Understanding thermal warping and sagging in enamelled steel parts through an integrated FE simulation

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Abstract

When a steel part is enameled, residual stresses are induced due to the difference in thermal dilatation between steel and enamel. Those stresses can give rise to buckling and warping. Especially slender designs, such as baking trays and architectural panels, are prone to those defects.

The present paper proposes a finite element procedure which allows simulating the complete cycle of forming, springback and enameling and as a result, allows predicting warping and buckling in enameled steel parts.

To that end, the phenomenological models describing the thermo-mechanical behaviour of porcelain enamels have been implemented in Abaqus. Those models allow accounting for both stress and structural relaxation and as a result allow simulating the complete enameling process, i.e. cooling down from around 850°C (liquid phase) to room temperature (solid phase).

The FEA methodology is validated based on two case studies: simulation of the Klotz test and prediction of warping in enameled baking trays.

1. Introduction

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Figure 1 sketches the stress development in a steel-enamel composite during firing. Once the enamel is sprayed onto the steel sheet the enameled sheet is fired to circa 850°C for about 4 minutes. In this time period an interdiffusion layer is formed in between the steel sheet and the enamel so as to link the two materials to each other. Then the enameled part is cooled to room temperature. At 850°C the enamel can be considered as a viscous liquid which is not able to carry any stress. During cooling the viscosity of the enamel increases and at a certain temperature (typically between 500°C and 600°C) stresses will start to build up in the enamel and steel due to the difference in thermal expansion, resulting in thermal warping:

- As long as the temperature is above T_g, the glass transition temperature of the enamel, the coefficient of thermal expansion (CTE) of the enamel is higher than the CTE of the steel, resulting in tensile stresses in the enamel layer and compressive stresses in the steel layer.
- Below T_g the CTE of the enamel is lower than the CTE of the steel. As a result the stresses in both enamel and steel diminish and become zero at T_n.
- Below T_n compressive stresses start to build up in the enamel layer while tensile stresses arise in the steel layer.

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To that end, the phenomenological models describing the thermo-mechanical behaviour of porcelain enamels have been implemented in the commercial FEA code Abaqus via user subroutines. Those models allow accounting for both stress and structural relaxation and as a result allow simulating the complete enameling process, i.e. cooling down from around 850°C (liquid phase) to room temperature (solid phase).

The FEA methodology is then validated based on two case studies: simulation of the Klotz test and prediction of warping in enameled baking trays.
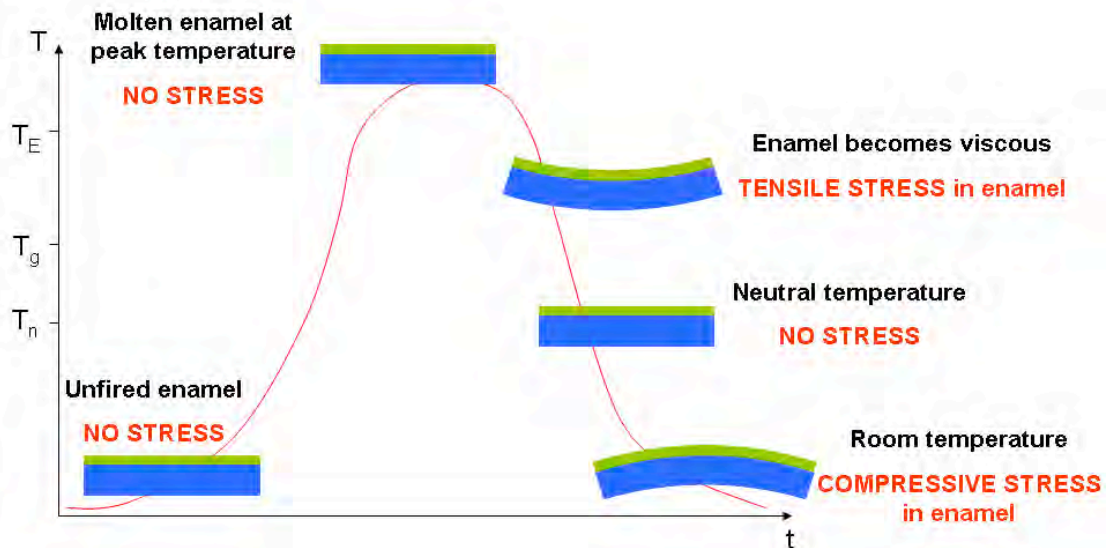
Figure 1 - Stress development in an enameled (green) steel (blue) part [1].

