**EXPERIMENTAL INVESTIGATION OF PROCESS INDUCED DEFORMATIONS OF AUTOMOTIVE COMPOSITES WITH FOCUS ON FAST CURING EPOXY RESINS**

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**Abstract**

Due to the non-isotropic nature of carbon fibre reinforced plastics (CFRP) unavoidable deformations occur during part production. These deformations often lead to dissatisfaction of tolerances or result in cost and time intensive rework of the tooling. In a cost driven production environment, similar to the automotive industry, it is essential to predict the deformations beforehand in order to compensate the used tooling. In future applications Fast Curing Epoxy Resins (FCER), with curing times of less than 20 minutes, will play a key role in order to enable high rate CFRP-production at lower cost. Until now, minimal experimental data exists for FCER systems. The present paper reports on a comprehensive experimental study on different FCER systems. It includes the characterization of neat resin samples as well as the quantification of the spring-in deformation of different L-profiles. Additionally, a study of parameters such as lay-up, temperature, cooling rate and fibre volume fraction concerning their influence on the process induced deformations is performed. Finally, the results are compared to slower curing systems. The findings of the study are relevant for the future development of robust prediction methods for process induced deformations of FCER-based composites.

1 INTRODUCTION

In order to meet strict emission reduction targets and to enable electro mobility it is essential to reduce the structural weight of future automobiles. An effective way to accomplish that reduction is the increased use of CFRP parts. Compared to branches like aerospace industries, sports goods production or the wind energy branch where the use of composites is already quite established, new questions arise. In particular the challenges of large scale production, more complex geometries and more strict tolerances have to be faced. Figure 1 shows a car structure with a B-pillar made of CFRP. The multi material mix used in that construction is exemplary for the complex nature of recent car designs. In order to guarantee precise and cost efficient assembly, CFRP parts must reach a high level of dimensional fidelity. Deformations that occur during part production have to be foreseen and counteracted on a virtual state early on in the part design process. Therefore it is necessary to understand and examine the mechanisms leading to deflections of the components during manufacturing.

The present paper is focused on fast curing epoxy resins (FCER) with processing times of less than 20 min. These systems are essential to enable high rate production of CFRP parts and to be able to compete economically with classical metal processing. Until now only minimal experimental data exists concerning FCER.

CFRP B-pillar



Figure 1: Car structure with CFRP B-pillar. Source: AUDI AG.

There are three different physical mechanisms causing deformations during CFRP production:

**Asymmetry:** As described by many authors a global, asymmetrical lay-up (e.g. fibre direction pure 0°/90°) leads to shape distortions due to the curing process and under temperature loading of a part. Even flat plates show severe deformations caused by coupling of in-plane strains and out-of-plane bending moments [22]. Besides global asymmetry, local asymmetry can also lead to undesired deformations. As described in [18] a local fibre volume gradient in through-thickness direction of a laminate results in a deflection of the part. The physical mechanism causing that deformation is the same coupling effect as in case of global asymmetry. This is also valid for a local gradient of degree of cure (DOC) [4], neat resin areas [10], local asymmetric fibre misalignment [2] and other possible effects in through-thickness direction of laminates. Examples for local asymmetry effects are depicted in Figure 2(a).

**Part-tool-interaction (Warpage):** Another physical source for process induced deformations is the interaction between the tooling equipment and the composite part. Usually the tooling material has a much higher coefficient of thermal expansion (CTE) than the laminate. At process temperature, in single-sided tooling setups, which are normally used in autoclave processes, this leads to a stretching of the composite layers close to the mould. This mechanical interaction (via friction) between the two partners induces tensile stresses in the tool-close-layers of the composite. During cure these residual stresses are “frozen” into the part and lead to a distortion concave to the tooling after cool down and demoulding (Figure 2 (b)). In the work of Albert and Fernlund [1] this effect is referred to as warpage or flange warpage to separate it clearly from the spring-in effect which only occurs in curved part areas and which is explained in the next section. Warpage can also occur in flat parts. The introduced nomenclature will also be used in this paper to differentiate between the sources of distortion.



