Quantification of Surface Strains in Erichsen Cupping Tests

Fabian S. Sorce[1], Sonny Ngo[2], Chris Lowe[2], Ambrose C. Taylor[1]

[1]Department of Mechanical Engineering, Imperial College London
[2]Long Term Development Laboratory, Becker Industrial Coatings Ltd, Liverpool

ISCST-20180919AM-A-CA4

Presented at the 19th International Coating Science and Technology Symposium,
September 16-19, 2018, Long Beach, CA, USA†.

Abstract
The thermosetting polyester-based coatings used in the coil coating industry experience large deformations as the coated steel is formed into white goods and architectural cladding. Failure of coatings on sheet metal during forming is a strain-governed process. The Erichsen cupping test is used to assess the formability, ductility and adhesion of the coating. It is a qualitative and robust quality control method and as such the behaviour of coatings during the test has not been previously characterised. A finite element model has been developed to calculate the surface strains for any level of indentation, and validated with the surface strains measured during cupping using digital image correlation. Master curves of the maximum strain versus Erichsen index have been determined, allowing the strain to failure of the coating to be determined from the Erichsen test. Understanding the coating behaviour during the test will allow the formability, material properties and chemical structure of the polymer to be linked more closely, enabling the development of better coatings.

Keywords: Erichsen cupping test, Erichsen Index, coil coating, digital image correlation, surface strain

Introduction
Coil coating is a technique used to produce pre-painted metal (PPM) sheet which is stored and transported in large coils. It is a highly efficient and automated process with many economic, processing and environmental benefits. PPM has many uses ranging from white goods to architectural cladding [1]. The coatings must have superior qualities such as good formability, ductility, weatherability, and adhesion in order to withstand operating environments but also the manufacturing process. One of the key concerns in manufacturing products from PPM is the formability of the coating and the ability for the coating to withstand failure by cracking and delamination. The Erichsen cupping test is an industry standard test which is used to evaluate such behaviours.

Historically the Erichsen cupping test was used to assess the quality of sheet metal. It is now used to gauge the resistance to failure of coatings. The test uses a 20 mm diameter hemispherical punch to slowly draw the PPM blank at room temperature, see Figure 1 for a schematic, whilst monitoring for failure of the coating. The test is an empirical testing procedure; and is typically performed in two modes in industry. A go / no-go approach is used in quality control to determine whether a coating meets the formability requirements, i.e. can it withstand failure at a given indentation level. To determine coating performance the test is run until failure of the coating is observed and the indentation depth in mm at failure is quoted as the Erichsen Index, IE. The results are comparative, so this is a qualitative, quick and robust quality control method. Hence, the behaviour and failure of coatings during cupping have not been previously characterised, and have not been linked to the mechanical properties of the coatings.

Commonly used in the coil coating industry are thermosetting polyester based coatings crosslinked with hexa(methoxymethyl)melamine (HMMM). The modulus of a 20 μm thick polyester coating (~2000 MPa at T_g-40 °C, and ~5 MPa at T_g+20 °C) is approximately 5 orders of magnitude smaller than that of the steel substrate (~200,000 MPa). Hence, if a coating adheres well to its substrate, the failure stress of the PPM will be governed by the substrate, and it can be assumed that the strain in the coating is equal to that of the surface of the sheet steel. The failure mechanism for coil coatings is therefore strain governed.

This paper quantifies the surface strains in the Erichsen cupping test in order to produce master curves of maximum strain versus the Erichsen index. The strains are determined experimentally using digital image correlation (DIC) to validate the results from a finite element (FE) model. The results are compared and the strain behaviour at different IE values evaluated. Knowing the strain behaviour of the coating during the test will ultimately enable the formability of a coating during the Erichsen cupping test to be linked to the mechanical properties of the coating.

