach ‘critical’ temperatures that may yield local structural instability and/or progressive failure (i.e. global instability).

Traditionally, the fire performance of intumescent coatings is typically based on compliance (and to some extent their performance) to the standard fire resistance test in furnace, where single coated elements are exposed to the standard temperature-time curve. Numerous research studies have emphasised the influence of heating conditions on the onset of swelling and the overall effectiveness of intumescence. Moreover, some studies have shown that slow growing fires or low heating regimes may cause an incomplete swelling of the intumescent coating, or even melting or delamination. Consequently, the onset of swelling of is key for assuring its effectiveness in providing thermal insulation to the steel substrate during fire. Past researchers have shown that the onset of swelling occurs for temperatures in the range of 200-300°C. There are limited research studies that have look at the effects of varied, non-standard heating regimes on the onset or effectiveness of swelling of thin intumescent coatings.

The study presented herein investigates the onset of swelling for a commercially available thin intumescent coating exposed to a wide range of heating regimes. Experiments are performed by using radiant panels and controlling incident radiant heat flux at the exposed surface of coated steel samples. This allows for the direct and precise control of the thermal boundary conditions at the exposed surface of tested samples. The onset of swelling criteria were defined in two ways: (1) visual observation of swelling during heating or (2) time-history of the protected steel temperature.

The outcomes of this work aim at yielding a sound understanding of the true effectiveness of thin intumescent coatings. Experimental results mainly show that onset of swelling is directly influenced by the heating regime and it occurs for test samples heated at constant incident radiant heat flux above 20 kW/m². The onset of swelling for the tested thin intumescent coating occurs for steel temperatures between 150 and 300°C and ‘mean coating temperature’ between 350 and 450°C. However, the steel temperature at onset of swelling is inversely proportional to the amount of constant incident heat flux at the exposed surface of tested samples, while the ‘mean coating temperature’ is directly proportional. As a conclusion, the time-history of net heat flux at the exposed surface of tested samples is not the only parameter that governs the onset of swelling for thin intumescent coatings.

KEYWORDS:

Thin intumescent coatings; onset of swelling; incident radiant heat flux; heat transfer modelling; fire testing; H-TRIS.
INTRODUCTION

Intumescent coatings (also known as reactive coatings) are widely used to protect load-bearing steel structural elements during fire. Upon heating, these initially thin coatings swell to form a low density, highly insulating foamed char that insulates steel substrate. Within the context of modern fire safety engineering design of steel structural systems, thermal insulation during fire may be key for assuring that steel does not reach ‘critical’ temperatures that may yield structural local instability and/or progressive failure (i.e. global instability) [1]. The increasing growth of thin intumescent coatings in the built environment is associated with the low impact on the aesthetics of bare steel elements, the cost-effective on-site or off-site application and the perceived good performance of the product across the industry [2]. Intumescent coatings are usually based on a combination of organic and inorganic components bound together in a polymer matrix [3]. Thin intumescent coatings are typically solvent-based or water-based products and their application is defined in a Dry Film Thickness (DFT), usually within the range of a few millimetres.

Traditionally, the fire performance of intumescent coatings is typically based on compliance (and to some extent their performance) to the standard fire resistance test in furnace, where single coated elements are exposed to the standard temperature-time fire curve [4, 5]. Numerous research studies have emphasised the influence of heating conditions on the onset of swelling and the overall effectiveness of intumescence [1, 3, 6-8]. Moreover, some studies have shown that slow growing fires or low heating regimes may cause an incomplete swelling of the intumescent coating, or even melting or delamination [1, 8]. Consequently, the onset of swelling has a key role for assuring the coating effectiveness in providing thermal insulation to the steel substrate during fire. Past researchers have shown that the onset of swelling occurs for temperatures in the range of 200-300°C [9-11]. Most of the past experimental research has been conducted using small-scale samples (few grams or milligrams), disregarding any heat transfer process within the expanding coating. There are limited research studies that have look at the effects of varied, non-standard heating regimes on the onset or effectiveness of swelling of thin intumescent coatings.

The study presented herein investigates the onset of swelling for a commercially available thin intumescent coating exposed to a wide range of heating regimes. Experiments are performed by using radiant panels and controlling incident radiant heat flux at the exposed surface of coated steel samples. This allows for the direct and precise control of the thermal boundary conditions at the exposed surface of tested samples. The onset of swelling criteria were defined in two ways: (1) visual observation of swelling during heating or (2) time-history of the steel temperature. This enables the definition of a threshold for the onset of swelling, found (based on exploratory work described herein) to be influenced by incident radiant heat flux at the exposed surface, overall net heat at the exposed surface and steel temperature.

