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Influence of the temperature cycle on local distortions in car panels caused by hot curing epoxies

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ABSTRACT

Adhesive bonding is becoming a more and more important joining technology in automotive industry. Hot curing epoxy adhesives are often used for structural bonds of car body shells. The cure process of the adhesive, however, can cause panel surface distortions. These distortions can occur close to the bond-line (local distortions) or concern the whole geometry of a part (global distortions). In order to avoid these defects, a fundamental understanding of how distortions develop is needed. In this work, the development of distortions is monitored over entire temperature cycles by means of a displacement measurement. The focus is on how different cure temperatures and heating rates affect the development and the final state of local distortions. It was found that distortions can already develop in the heating phase before the cure temperature is reached. Changes in the heating rate influence the development of distortions.

1. Introduction

Hot curing one-component epoxy adhesives are often used in automotive industry. They provide excellent chemical resistance, high strength and a good oil absorption needed in the manufacturing process of car bodies. Furthermore, the elevated temperature needed for the cure process of the adhesive is reached during the heat treatments for the baking process of the coatings. Thus, apart from a pre-cure treatment additional time-consuming steps do not need to be integrated in the manufacturing process.

One of the main challenges of adhesively bonded car body shells is the prevention of surface defects. These defects develop during coating [1] or, in an even earlier stage, during bonding: the cure process of the adhesive can cause distortions, i.e. unwanted, visible deformations of the adherends. Distortions can not only occur close to the adhesive bond lines (local distortions), they can also affect the overall geometry of a structure through bulging effects (global distortions).

In order to prevent these distortions by means of proper control of the bonding process, a fundamental understanding of how the distortions develop over time is essential.

1.1. Literature review

The goal of this research is to monitor how local distortions caused by one-component epoxies develop during cure over different temperature cycles.

Eis [2] investigated the mechanisms that cause surface distortions during the adhesive bonding process of car body shells. He names squeeze-out of the adhesive from the bonding area (where the squeezed out adhesive shrinks and bends the upper panel over an edge of the lower on), the chemical shrinkage of the adhesive, the thermal shrinkage of the adhesive during cooling down and an in-homogeneous temperature distribution of the assembly, which leads to relative movements of the adherends, as causes for panel distortions. He provides strategies for different deformation cases to reduce distortions, including measures as lowering the cure temperature, reducing the adhesive squeeze-out or reducing temperature gradients in the structure.

Experimental investigations on bonding defects and panel surface distortions mainly focus on a state after manufacture [3–7]. In that state the development of distortions is already completed. Only in a few works distortions are monitored over time when the adhesive material is chemically reacting under temperature changes: Hahn and Jendrny [8] monitored distortions by means of a displacement measurement over time, but only for one specific temperature profile. The authors did not address the influence of the temperature rate during the heating phase on the

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final distortions. Eis [2] monitored distortions caused by foaming polyurethanes for different temperature rates. These adhesives expand during the setting process in order to bridge larger bonding gaps. He concluded that, for specific adhesives, the rate can affect the foaming, i.e. expansion, process and, therefore, influence the final distortion after the cure cycle. One-component epoxies were not investigated.

Besides experimental research, there have also been several different approaches to predict deformations due to curing epoxies. Some prediction models are based on linear elastic material behavior [9–13]. In other approaches viscoelastic properties are assumed [7,8,14], but the stress development during the heating phase was neglected. The assembly was assumed to reach the elevated maximum temperature in a stress-free state and to stay stress-free until the cooling down phase starts. The cure process was neglected. For residual stresses, only the cooling down phase was taken into account. Some authors found the glass transition temperature to be the stress-free temperature in sandwich structures [15]. In other publications, temperature dependent and degree of cure dependent viscoelastic material laws are proposed [16,17]. With these models the stress build-up during the entire temperature cycle, i.e. also in the heating and the holding phase, can be taken into account. However, to apply this approach to a specific adhesive many characterization tests are necessary, since material parameters need to be determined as functions of temperature, time and degree of cure. With regard to car panel distortions, the question arises if the newer approaches offer better predictions and if they describe the process more realistically. The lack of experimental data for the entire development process of distortions limits an analysis of this topic.