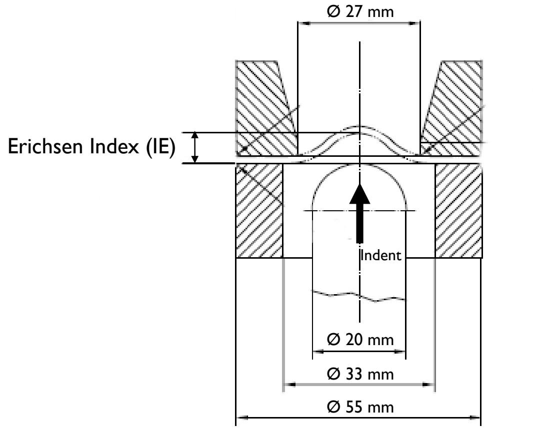


Figure 1: Schematic of Erichsen cupping test (cross-section), adapted from [2].

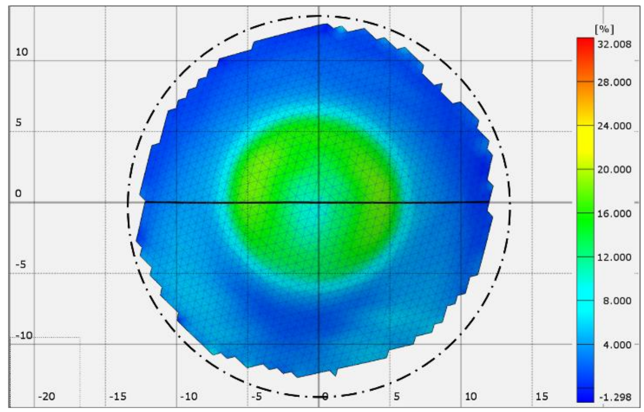


Figure 2: Representative surface strain map of Erichsen cupping test at IE = 6 mm (top view) determined by 3D DIC.

Material

Coated steel panels of approximately 0.6 x 150 x 250 mm^3 were prepared. The steel substrate was hot-dip galvanised (HDG) (pure zinc with a small addition of aluminium (< 0.2 %)) construction grade steel with a low carbon content (< 0.5 %) and a primer layer of 5 – 9 µm (a crosslinked polyester-melamine derivative with strontium chromate). The ratio of resin to crosslinker used was 80:20. Hexa(methoxymethyl)melamine (HMMM) was used as the crosslinking agent, whilst the polyester resin was formulated based on adipic and phthalic acid anhydride, a triol, solvents and a catalyst. TiO_2 white pigment was used to provide contrast against the black spray paint speckles used in DIC. The paint formulation was applied to individual panels with a draw-down bar to achieve a dry film thickness (DFT) of approximately 20 µm. The paint was cured at 295 °C in an electric oven for 35 s to achieve a peak metal temperature (PMT) of 232 °C and the panels were quenched in water. The panels were subsequently cut to a size of 50 x 50 mm^2 using a guillotine.

Experimental

An Erichsen cupping rig with the standard geometry [2, 3] was manufactured and mounted in an Instron 3369 universal testing machine. This was used to determine the force versus indentation depth during the cupping process, at an indentation rate of 3 mm/min. The HDG steel blanks were indented to IE values from 1 mm to 10 mm at 1 mm intervals. The domed samples were sectioned using electrical discharge machining (EDM) to reveal the profiles of the domes at their mid-point. These profiles were photographed and digitised using Matlab, allowing the experimental profiles to be compared directly to those measured using DIC and predicted using the FE model. The springback behaviour of the cupping test was also investigated, and this showed that the effects were negligible.

There is no analytical solution to calculate the strain in the dome produced in cupping tests due to its complexity. Digital image correlation (DIC) is an optical technique used to measure surface strains during a test by tracking speckle patterns on a sample. 3D DIC utilises two calibrated cameras to measure both in-plane and out-of-plane motion and give strains in 3D, resulting in measured major and minor strains. An ARAMIS system from GOM was used, with an ARAMIS 5M sensor configuration with two 50 mm lenses. A measuring distance of 310 mm, a camera angle of 25° and a slider distance of 98 mm were used. The depth of field is aperture dependent, so an aperture of ~ 16 was used to give the system a depth of field of 11 mm, as the HDG steel substrates failed at an IE of approximately 10 mm. The results were analysed using GOM Correlate Professional software, using a surface component mesh with a facet size of 60 pixels and a point distance of 40 pixels. The dome profiles and the surface strains were calculated, see Figure 2 for an example of the surface major strain map produced.