2. Mechanical behaviour of enamel

Enamel shows two kinds of relaxation behaviour, stress relaxation and structural relaxation [2]. As a result, the mechanical behaviour of enamel is history dependent (cfr. plasticity in steels). Moreover, both types of relaxation are highly temperature dependent.

2.1. Stress relaxation

Stress relaxation is comparable to the behaviour observed in a visco-elastic material, meaning that the response of the material to a constant stress or strain is time-dependent:

- Application of a constant strain (Figure 2) will result in a stress that exponentially decreases to a certain value (at infinity).
- Application of a constant stress will result in a gradually increasing strain. The total strain is composed of 3 parts: the instantaneous elastic strain ε_E, the delayed elastic strain ε_D and the viscous strain. After removal of the stress the elastic strains, ε_E and ε_D, are recovered, while the viscous strain is permanent.
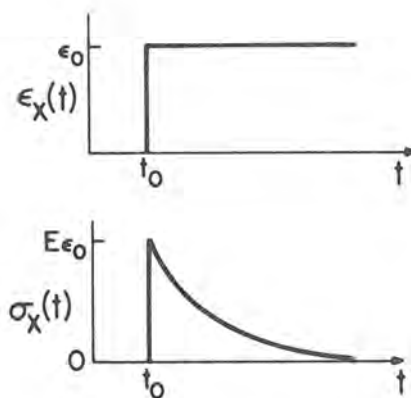

Figure 2 - Visco-elastic behaviour: application of a constant strain [2]

The constitutive equation of visco-elasticity is as follows [3]:

$$\sigma_{ij}(t) = 2\int_0^t G(t-t') \frac{\partial e_{ij}(t')}{\partial t'} dt' + \delta_{ij}\int_0^t K(t-t') \frac{d\varepsilon_{ii}(t')}{dt'} dt' \qquad (3.1)$$

With σ_{ij} the stress tensor, t the time, t' a running parameter for time, e_{ij} the deviatoric strains, ε_{ii} the trace of the strain tensor, G(t) and K(t) the time dependent shear and bulk modulus respectively. The time dependent relaxation moduli are usually defined by means of a Prony series expansion:

$$G(t) = G_0\left[1 - \sum_{i=1}^{N_G} w_i^G\left(1 - \exp(-t/\tau_i^G)\right)\right] \qquad (3.2)$$

$$K(t) = K_0\left[1 - \sum_{i=1}^{N_K} w_i^K\left(1 - \exp(-t/\tau_i^K)\right)\right] \qquad (3.3)$$

With G_0 and K_0 the instantaneous shear and bulk moduli, N_G and N_K the number of Prony series terms, w_i^G and w_i^K weight factors, τ_i^G and τ_i^K relaxation times.

The stress relaxation behaviour is highly temperature dependent: it occurs very fast at high temperature ($T > T_g$) while it can be barely observed at room temperature (in fact glass can be considered as a purely elastic material at room temperature). It was, however, observed that this stress relaxation behaviour is thermo-rheologically simple [2], meaning that it can be taken into account by rescaling the time as a function of temperature:

$$\varsigma(t) = \int_0^t A(T(s))ds \qquad (3.4)$$

where ς is referred to as the reduced time or shifted time and A (see equation (3.7)) is the shift function at a temperature T.

2.2. Structural relaxation

Structural relaxation refers to the fact that the thermal expansion not only depends on temperature but also on temperature history. Figure 3a shows the change in volume during cooling through the glass transition. The glass transition temperature T_g is defined as the temperature at which the slope dV/dT changes from the high value characteristic of the liquid, α_l, to the low value characteristic of the glass, α_g, where α represents the coefficient of volumetric thermal expansion. The dashed line represents the volume of the liquid in equilibrium. The slower one cools, the longer one stays on this line of equilibrium. Thus, the glass transition is a kinetic effect and the glass transition temperature depends on the cooling rate, as shown in Figure 3b. This figure also indicates that the instantaneous volume not only depends on the instantaneous temperature but also depends on the temperature history.
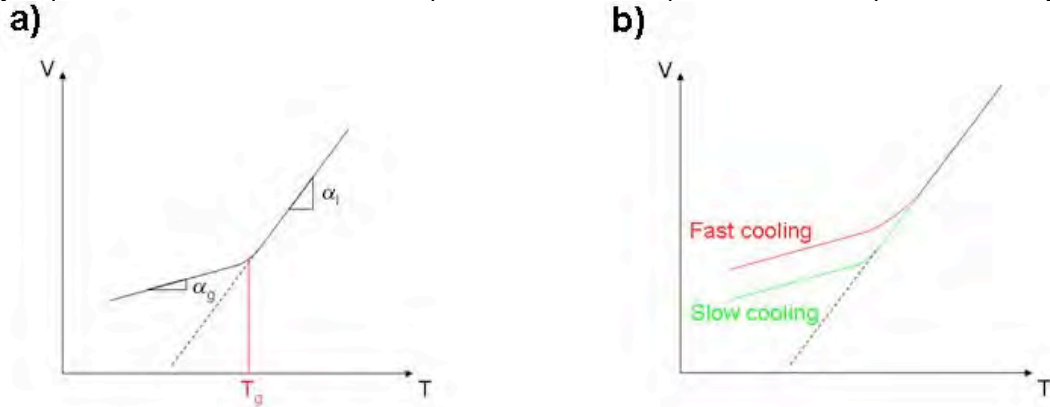