Figure 2: (a) Examples for local effects leading to additional deformations (decrease of enclosed angle). (b) Warpage effect due to part tool interaction.

**Anisotropy (Spring-In):** The anisotropic nature of composites leads to another form of distortions [17]. During the curing process of a composite part the matrix material experiences considerable shrinkage whereas the fibre lengths remain nearly constant. In the compound this difference leads to smaller strains in fibre direction and comparatively higher strains in direction transverse to the fibres. Thus, for typical laminates, the matrix dominated trough-thickness strains are much higher than the occurring in-plane strains (|*εr*| >> |*εt*|). In curved part areas this characteristic leads to a considerable thickness reduction whereas the arc length in the curved area remains nearly constant. After demoulding an unavoidable decrease of the enclosed angle *φ'* is the result (Figure 3). The cure shrinkage of the matrix, which is the main driver of this mechanism, consists of two portions: chemical cure shrinkage which is caused by the formation of polymer chains during consolidation and thermal shrinkage which develops during cool down from process to room temperature [19]. In literature the described effect is referred to as spring-in phenomenon [1].



Figure 3: Spring-in deformation of an L-profile.

Focus of this work is the examination of this spring-in phenomenon which was identified as most relevant for applications in the automotive industries. Single-sided tooling setups are rare in a high rate production environment. Instead closed mould RTM and prepreg press technology are mainly used. The three aforementioned mechanisms are sources for process-induced deformations. Nonetheless, local/global asymmetry will be addressed in future work and remains disregarded in the present paper.

2 Background

In most state of the art processes the described deformations are unsatisfactorily considered. This often leads to severe violation of tolerances and makes assembly of the affected parts impossible. In consequence expensive rework of the tooling or the parts is necessary. Sometimes even a reconstruction of the mould is needed which is not only very cost but also time intensive. In the past decades there has been a lot of work on process induced deformations of composite parts. Many aspects have been investigated by different researches. Nevertheless, only limited data exists regarding the closed mould RTM process [23]. The majority of the authors concentrated on prepreg systems classically used in aerospace applications. Nowadays, no published data exists concerning FCER.

Several parameters and their influence on the spring-in effect in composite parts have been examined in previous work. Following the definition given by Albert and Fernlund [1] they can be divided into two groups: intrinsic parameters and extrinsic parameters.

**Intrinsic Parameters:** A proportional dependency between the desired part angle *φ'* and the induced deformation ∆*φSPI* could already been shown in early publications. Radford et al. [19] developed the geometrical relation:

|  |  |
| --- | --- |
|  | (1) |

wherein *εt* and *εr* is the strain during processing in tangential respectively in radial direction of a curved composite part. According to equation (1) the only geometrical parameter influencing the spring-in-deformation is the enclosed angle. Neither the part thickness nor the radius of the curved laminate has a considerable impact on the resulting deformation. In case of the part thickness these findings were verified in [21]. Bapanapalli et al. [3] detected a weak dependency between thickness and deformation for thin parts. The independency from the corner radius was confirmed by [7] and [20].

The influence of the laminates’ lay-up on the process induced deformations was also studied by many researchers and a lay-up dependency could be verified in all of them. Laminates with a high degree of anisotropy e.g. UD-laminates showed a higher dependency whereas quasi-isotropic laminates showed a weak or no dependency [14]. Analytical prediction methods based on the classical laminate plate theory (CLPT) estimating the influence of this lay-up dependency were qualitatively in good accordance with experimental findings [18].

Another influencing factor is the fibre volume fraction (*Vf*). Several publications showed a sensitive reaction of the shape distortions to a change in *Vf* [10, 13]. CLPT based approaches to predict corresponding deformations were given by [11].