For subsequent calculations, strain values were taken along a plane cutting through the centre of the dome. A table top Erichsen cupping test machine was used to perform the cupping test as this provided adequate space for the ARAMIS system. The indentation depth was independently measured, and showed good agreement with the DIC data.

The steel failed before the coating in all of the Erichsen cupping tests presented here, as the formability of the coating was far superior to that of the steel.

Finite Element Modelling

The Erichsen cupping test was modelled using PAM-STAMP Professional software, which is designed for the simulation of metal forming. A suitable HDG steel was chosen from the PAM-STAMP material library. Two models were produced using different mesh densities. The fine mesh used shell elements with a characteristic length of 0.087 and the coarse mesh of 0.5, representing a 0.6 mm thick blank with dimensions of 50 x 50 mm^2. Adaptive meshing was disabled so that the mesh density remained constant throughout. A clamping force of 10 kN was applied to the blank as recommended by the standard [2, 3], and a coefficient of friction of 0.1 was used between the indenter and blank.

Results and Discussion

The experimental shape of the dome formed during the cupping test is shown in Figure 3 for different Erichsen indices. The dome thickness is indicated by the thickness of the line, and it can be seen that the metal becomes thinner at higher IEs. For IE = 10 mm there is a clear reduction in dome thickness where the dome subsequently fails. The dome profiles determined experimentally and from the FE model agree as shown by the examples in Figure 4 at IE = 3 mm and IE = 8 mm. The excellent agreement between the three independent methods (FE model, digitised image and DIC surface profile) of determining the dome shape give confidence to the results. The dome profiles generated from the coarse and fine model matched perfectly.

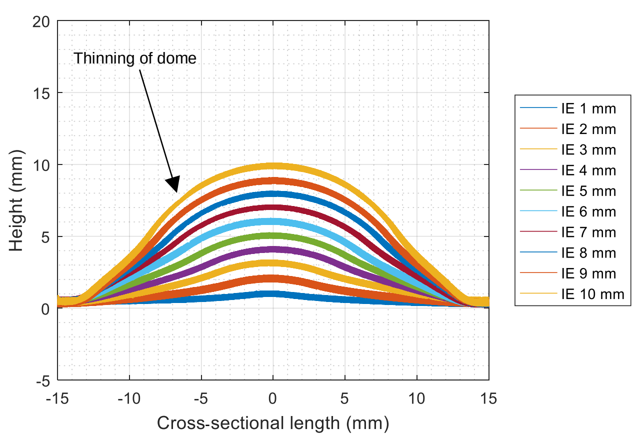


Figure 3: Progression of the experimental cross-sectional profiles of the dome for increasing Erichsen Index (IE).