Figure 3 – a) Definition of glass transition temperature T_g, b) Influence of cooling rate on T_g

In fact, the cooling rate and the temperature history influence the state of the structure of the glass, which in turn, influences the thermal expansion and the stress relaxation behaviour. In 1946 Tool [4] introduced the ficticious temperature T_f to characterize the state of the structure of the glass:

$$T_f(t) = T(t) - \int_0^t M_v\left[\varsigma(t) - \varsigma(t')\right]\frac{dT(t')}{dt'}dt' \qquad (3.5)$$

With M_v the volume relaxation function [5] and ς the shifted time, which can be computed as:

$$\varsigma(t,T,T_f) = \int_0^t A(T(s),T_f(s))ds \tag{3.6}$$

with A(T,Tf) the shift function, which is defined as:

$$\ln\left(A\left(T,T_f\right)\right) = \frac{H}{R_g}\left(\frac{1}{T_R} - \frac{x}{T} - \frac{1-x}{T_f}\right) \tag{3.7}$$

with H the activation energy of the enamel, R_g the universal gas constant, T_R the reference temperature, i.e. the temperature at which the stress relaxation function is measured, and x a constant (0 < x < 1), which defines the impact of the structural state on the shift function. Then the volume V_t can be computed as:

$$V_{t,2} = V_{\infty,1} - \alpha_g\left(T_f - T_2\right) - \alpha_l\left(T_1 - T_f\right) \tag{3.8}$$

With $V_{t,2}$ the instantaneous volume at temperature T_2 and $V_{\infty,1}$ the equilibrium volume at temperature T_1. Narayanaswamy generalized Tool's work [2] and stated that the response function $M_v(t)$ should be of the form:

$$M_v\left(\varsigma\right) = \sum_{i=1}^{n} C_i \exp\left(-\varsigma/\lambda_i\right) \tag{3.9}$$

With C_i a weight factor related to a relaxation time λ_i ($\Sigma C_i = 1$).

2.3. FEA implementation

Markovsky and Soules [6] developed an efficient and stable algorithm to compute the ficticious temperature T_f:

$$T_f^i(t) = \frac{\lambda_i T_f^i\left(t - \Delta t\right) + T(t)\Phi_v \Delta t}{\lambda_i + \Phi_v \Delta t} \tag{3.10}$$

With

- T_f^i the ith ficticious temperature

- $\Phi_v = \exp\left(\frac{H}{R_g}\left(\frac{1}{T_R} - \frac{x}{T(t)} - \frac{1-x}{T_f(t-\Delta t)}\right)\right)$

The actual ficticious temperature T_f can then be computed as:

$$T_f(t) = \sum_{i=1}^{n} C_i T_f^i(t) \tag{3.11}$$

The above algorithm was implemented in the FEA code Abaqus via user subroutines.

3. Klotz test

3.1. Introduction

In this section it will be verified if the above described equations, indeed allow to accurately describe the mechanical behaviour of the enamel, by comparing an experimentally measured Klotz curve to a simulated one. The "Klotz" test, named after the German company who build the first testing device to measure deflection in steel-enamel composites, is a device in which an enameled steel sample (see Figure 4) is heated through Joule effect. During the test one measures the temperature at the enamel surface at the point indicated by the orange circle. It should be noted that the temperature will not be constant over the enamel layer. The temperature is measured by an infrared pyrometer, while the tip displacement (blue circle, displacement is measured along the Z-direction) is measured with a Linear Variable Displacement Transducer (LVDT). It should be noted that, up to now, Klotz tests were always performed on pre-enameled samples. The new device that was recently installed at ArcelorMittal Global R&D Gent, allows simulating the complete firing cycle.