EXPERIMENTAL INVESTIGATIONS

Fire test method

Within the scope of this study, a Heat-Transfer Rate Inducing System (H-TRIS) method was used. This fire test method allows for the direct control of incident radiant heat flux at the exposed surface of the test samples, i.e. control of the time-history of incident heat flux [12]. This is possible by controlling the relative position between the target exposed surface of the test sample and an array of radiant heaters coupled with a computer-controlled mechanical linear motion system (see Fig. 1). This H-TRIS is built from a single high-performance gas-fired radiant heater mounted on a supporting frame (see Fig. 1). This experimental setup enables the careful visual inspection of test samples during fire testing (e.g. gauging the rate of swelling of intumescent coatings), technically challenging during a conventional standard furnace test [13].

Experimental campaign

Within the scope of this work, 200x200 mm² steel plates with a thickness of 10 mm (section factor $A/V_s = 100$ m⁻³), were professionally coated with a commercially available solvent-based thin intumescent coating. The initial applied DFT was 1600 μm (± 200 μm). During the experimental campaign, individual uncoated and coated test samples were heated during 30 minutes under constant incident radiant heat flux, varying within 10 and 55 kW/m². During testing, individual samples were positioned on custom-built sample holder (Fig. 1) and the unexposed surface (backside) of the steel plate was insulated using a low density insulating material to minimise heat losses at the back of the test sample. Steel temperature was recorded using K-type thermocouples attached at the unexposed surface of each sample, placed at different locations. The transient rate of swelling of the coating was measured by image processing of videos taken using a high-resolution
camera and the exposed surface temperature at the coating swelling front was gauged using an Infra-Red camera (Fig. 1).

Fig. 1. Schematic illustration (left) and photography (right) of the experimental setup.

Criteria for onset of swelling

In available literature, there is no reference known to authors that has presented a unified, standard definition for the onset of swelling for intumescent coatings during heating. Within the scope of the work described herein, onset of swelling for intumescent coatings was defined in accordance to two criteria:

- **Minimum swelling** - considering the applied DFTs, the minimum swelled coating thickness was defined at 5 mm (Fig. 2).
- **Steel temperature divergence** - when the steel temperature protected by a reactive coating diverges from the steel temperature protected by an inert insulation (coating prior to swelling), mainly because of a rapid change in its thermo-physical properties. Mathematically, this was defined as the minimum slope change in the steel temperature gradient, i.e. the minimum in the second derivative (Fig. 2).

Fig. 2. Steel temperature at the unexposed surface and swelled coating thickness for test samples (uncoated and coated): criteria for onset of swelling applied to experimental data and heat transfer model data for a typical test sample tested at a constant incident radiant heat flux of 40 kW/m².

Heat transfer model

An explicit one-dimensional heat transfer model was formulated in order to simulate and understand the thermal boundary conditions and the heat transfer within the tested samples. The model is a finite differences numerical method developed by Emmons and Dusinberre [14, 15] and it solves explicitly a conduction problem by resolving energy-balance equations in the main direction of the heat flow. The model is based on finite differences and discretization into exposed, interior and unexposed elements. The thermal boundary conditions at the exposed surface of the test sample was defined as an incident radiant heat flux $q_{\text{inc}}$ with
convective $q_{\text{loss,conv}}''$ and radiative $q_{\text{loss,rad}}''$ heat losses. Adiabatic conditions were assumed at the unexposed surface. The material properties used were:

| Steel | Intumescent coating (prior to swelling) |
|-------|----------------------------------------|
| • Thickness: $d_s = 0.01\,m$ | • Thickness: $d_c = \text{initial DFT}$ |
| • Density: $\rho_s = 7850\,kg/m^3$ [5] | • Density: $\rho_c = 1550\,kg/m^3$ |
| • Specific heat capacity: $c_{p_s}$ [5] | • Specific heat capacity: $c_{p_c} = 1375\,J/kgK$ |
| • Thermal conductivity: $\lambda_s$ [5] | • Thermal conductivity: $\lambda_c = 0.10\,W/mK$ |
| • Emissivity: $\varepsilon_s = 0.75$ | • Emissivity: $\varepsilon_c = 0.90$ |