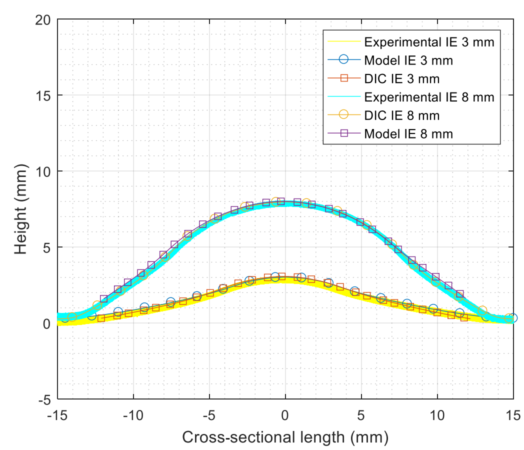
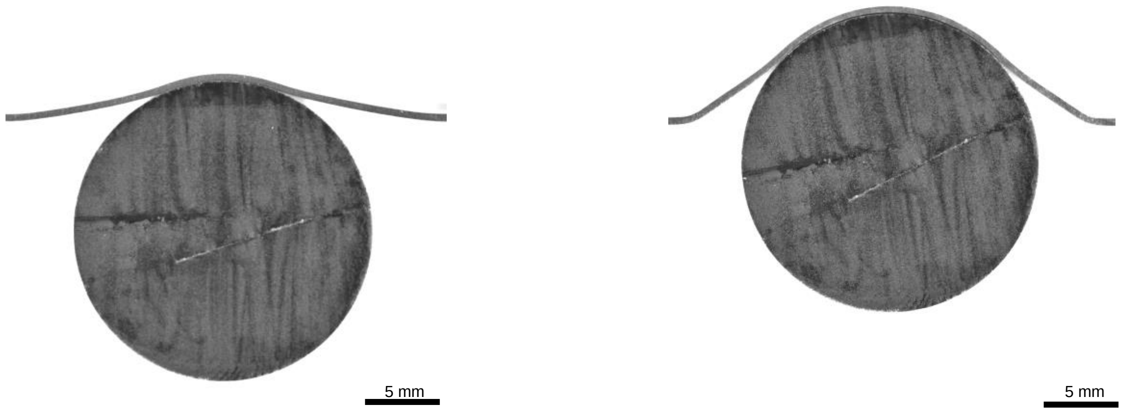


Figure 4: Comparison of experimental and computational cross-sectional profiles at IE = 3 mm and IE = 8 mm.

The dome profile is controlled by the contact between the indenter and the blank. In Figure 3 there are two distinct parts of the curve for each dome profile: (i) the area in contact with the indenter which conforms to the sphere and (ii) the area free of contact which can be approximated as being linear in cross-section. From examination of cross-sectional profiles of domes and the indenter (e.g. Figure 5) it can be concluded that the interface between these two zones is at the point where there is no longer contact between the indenter and the blank. The progression of the major strain against the cross-section length with increasing IE is shown in Figure 6 for (a) the coarse mesh model and (b) the fine mesh model. As the indentation depth increases the position of the maximum strain moves away from the centre (top) of the dome. This is a result of an increase in the contact area between the indenter and the blank (see Figure 5), and hence increased friction. The rate at which the positon of maximum strain moves outwards decreases with the indentation level.

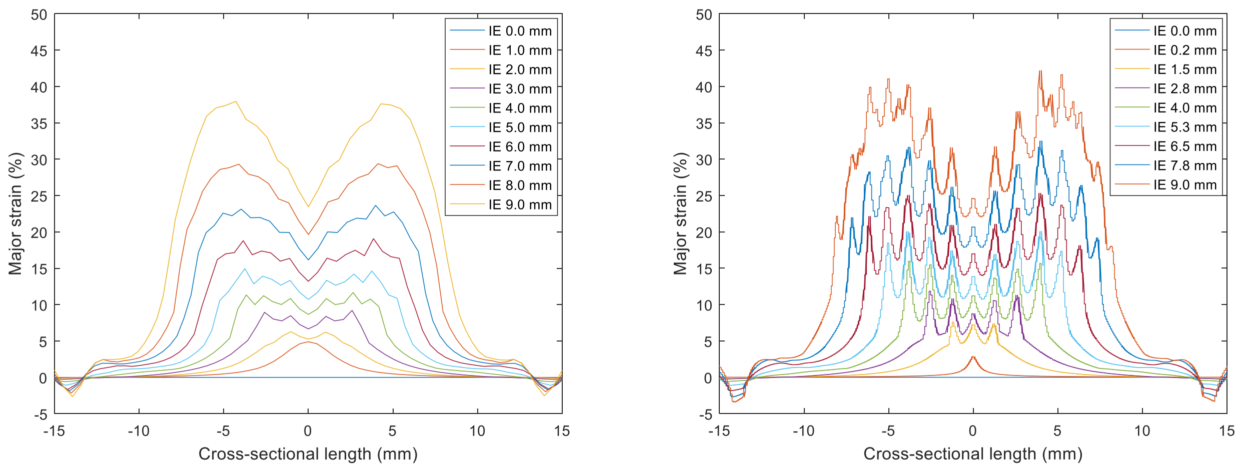
The initial location of maximum strain at low levels of IE on top of the dome is because initially the blank is subjected to clamped 3-point bending. At such low indentation levels the indenter effectively makes a point contact with the sheet causing low levels of strain to be observed without significant curvature being induced (see IE = 1 mm in Figure 3).