Klotz samples are prepared as follows: a ground layer (green layer in Figure 4) is applied at both sides of the steel sample (red layer in Figure 4). Then a thick layer of top enamel (light grey layer in Figure 4) is applied at the back of the sample, only in the central part. In general, the steel layer is 1.5 mm thick, while the ground layers are about 100 μm thick. The top layer has a thickness of around 300 μm.

During the test both ends of the U-shaped sample are clamped. It should be noted that the sample is put vertically in the device. Then a potential difference V is applied so as to generate a current inside the sample. Due to the Joule-effect, the sample is then heated. When using pre-enameled samples, the samples are usually heated to 600°C à 650°C to make sure that all stresses in the enamel and steel layers have been relaxed. Sometimes the temperature is kept constant at this high value for about 30 to 60 seconds. Then the sample is cooled (no active cooling).

Figure 5 shows a typical temperature-displacement curve which results from the Klotz-test and indicates some typical values which can be deduced from the measured curve:

- The red solid line represents the temperature-displacement curve during heating.
- The blue solid line represents the temperature-displacement curve during cooling.
- One can deduce the transition temperature T_g of the enamel (magenta point)
- The neutral temperature T_n (green point) of the steel-enamel composite can be determined as the lower crossing point of the zero-line (orange dashed line) with the cooling curve. The zero-line can only be determined after the test, as one first has to heat the sample (> 600°C) so as to relax the stresses inside the enamel and steel layers in order to remove all deformation.
- The value f_d is a measure for the maximum compressive stresses inside the enamel layer, while the value f_z is a measure for the maximum tensile stresses which arise in the enamel during cooling.
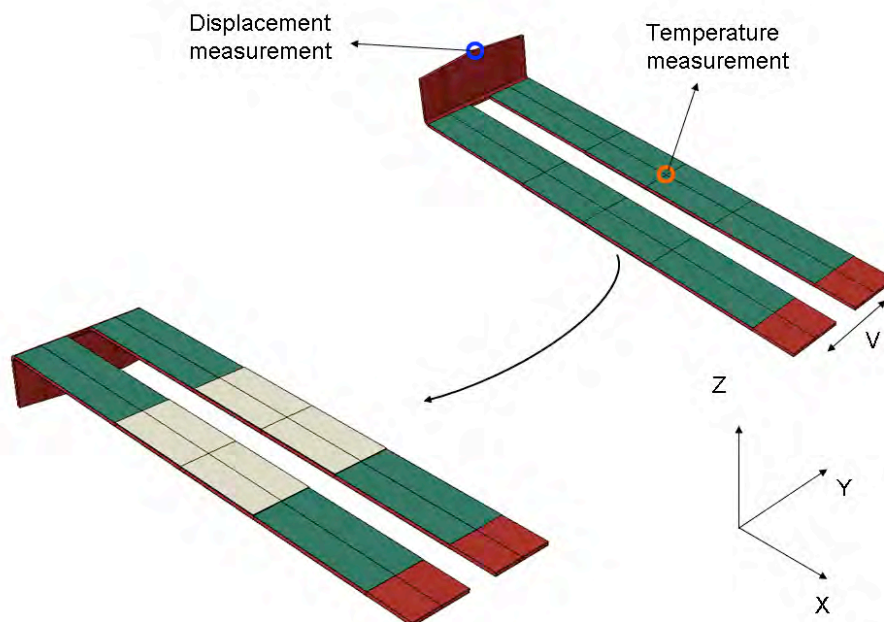