The adopted explicit heat transfer model was validated using experimental temperature data (Fig. 2) in order to verify the acceptability and rationality of the results. In addition, using the adopted heat transfer model, the time-history of net heat flux at the exposed surface was investigated. The net heat flux $q_{\text{net}}''$ was obtained by subtracting the estimated heat losses $q_{\text{loss,tot}}''$ (convective $q_{\text{loss,conv}}''$ and radiative $q_{\text{loss,rad}}''$ component) from the incident heat flux $q_{\text{inc}}''$. Moreover, the accumulative thermal energy flux $E_{\text{th}}''$ absorbed by the test sample at onset of swelling was calculated as the area under the net heat flux curve (Fig. 3):

$$E_{\text{th}}'' = \int_0^{t_{\text{act}}} q_{\text{net}}'' \, dt$$

Fig. 3. Incident radiant heat flux, heat losses (convective and radiative component) and accumulative thermal energy flux for a coated test sample tested at a constant incident radiant heat flux of $40\,kW/m^2$.

RESULTS AND DISCUSSION

Onset of swelling

The time necessary to onset of swelling according to the two previous criteria was evaluated for all the tests conducted under different constant incident radiant heat fluxes. Figure 4 shows how time to onset of swelling decreases with increasing incident radiant heat flux and how the two criteria are comparable. Particularly, the minimum incident heat fluxes to reach onset of swelling was found at $23\,kW/m^2$ and no swelling was registered for samples tested under $20\,kW/m^2$. As a conclusion, the critical constant incident radiant heat flux for swelling to occur for this thin intumescent coating was found to be between $20$ and $23\,kW/m^2$ (Fig. 4).

Accumulated thermal energy flux at onset of swelling

The net thermal energy flux accumulated by test samples prior to the onset of swelling was estimated using the adopted heat transfer model (Fig. 5). A clear trend was not visible, but it was found that swelling only occurred above a minimum accumulated net thermal energy flux of $7\,MJ/m^2$, regardless of the constant incident heat flux imposed on the test sample.
Steel and coating temperature at onset of swelling

Figure 6 shows the steel temperature at the time when the onset of swelling was achieved in accordance with the two criteria. Once again, the two criteria show a similar trend. Particularly, thin intumescent coating swelled for steel temperatures between 150 and 300°C and evidenced an increase of steel temperatures at onset of swelling for samples tested at lower heat fluxes.

For samples tested at a constant incident heat fluxes of 25, 40 and 55 kW/m², the surface temperature of the coating was measured using an Infra-Red camera: the coating emissivity $\varepsilon_c$ was set equal to 0.90. Subsequently, the ‘mean coating temperature’ was calculated as the average between the surface and steel temperature. Figure 7 shows that the ‘mean coating temperature’ at onset of swelling varies between 350 and 450°C and evidenced an increase of ‘mean coating temperature’ for samples tested at higher heat fluxes.

CONCLUSIONS

This paper presented a systematic investigation on the onset of swelling for thin intumescent coatings exposed to various levels of constant incident radiant heat flux. Based on the experimental outcomes of this work, this research study aimed at yielding a sound understanding of the true effectiveness of thin intumescent coatings. From the results analysed herein, the following concluding remarks may be drawn:

- This research study confirms that many aspects of thin intumescent coatings’ behaviour, like the onset of swelling, are directly influenced by the heating regime at the exposed surface of tested samples;
The onset of swelling for thin intumescent coatings can be assessed according to two criteria, one related to the minimum swelled coating thickness and one to the coated steel temperature;

- The onset of swelling occurs for test samples heated at constant incident radiant heat flux above 20 kW/m²;
- The accumulated net thermal energy flux at the time of onset of swelling remains steady and above 7 MJ/m² for the range of heating regimes investigated herein;
- The onset of swelling for the tested thin intumescent coating occurs for steel temperatures between 150 and 300°C and it is inversely proportional to the amount of constant incident heat flux at the exposed surface of tested sample;
- The onset of swelling occurs for the tested thin intumescent coating occurs for ‘mean coating temperature’ (as defined herein) between 350 and 450°C and it is proportional to the amount of constant incident heat flux at the exposed surface of tested samples;
- The time-history of net heat flux at the exposed surface of tested samples is not the only parameter that governs the onset of swelling for thin intumescent coatings.

Future research needs to deepen the key aspects related to intumescence. In particular, future studies of this work will focus on the influence of DFT and the influence of different time-histories of incident radiant heat flux on the onset of swelling of thin intumescent coatings.

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