(a) (b)

Figure 5: Experimental cross-sectional profiles of dome and indenter at (a) IE = 3 mm and (b) IE = 8 mm.

Similar trends in the major strain are observed for both coarse and fine FE models. However, the fine mesh model results show significant oscillations, see Figure 6 (b), suggesting that the solver is sensitive. These oscillations are believed to be an artefact of the model and are comparable to the effect of over-fitting a polynomial. The negative strain values at the edges are a result of the clamping of the blank (die diameter is 27 mm) and the coil coating being put into compression between the steel and the die.



(a) (b)

Figure 6: (a) Progression of major strain at midpoint cross-section of (a) the coarse model and (b) the fine model.

The progression of the major strain, measured using DIC along a cross-section through the midpoint of the dome, with indentation is shown in Figure 7. The maximum strains move away from the centre of the dome as the IE increases, as was observed in the FE model results shown in Figure 6. The behaviour is similar to that in the coarse model confirming that the oscillatory behaviour of the strain in the fine model is an artefact. The model data shows results for the whole cross-section of the blank, whereas experimentally there is no way to monitor the behaviour within the clamped region. The nature of using two angled-cameras and the shape of the testing rig means that the area to be examined is slightly less than that of the die as the dual line of sight needed is partially blocked at the edges. Both the major strains and the dome DIC data are comparable to the model data. The minima points observed are smaller than those seen in the model.

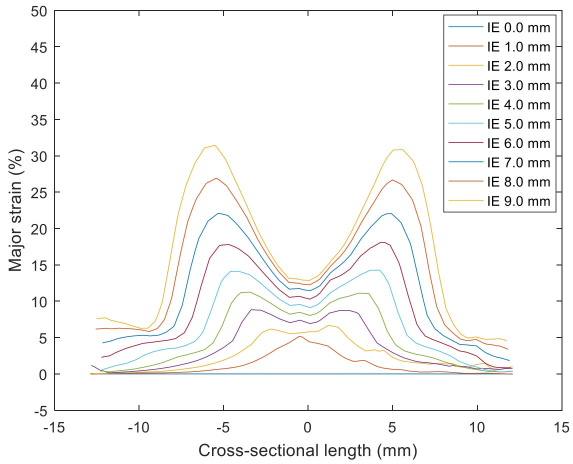


Figure 7: Major strain progression as measured by DIC.

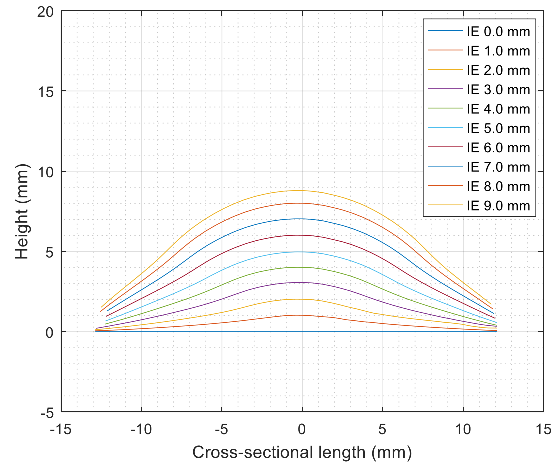


Figure 8: Dome profile progression as determined by DIC.