Figure 4 - U-shaped sample which is used during Klotz test: the red layer indicates the steel sample, the green layers indicate the ground enamel and the light grey layer indicates the top enamel.
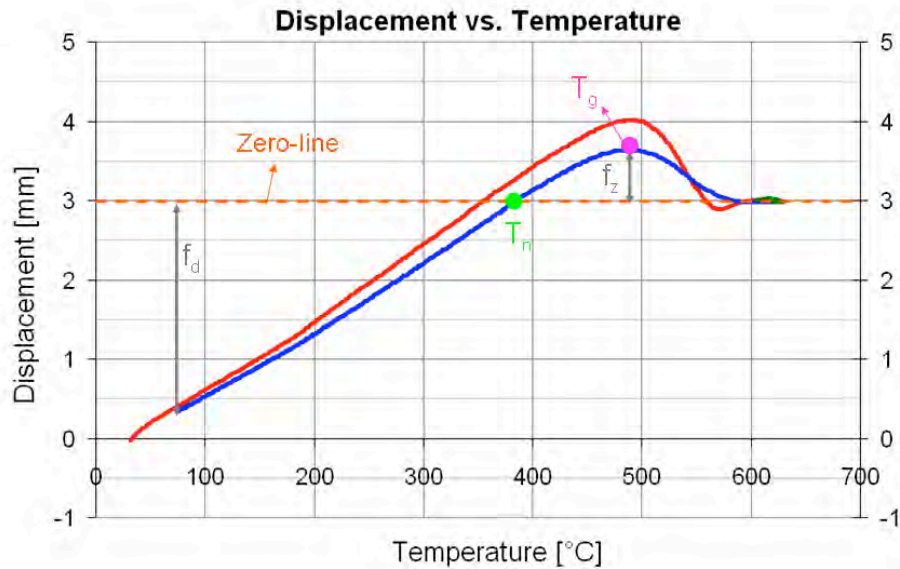
Figure 5 - Typical Klotz-curve and indication of some characteristic values: the red curve indicates the heating cycle, while the blue curve indicates the cooling cycle.

3.2. Comparison: FEA vs Experiment

The Klotz test was simulated by means of a sequentially coupled temperature-displacement analysis. Composite shell elements were used to model the enameled steel part. The mechanical behaviour of the enamel was described by means of the equations summarized in Section 2. The mechanical behaviour of the steel was described as follows:

- Temperature dependent Young's modulus
- Temperature dependent hardening behaviour (von Mises yield surface)
- Temperature dependent expansion coefficient

Figure 6 compares the experimentally measured Klotz curve to the simulated curve. The experimental and numerical curves are very similar. Therefore it can be concluded that the implemented mechanical model accurately describes the behaviour of enamel in a broad temperature range and allows simulating the complete firing cycle.
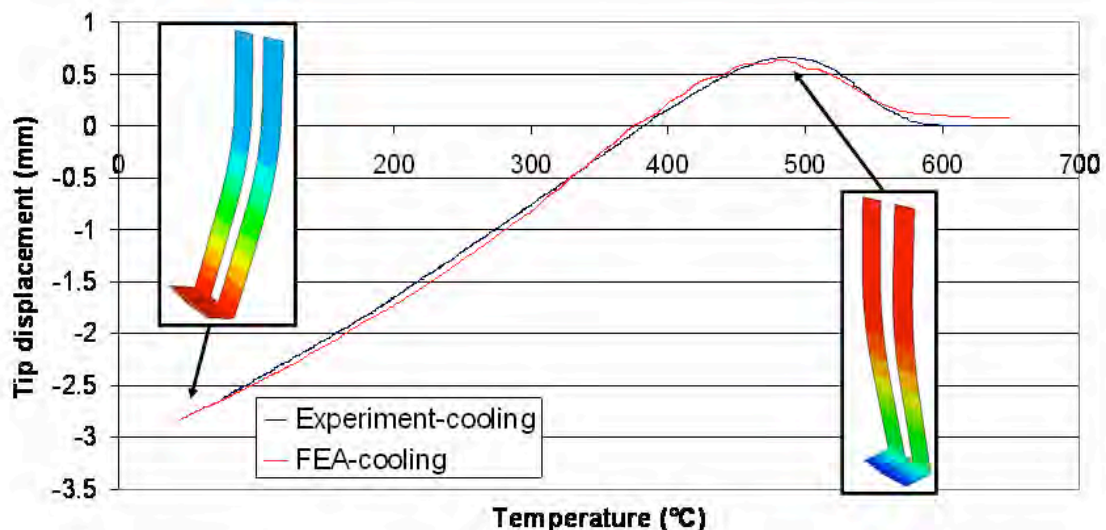

Figure 6 - Comparison of experimental and numerical Klotz curves. For clarity, only the cooling curves have been plotted.