One of the most relevant parameters influencing the process induced deformations is chemical cure shrinkage [19]. This chemical contribution to the overall shrinkage can be attributed to the formation of polymer chains during the consolidation of the matrix. The magnitude of the cure shrinkage depends on several different factors and varies widely with the selected matrix system and the used fibre material. Different modelling approaches and measuring techniques have been chosen to account for that effect. There is still no universal solution to the problem. No definite measuring method exists to determine either the pure resin shrinkage or the through-thickness shrinkage of arbitrary composite. As a consequence chemical shrinkage is still subject to many ongoing studies. Considering FCER, literature sources suggest that the expected cure shrinkage is considerably higher than in case of classical slower curing systems [22] which would lead to higher spring-in deformations. Until now, no experimental data exists to support or contradict that hypothesis.

**Extrinsic Parameters:** Extrinsic parameters are mainly affected by the applied process cycle and the used tooling. One of these parameters is the process temperature. A number of publications found it to be proportional to the resulting spring-in angle [18, 21]. The difference between the process temperature and ambient temperature determines the absolute value of the thermal contribution to the overall deformation. The thermal component is reversible and also leads to distortions during operation of curved CFRP parts when exposed to thermal loading.

Another parameter studied by many researches is the cooling rate. It is discussed controversially in literature. Some authors attribute different deformations to different cooling rates [24] whereas others detect no difference after a freestanding post cure [21]. Further work is needed to verify the influence of the cooling rate.

The influence of the curing time was also investigated by some authors [24]. A dependency between spring-in angle and curing time could be found if the maximum degree of cure was not reached. If the resin is not fully cured the chemical shrinkage is proportional to the resin’s degree of cure [4].

The warpage deformations resulting from tool-part-interaction described in section 1 are mainly driven by the properties of the tooling material. Especially the CTE of the mould influences the resulting deformations. Previous work has shown that deformations increase if the difference between the CTE of the tool and the CTE of the composite part is high. If the CTE of the tool is in the same order of magnitude as the composites (e.g. in case of invar tooling) the warpage deformations become negligible. Generally, warpage deformations were found to be relevant only for thin parts up to a thickness of 2.5 mm [5, 13]. For thicker parts the increasing part stiffness prevents warpage distorsions. Double-sided tooling setups are not prone to induce warpage deformation. In that case the residual stresses described in section 1 are induced symmetrically and balance out which leads to no significant additional deformations [13].

**Goals of the paper as result of the literature study:**

* Conduction of a parametric study using closed mould RTM-technology and FCER. No published data could be found for that combination regarding process induced deformations. Especially effects discussed controversially in literature (e.g. cooling rate) are to be examined.
* Quantification of spring-in deformations for different FCER systems and relating the results to classical slower curing systems.
* Use of simple analytical models to predict the spring-in deformations in order to evaluate the quality of such methods for FCER.

3 ANALYTICAL

Linear thermo elastic models were used in order to estimate the expectable spring-in angles of a CFRP-L-profile. Two different CLPT-based modelling strategies were implemented within a MATLAB code. The general schematic sequence of both approaches is shown in Figure 4.



Figure 4: Flowchart of analytical calculations.

Both start at a micro mechanical level where fibre and matrix properties are combined by using rules of mixture from literature [22]. The resulting thermo-mechanical properties of a single unidirectional (UD) layer are subsequently used in a CLPT-based deformation analysis. As thermal loading of the laminate the temperature difference ∆T between process and ambient temperature is chosen. No further external mechanical loads are considered. The result of that analysis is the strain state of the laminate due to thermal loading. To account for the thermal strains in thickness direction it was assumed that the global CTE transverse to the laminate is equal to the CTE transverse to the fibre direction in a single UD-layer (*αT*┴,*UD* = *αTglob,z*). As a last step, in order to predict the deformations of a CFRP-L-profile, the Radford-Approach (eq. (1)) is used. The values for the strains in tangential direction (εt) respectively in radial direction (εr) are obtained from the analysis described above. The equation gives the resulting deviation ∆*φSPI* = *φ*' - *φSPI* from the nominal angle φ' (see Figure 3).