A comparison between the model data and the DIC data at IE = 3 mm and IE = 8 mm is shown in Figure 9. There is close agreement with the behaviour of the maximum strains, yet disparity between the strain levels at the top of the dome. This is more noticeable at higher IEs. The DIC measured strains at the outer fringes are much higher than their experimental counterparts. There is of course an associated error and level of noise with DIC measurements and this behaviour at low levels of strains is attributed as such.

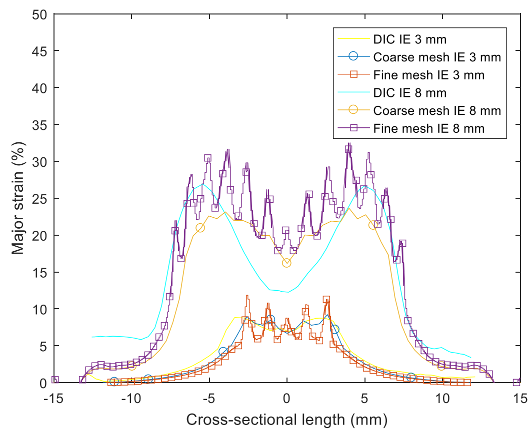


Figure 9: Comparison of the computed major strains and measured strains at IE = 3 mm and 8 mm.

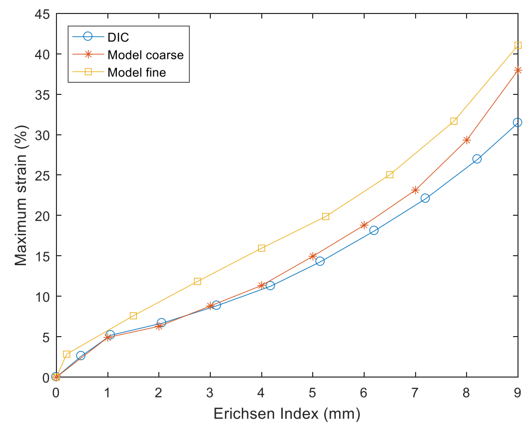


Figure 10: Comparison of master curves of maximum surface strain against the Erichsen index.

The master curves of the maximum strain in the coating versus the Erichsen index are shown in Figure 10. There is very good agreement between the coarse mesh model and that determined experimentally. There is increased deviation between the two at high Erichsen index values where large deformations of the shell elements occur as failure in the steel is imminent. The fine model overestimates the maximum surface strains in the dome as a result of an oscillatory artefact occurring within the solver.

Conclusions

The Erichsen cupping test has been used in a comparative capacity for many years. This work has successfully quantified the surface strains which coatings are subjected to. The findings are validated by both experimental and model data. 3D DIC was used to measure the surface strains during the Erichsen cupping test. Both a coarse and a fine density mesh model have been produced with similar trends in both sets of data observed. There is excellent agreement between the model and experimental data giving confidence to the results. Master curves enabling users to compare the maximum strain to the IE have been determined. At the limit of the formability of the sheet metal, the strain behaviour becomes less predictable. At this point, IE > 9 mm, failure is imminent and is governed by inherent defects in the substrate. Knowing the coating behaviour during the test provides the framework to link the formability, material properties and chemical structure of the polymer to develop better coatings.

Acknowledgments
The authors would like to acknowledge Becker Industrial Coatings for funding this research and the IMechE for providing financial assistance towards the conference costs.

References
1. Sander, J. Coil Coating. Hanover: Vincentz Network; 2014.

2. British Standards Institution. BS EN ISO 20482:2003. *Metallic materials — Sheet and strip — Erichsen cupping test.* London: BSI. 2003.

3. British Standards Institution. BS EN ISO 1520:2006. *Paints and varnishes - Cupping test.* London: BSI. 2006.