Figure 7 plots the evolution of the longitudinal stress through the thickness of the Klotz sample at room temperature. This figure clearly indicates that the stresses inside the enamel are compressive stresses, while the stresses inside the steel are mainly tensile stresses.
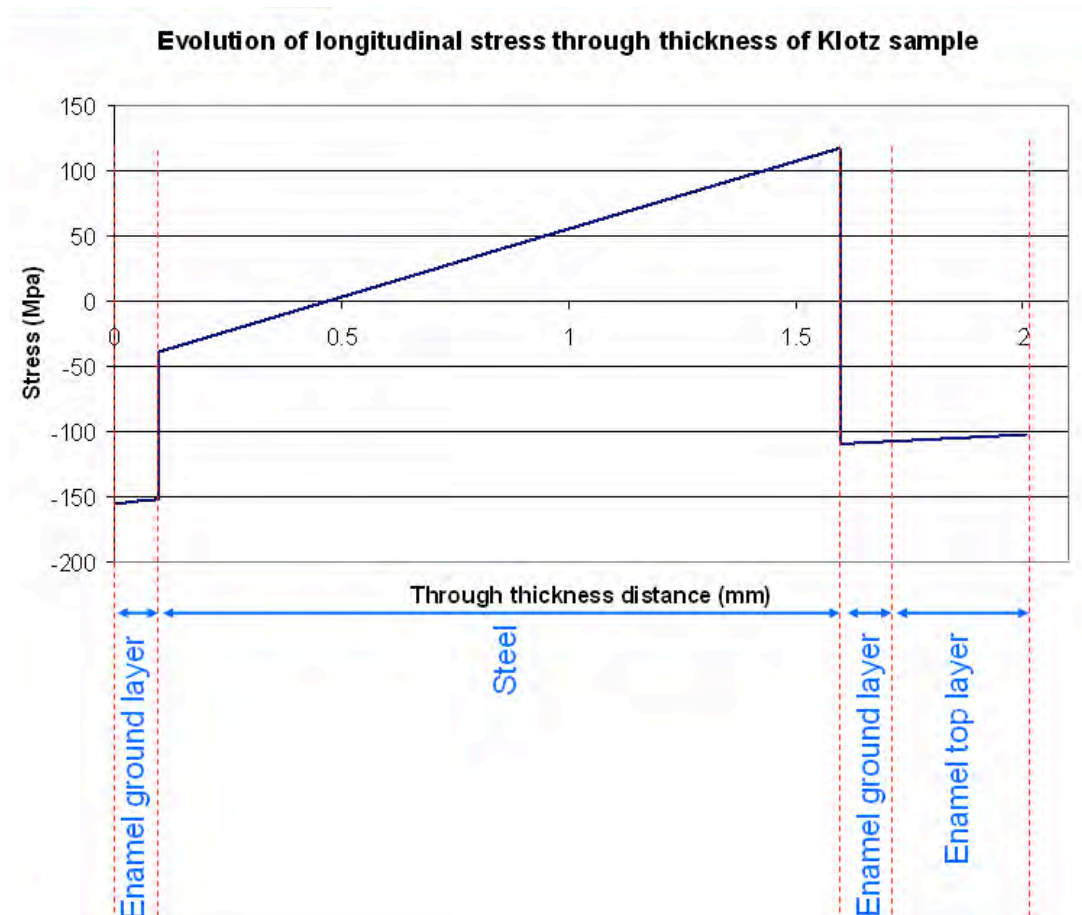
Figure 7 - Evolution of longitudinal stress through thickness of Klotz sample at room temperature

4. Case study: warping of enameled baking tray

4.1. Experimental set-up

In general, baking trays are slender structures. Therefore they might suffer from warping after enameling. An experimental study was launched to investigate the influence of several parameters on the warping defect and to further validate the FEA procedure.

Figure 8 shows the baking tray that was used in this study. It has overall dimensions of 250 mm x 330 mm X 0.5 mm and is made out of DC03ED (Solfer). Two depths were considered: 5 mm and 10 mm. After deep drawing, a pyrolitic enamel was applied at both sides of the baking tray. The thickness of the enamel layer, however, was varied. Three different situations were considered: 250 µm at the front and 50 µm at the back, 50 µm at the front and 50 µm at the back and 50 µm at the front and 250 µm at the back. Finally the baking tray was heated in a tunnel furnace (4 minutes at 850°C). Each experiment was repeated 3 times.

The warping defect was measured by fitting a plane through 3 corner points and by determining the distance from the 4th point to this plane (see Figure 9). The warping defect was measured before and after the enamel firing cycle, so as to isolate the warping defect caused by the enameling process.