Chemical shrinkage was considered using two different modelling approaches: The first method was implemented analogous to Darrow and Smith [5] who suggested adding a chemical component to the CTE of the matrix αM'to account for cure shrinkage. This addition is made before using rules of mixture in the micromechanical step of the procedure. The modified CTE *αM* is given by:

|  |  |
| --- | --- |
| , | (2) |

wherein Δ*T* is the temperature difference between process and ambient temperature and *Vc* the volumetric reduction of the neat resin. The advantage of the outlined strategy is that strains of UD-layers occurring parallel to the fibres can be considered.

The second modelling strategy follows the approach used by Kappel [13]. In that approach the chemical shrinkage is taken into account as additional strain of a unidirectional layer. The assumption is made that there is no strain due to cure shrinkage parallel to the fibre direction (*ε*║ = 0), all volumetric shrinkage is contributing entirely to the transverse strain *ε*┴,UD of the layer. Considering the fibre volume fraction *Vf* this leads to the equation:

|  |  |
| --- | --- |
|  | (3) |

The additional negative strain of the separate UD-layers is introduced into the CLPT-analysis analogous to classical thermal strains. This strategy bears the advantage that the chemical shrinkage is considered after the micromechanical step. Therefore it is possible not only to use characteristic quantities of fibre and resin separately but also to use test results from UD or biaxial samples.

The analysis is conducted in order to estimate the influence of different modelling parameters onto the spring-in deformations of an L-profile. A special focus lies on the fibre volume content and its effect on process induced deformations. Exemplary results for both used modelling strategies are depicted in Figure 5. Both graphs show the predicted spring-in angle over the fibre volume content. Besides the total spring-in deformation the chemical and thermal component given by the model are shown. The material data given in Table 1 for the *Momentive Epikote 05475* system is used for the calculations. A lay-up of [(-45/+45)2(90/0)]S is considered. As thermal loading the temperature difference between process temperature T*process* = 115°C and the ambient temperature T*ambient* = 25°C is taken into account (∆T = -90°C). As relative volumetric shrinkage the measured value from a rheometric cure shrinkage analysis is used, which revealed a post-gelation shrinkage of *VC* = -0.025 (see section 4.1).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Property | Unit | Fibre T620 | Matrix Epikote | Matrix RTM6 | Source |
| Fibre | *Ef*║ | [N/mm²] | 230000 | – |  | [22] |
|  | *Ef*⫠ | [N/mm²] | 15000 |  |  | [22] |
|  | *Gf*⫠║ | [N/mm²] | 50000 |  |  | [22] |
|  | * f*⫠║ | – | 0.23 |  |  | [22] |
|  | *α f*║ | [10-6/K] | -0.56 |  |  | [22] |
|  | *α f*⫠ | [10-6/K] | 12.5 |  |  | [22] |
| Matrix | *Em* | [N/mm²] |  | 2900 | 2890 | [16,9] |
|  | * m* | – |  | 0.35 | 0.35 | [22] |
|  | *αm* | [10-6/K] |  | 65.0 | 52.7 | test data (TMA) |
|  | *Vc* | – |  | -0.025 | -0.033 | test data (rheometry) |

Table 1: Material data for analytical modelling.

Both modelling approaches show the same qualitative results: In both cases the fibre volume content has a relevant impact on the predicted spring-in deformation. Both curves show a maximum point for relatively low fibre volume contents. In the technically relevant sector between 30% and 65% both models predict an almost linear decrease of the spring-in angle with increasing fibre volume content. This first approach gives lower overall spring-in results than the second one. The maximum deformation when altering the fibre volume content is reached at *Vf*= 15% with a ∆*φSPI* of approximately 0.96°. The curve of the second modelling approach reaches its maximum at a slightly higher fibre volume content of *V*f= 12% and a deformation of ∆*φSPI* = 1.26°. Generally, the second strategy gives higher spring-in predictions than the first one. This behaviour is expected and can be attributed to the different introductions of chemical shrinkage in the two models. In model one the chemical shrinkage is divided equally in all three space directions and the matrix’ CTE is adapted. In the second strategy it is assumed that all volumetric shrinkage is taking place in only two space directions transverse to the fibres of an UD-layer therefore it is divided into two equal fractions which are subsequently introduced as additional strains. This difference leads to higher spring-in predictions in model 2.