1.2. Research question of interest

The cure process is accompanied by different parallel processes: On a microscopic level, the polymer chains cross-link to a dense network. Macroscopically, this leads to an increase in the mass density, i.e. chemical shrinking occurs. The mechanical properties of the adhesive change as well. An increasing temperature leads to a decrease in the viscosity. The progress in cure increases the viscosity. In addition, the adhesive transfers from a viscous fluid to viscoelastic solid. It develops the ability to sustain static load other than hydrostatic, i.e. an equilibrium shear modulus develops. Moreover, geometrical changes of the entire structure occur due to temperature changes. The adhesive and the adherends expand and shrink thermally.

The combination of these processes lead to stresses in the materials and between the adhesive and the adherends. If these stresses are big enough, they will force the steel sheet to deform, i.e. panel distortions occur.

The cure process is temperature dependent. Therefore, changes in the temperature cycle, e.g. a different temperature rate during heating or a different (maximum) cure temperature, are expected to affect the development and the final state of distortions. Therefore, the following questions arise:

- How do local distortions develop during a temperature cycle?
  - Are current models able to describe this development?
  - When do distortions start to occur? Does the temperature rate affect this point?
- How does the temperature cycle affect the final distortion?
  - How does the maximum temperature (holding phase) influence the remaining distortion?
  - How does the temperature rate in the heating phase influence the final distortion?

2. Strategy

In order to answer the research questions, the development of local distortions in a steel sheet will be monitored over time for different temperature cycles.

Car panel distortions result from a three-dimensional displacement field in a complex structure. Capturing the displacement function for each material point of a body over the entire cure process would lead to both experimental difficulties and challenges in data analysis. The approach chosen here is to perform displacement measurements on a test specimen that is a simplified representation of a bond line in a situation in which local distortions occur. Fig. 1 shows a drawing of such a scenario. While in a liquid state, the adhesive is squeezed out at the edges of the bond line. Subsequent shrinkage due to cross-linking or cooling pulls down the upper panel and causes distortions [2].

The displacement curve of a single point of a steel sheet right above a bond line is monitored. This out-of-plane displacement is caused by the changing properties of the adhesive. Assuming the adhesive causes distortions by displacing the sheet locally at the bond line, the displacement curve obtained indicates how distortions in the entire panel develop over time. The test is performed for different temperature cycles.

3. Experiment and displacement estimate

3.1. Specimen

The test specimen is an assembly of an aluminum substructure (see Fig. 2) and a steel sheet. The steel sheet with the dimensions 20 mm × 85 mm × 0.70 mm is placed on top of the substructure above the 2-mm-deep bonding gap. Two aluminum blocks, screwed to the substructure, prevent the steel sheet from lifting upwards but allow an in-plane movement (no clamping) of the steel sheet in the longitudinal direction (see photograph in Fig. 3). A 10-mm-broad line of adhesive is applied between steel sheet and substructure. The out-of-plane (y-direction) displacement d of the central point of the steel sheet above the adhesive bond line is recorded (see Fig. 3).

3.2. Materials

The substructure with the two blocks are made of Aluminum 6082. Steel DX54D+Z from Tata is used for the sheet. The adhesive

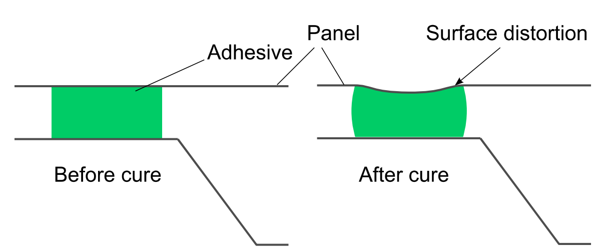

Fig. 1. Local panel distortion resulting from adhesive cure [2].

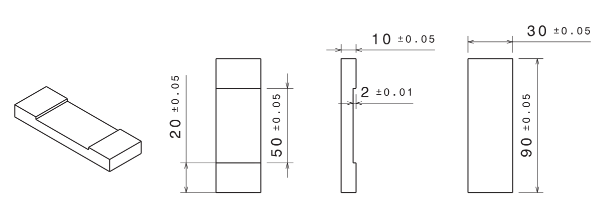

Fig. 2. Dimensions of the substructure of the specimen in millimeters.