Figure 8 - Geometry of baking tray (overall dimensions: 250 mm x 330 mm)
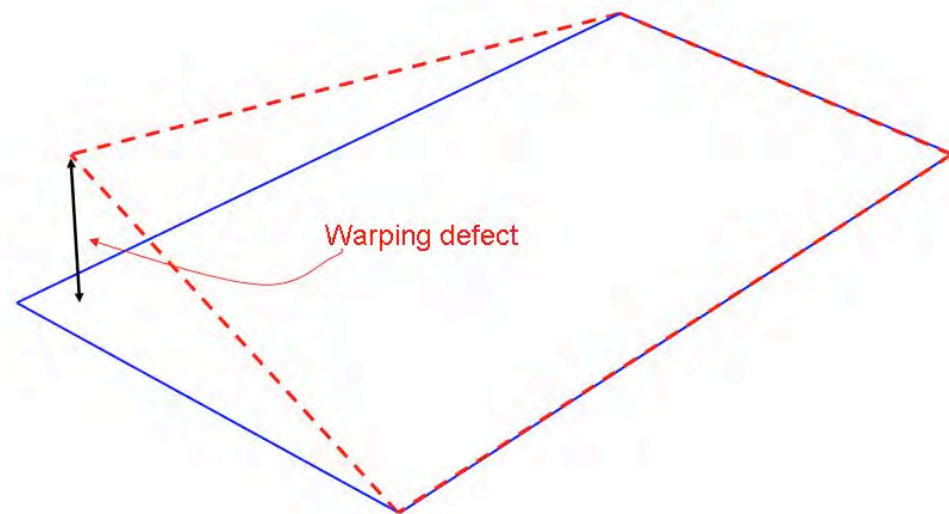

Warping defect

Figure 9 - The warping defect was measured by fitting a plane through 3 corner points and by determining the distance from the 4th point to this plane.

4.2. FEA procedure

Figure 10 schematically summarizes the adopted FEA procedure:

- Forming step:
  - The deep drawing operation was simulated by means of Abaqus/Explicit. In general, an explicit analysis will be less computationally expensive – compared to an implicit analysis - to simulate forming processes.
  - Next, springback was computed by means of Abaqus/Standard by transferring the material state (stresses, strains and state variables) and the sheet thickness from Abaqus/Explicit.
- Enameling step
  - Heating of the deformed steel sheet up to 850°C (again taking into account the residual stresses and strains obtained after springback)
  - Adding the layers of enamel by changing from a standard shell section to a composite shell section (again the stresses and strains existing in the steel layer are transferred). *Remark: The enamel layer only starts to build up stresses during cooling. Therefore it is only added at the peak temperature.*
  - Cooling to room temperature
  - It should be noted that the enameling step was simulated by means of a sequentially coupled temperature-displacement analysis.
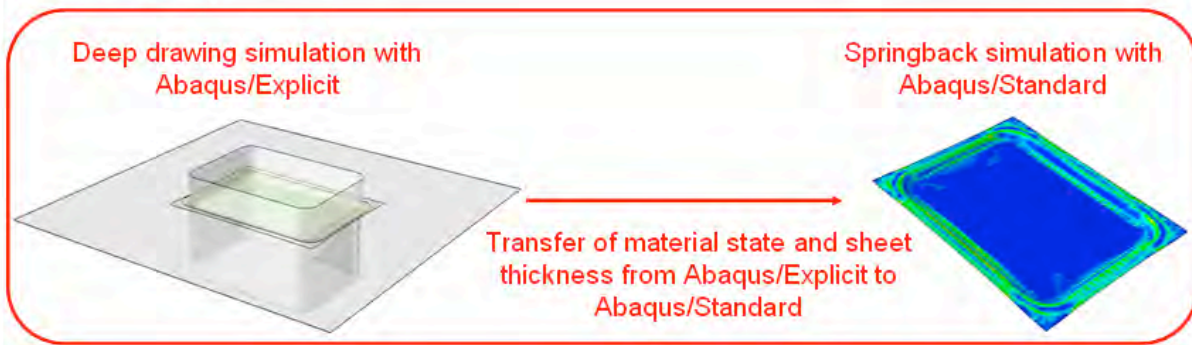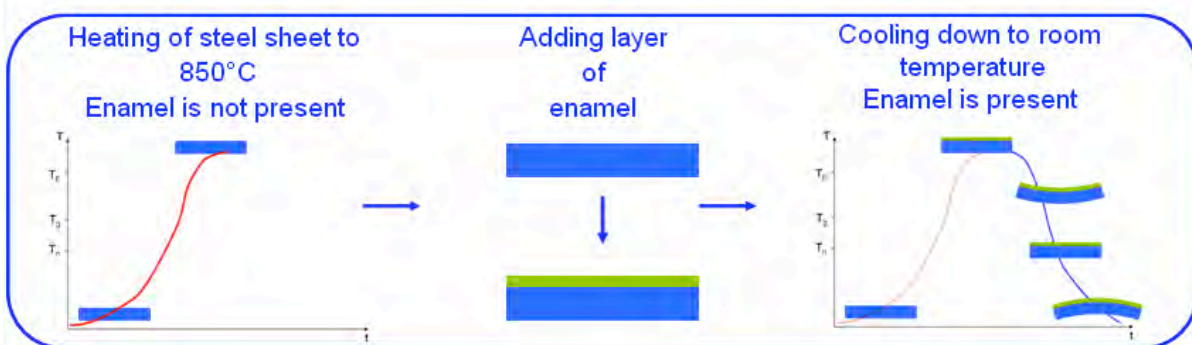
Figure 10 - FEA procedure: simulation of forming process and enamel firing cycle