Figure 5: Results of analytical spring-in prediction for *Epikote* *05475* matrix system plotted over fibre volume content. Lay-up [(-45/+45)2(90/0)]S, temperature difference ∆T = -90°C and chemical cure shrinkage *Vc* = 2.5%. (a) Modelling approach 1 with alteration of the matrix CTE to account for chemical cure shrinkage. (b) Modelling approach 2 with additional strain of UD-layers to account for chemical cure shrinkage.

4 EXPERIMENTAL

4.1 Volumetric Shrinkage

The volumetric shrinkage of the examined RTM systems is determined by using contact rheometry. In the applied rheometry setup two cylindrical aluminium plates with a diameter of 40 mm are employed (see Figure 6). A pre-set gap of 1 mm between the two plates is chosen. The premixed resin sample is placed into this gap in a liquid state. During the cure reaction of the sample, after passing the gelation point, the resin starts adhering to the plates. By taking advantage of that characteristic the chemical volumetric shrinkage after gelation can be determined. This part of the total shrinkage is the component which causes the spring-in deformation. Shrinkage taking place before gelation, in the liquid state of the resin, does not contribute to the distortions [23]. Curing temperature is applied using an electric heater surrounding the sample. For the thermal component of the resin’s shrinkage a standard thermo mechanical analysis (TMA) was used. The analysis described above was carried out only for the RTM systems examined in this study. For the used prepreg systems a rheometric analysis was not possible since no neat resin samples were available.



Figure 6: Schematic lay-out of the rheometry measurement of neat resin samples.

4.2 Resin transfer moulding process

In this study a closed mould RTM process similar to state of the art automotive applications is used. The produced part is an L-profile with a flange length of approximately 58 mm and a width of 248 mm. The inner radius of the part is 5 mm. The nominal laminate thickness of the parts is 2 mm. As mould material a standard tool steel is selected. The enclosed angle of the tool is 90°. The temperature control is realised by water cooling/heating. An isothermal process was realised in all investigations. The textile fibre material is preformed on a specialised vacuum station with the help of an elastomeric membrane. During the preforming process the thermoplastic binder is activated by infrared heating at a temperature of 150°C for a duration of 20 s. Then the preforms are placed into the mould which is prepared with a chemical release agent. The mould is closed and vacuum is applied in order to support the consecutive injection process (*pvac* < 10 mbar). For the two component FCER a gear driven injection unit (*Hilger+Kern* *eldomix*®) with a static mixer is used. It guarantees high reproducibility of the mixing as well as short injection times and fast mould filling. The latter are needed to process the fast curing resins before gelation. For all experiments of the study an injection pressure of *pinjct.* = 8 bar is selected.

4.3 Prepreg manufacturing

The analysed prepreg materials are processed in a standard autoclave procedure. To enable comparability with classical aerospace systems a single-sided tooling setup is selected. Figure 7 illustrates the used vacuum bagging setup. The aluminium tool provides a radius of 5 mm. The enclosed angle of the tool is 90°. The nominal part thickness of the considered lay-ups is 2 mm. The specimens are 45 mm wide and have a flange length of 50 mm. The lay-up is placed directly onto the aluminium tooling which is prepared with a chemical release agent beforehand. One additional layer of peel ply and a breather fleece are placed on top of the prepreg material. Finally a vacuum foil is put on top and sealed. Before processing in the autoclave, vacuum is applied (*pvac* < 10 mbar). The process cycle is selected according to the respective manufacturer’s specifications. Autoclave pressures of *pautocl.* = 8 and p*autocl.* = 9 bar are used.



Figure 7: Schematic lay-out of vacuum bagging arrangement.

4.4 Experimental test program

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ID | Type | *N* | Resin | Fibre | Fabric type | FAW | *V*f | Lay-up | Cure cycle | Cool. rate |
| [-] | [-] | [-] | [-] | [-] | [-] | [g/m²] | [-] | [-] | [min/°C] | [k/min] |
| *A-01* | RTM | 7 | *Epikote* | T620 | NCF-BIAX | 300 | 0.51 | [(-45/+45)2(90/0)]S | 7 @ 115 | 5.0 |
| *A-02* | RTM | 3 | *Epikote* | T620 | NCF-BIAX | 300 | 0.51 | [(-45/+45)(90/0) 2]S | 7 @ 115 | 5.0 |
| *A-03* | RTM | 3 | *Epikote* | T620 | NCF-BIAX | 300 | 0.51 | [((90/0) 3]S | 7 @ 115 | 5.0 |
| *A-04* | RTM | 3 | *Epikote* | T620 | NCF-BIAX | 300 | 0.53 | [(-45/+45)3]S | 7 @ 115 | 5.0 |
| *A-05* | RTM | 3 | *Epikote* | T620 | NCF-BIAX | 300 | 0.51 | [(-45/+45)(90/0) 2]S | 7@ 125 | 5.0 |
| *A-06* | RTM | 3 | *Epikote* | T620 | NCF-BIAX | 300 | 0.51 | [(-45/+45)(90/0) 2]S | 7 @ 135 | 5.0 |
| *A-07* | RTM | 3 | *Epikote* | T620 | NCF-BIAX | 300 | 0.52 | [(-45/+45)(90/0) 2]S | 7 @ 145 | 5.0 |
| *A-08* | RTM | 3 | *Epikote* | T620 | NCF-BIAX | 300 | 0.51 | [(-45/+45)(90/0) 2]S | 7@ 115 | 0.5 |
| *A-09* | RTM | 3 | *RTM6* | T620 | NCF-BIAX | 300 | 0.51 | [(-45/+45)(90/0) 2]S | 120@ 180 | 5.0 |
| *A-10* | Prepreg | 3 | *Pyrofil* | TR50 | NCF-UD | 150 | 0.52 | [(-45/+45)(90/0) 2]S | 10@ 135 | 0.5 |
| *A-11* | Prepreg | 3 | *HexPly* | unkn.. | NCF-UD | 150 | 0.51 | [(-45/+45)(90/0) 2]S | 10@ 135 | 0.5 |
| *A-12* | Prepreg | 4 | *DT 120* | T700 | WF-BIAX | 380 | 0.50 | [(-45/+45)(90/0) 2]S | 40@ 135 | 0.5 |

Table 2: Experimental test program *Epikote, RTM6, Pyrofil, HexPly* and *DT 120* are abbreviations for *Momentive Epikote 05475, Hexcel Hexflow RTM 6, Mitsubishi PYROFIL #360, Hexcel HexPly M77, Deltapreg DT120 respectively. N* is the number of produced specimens*.*

Table 2 gives an overview on the experimental test program. The fibre volume fraction is identified as critical influencing parameter in section 3. Therefore, it is kept approximately constant during the experimental part of this work for comparison reasons (*Vf*= 0.50-0.53). In case of the two RTM systems it has been verified by weight comparisons between the preform and the fabricated L-profile. For the prepreg specimens the manufactures specifications are considered [6, 8, 15]. *Hexcel Hexflow RTM 6* and *Deltapreg DT120* with curing times of 120 respectively 90 min are selected as slower curing reference systems. For the *Hexcel HexPly M77* the exact fibre type is not provided by the manufacturer. For each configuration a minimum of three parts was produced. The number of produced parts per configuration is given as *N* in Table 2.