4.3. Results

The results are summarized in Figure 11. This graph plots the influence of the deep drawing depth (5 mm and 10 mm) and the enamel thickness on the warping defect generated by the enamel firing cycle and compares the FEA predictions to the experimental results.

The warping defect is plotted as the difference in warping before and after enameling, i.e. (warping defect after enamel firing cycle) – (warping defect after springback). The x-axis plots the difference in enamel thickness between front and back.

From this graph the following conclusions can be drawn:

- The FEA predictions are in good agreement with the experimental results
- The deep drawing depth has a clear influence on the generated warping defect, which is quite obvious: the deeper the tray, the stiffer it behaves.
- Apparently, applying a thick layer of enamel at the back causes the larger warping defect.
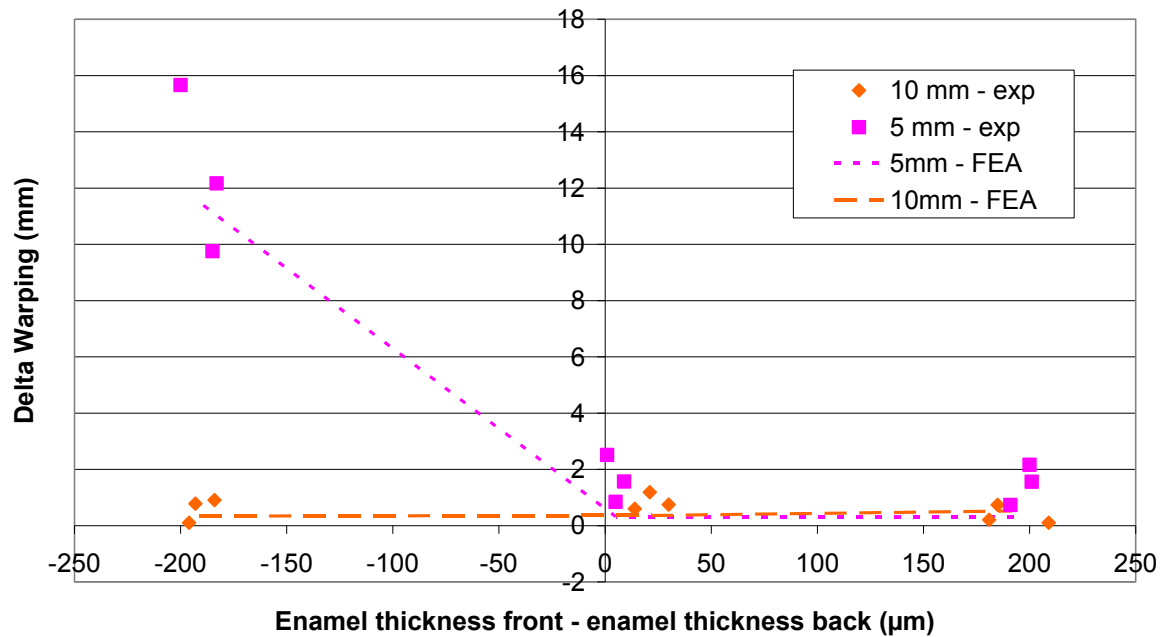
Figure 11 – Comparison between experiment and FEA: influence of deep drawing depth and enamel thickness on warping defect

5. Conclusions and Future Work

This paper presents a comprehensive description of the mechanical behaviour of enamel and its FEA implementation and proposes a FEA methodology which allows simulating the complete cycle of sheet metal forming, springback and enameling, taking into account the enamel solidification process.
The presented methodology was validated based on two case studies: simulation of the Klotz test and prediction of warping of small baking trays.
Future work consists of taking into account the phenomena of stress relaxation and creep in the steel layer, as those phenomena are most probably activated during the enamel firing cycle.

6. References

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