4.5 Evaluation of spring-in and warpage

A *GOM 3D ATOS* scanner is used to evaluate process distortions. It provides a 3D point cloud while the corresponding mesh density is around 0.8 pt/mm². To analyse the resulting point cloud the measurement software *GOM Inspect* is used. In a first step the point cloud is transferred into a polygonised mesh. To distinguish between flange warpage and spring-in deformation (see Figure 3) the method depicted in Figure 8 is used. At first a best fit cylinder is placed into the radius area of the part. This is done by using an implemented feature of the *GOM* software. Subsequently three more isocentric cylinders with a distinct radius are generated (*r1* = 7 mm, *r2* = 9 mm, *r3* = 42 mm). The two areas (red) defined by the cutting lines between the flange and cylinders 1 respectively 2 are considered to determine the spring-in portion of the deformation. In these areas two best fit planes are generated and the angle between the planes’ normal vectors is assessed. In that manner only areas close to the radius section of the L-profile are taken into account for the measurement of the deformation. Flange warpage is negligible. To evaluate flange warpage the areas between cylinders 1 and 3 (blue) are used analogously to the method described above. The resulting angle contains spring-in deformations as well as additional deformations due to flange warpage. Reproducibility of the evaluation process has been verified by means of measurement repetitions. The angle containing both, spring-in deformation and flange warpage, is denominated *φTOT* and the angle containing solely the spring-in fraction is denominated *φSPI.*.



Figure 8: Different areas are considered for measurement of deformation. Blue: including flange warpage. Red: Spring-in deformation without flange warpage.

5 Results

5.1 Experimental study of parameters

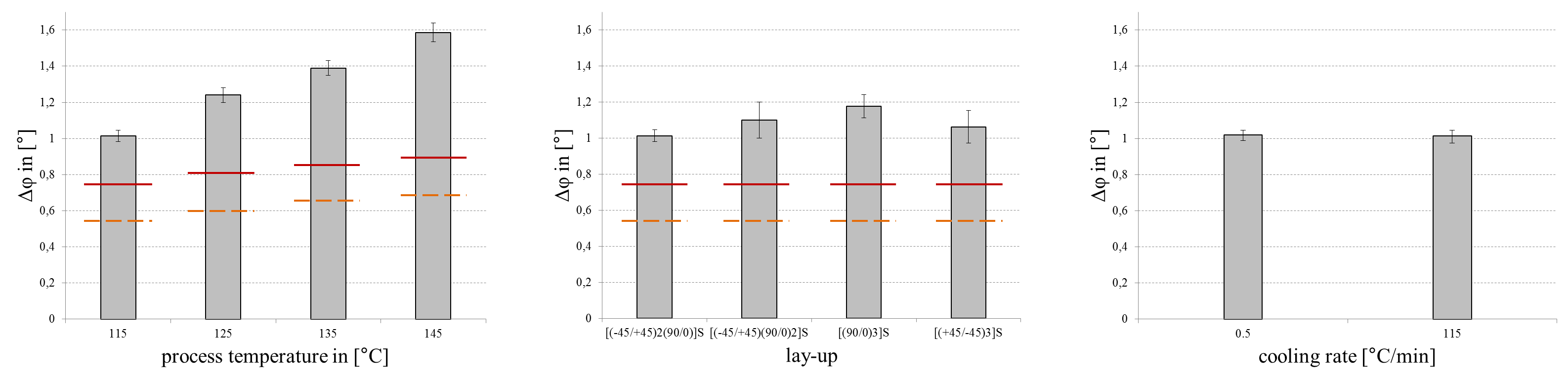
|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| ID | Type | Resin | *V*f | Cur. Temp. | Cool.rate | **Δ*φSPI*** | *SΔφ* |
| [-] | [-] | [-] | [-] | [°C] | [°C/min] | **[°]** | [°] |
| *A-01* | RTM | Epikote\* | 0.51 | 115 | 5.0 | **1.01** | 0.03 |
| *A-02* | RTM | Epikote\* | 0.51 | 115 | 5.0 | **1.10** | 0.03 |
| *A-03* | RTM | Epikote\* | 0.51 | 115 | 5.0 | **1.18** | 0.06 |
| *A-04* | RTM | Epikote\* | 0.53 | 115 | 5.0 | **1.06** | 0.09 |
| *A-05* | RTM | Epikote\* | 0.51 | 125 | 5.0 | **1.24** | 0.06 |
| *A-06* | RTM | Epikote\* | 0.51 | 135 | 5.0 | **1.39** | 0.09 |
| *A-07* | RTM | Epikote\* | 0.52 | 145 | 5.0 | **1.59** | 0.08 |
| *A-08* | RTM | Epikote\* | 0.51 | 115 | 0.5 | **1.02** | 0.03 |
| *A-09* | RTM | RTM6\* | 0.51 | 180 | 5.0 | **1.41** | 0.10 |
| *A-10* | Prepreg | Pyrofil\* | 0.52 | 135 | 0.5 | **1.42** | 0.05 |
| *A-11* | Prepreg | HexPly\* | 0.51 | 135 | 0.5 | **1.07** | 0.05 |
| *A-12* | Prepreg | DT 120\* | 0.50 | 135 | 0.5 | **0.80** | 0.02 |

Table 3: Spring-in results. *\*Epikote, RTM6, Pyrofil, HexPly* and *DT 120* are abbreviations for *Momentive Epikote 05475, Hexcel Hexflow RTM 6, Mitsubishi PYROFIL #360, Hexcel HexPly M77, Deltapreg DT120 respectively.*

**Process Temperature:** As first parameter the process temperature is altered. The lay-up, the process time, the fibre volume content, the fibre type and the geometry of the part are kept constant during the tests. The results are shown in Figure 9 (a). The spring-in deformation of the L-profiles increases with increasing temperature. As published by other authors, this behaviour can be approximated linearly with good accuracy. The models introduced in section 3 both qualitatively capture the behaviour due to a change in process temperature. However, both modelling strategies underestimate the overall spring-in.

**Lay-up:** All four possible symmetric lay-up combinations under the boundary conditions of biaxial fibre material and a tool cavity thickness of 2 mm are tested. The other process parameters are kept constant during these tests (see Table 2). The results are depicted in Figure 9 (b). Only a weak dependency of the lay-up on the spring-in angle is detected. Due to the biaxial nature of the fibre material no laminates with a high order of anisotropy (e.g. pure 0°) could be created. This result is in good accordance with other studies [14]. If the lay-up is quasi-isotropic or shows quasi-isotropic tendencies the influence of additional layers respectively other fibre directions on the resulting deformations is weak.

**Cooling rate:** Figure 9(c) shows the influence of the cooling rate on the spring-in angle. No significant change is detected. The considerably slower cooling rate of 0.5°C/min shows approximately the same spring-in angles as the faster cooling rate of 5°C/min. This contradicts the findings of [24] wherein a faster cooling rate leads to considerably higher deformations. For all other experiments with RTM systems in this study, the faster cooling rate was selected.



*(a)*

*(b)*

*(c)*

Figure 9: Results of parametric study. Yellow dotted line: First analytical approach. Red line: Second analytical approach.

Generally the deformation measurement data of all specimens showed a high reproducibility with an average standard deviation of *SΔφ* = 0.06°. This promises high potential for reproducible prediction methods. Both linear analytical modelling approaches underestimated the occurring spring-in angles but were able to give qualitative estimations. The reason for this quantitative deviation may be found in the rheometric analysis. The measurement data for the chemical volumetric shrinkage of the neat resin influences the calculation results to a large extent. Boundary effects between the aluminium plates of the rheometer and the sample may have led to uncertainties in the values of chemical shrinkage or the assumption made in section 4.1, that only the resins shrinkage after gelation contributes to the deformations, is not valid. The measured values are considerably lower than in other studies [12]. Further work is needed to understand the occurring effects. All RTM specimens were tested for flange warpage as described in section 4.5. No considerable flange warpage could be detected (*φTOT ≈ φSPI*). This supports the thesis that double-sided tooling setups of a closed mould RTM process do not induce asymmetrical residual stresses into the parts as it is the case for single-sided setups. Thus, none of the occurring deformations could be attributed to tool-part-interaction.

5.2 Spring-in quantification of different FCER-based L-profiles

In Figure 10 the spring-in test results for different FCER are shown. All examined laminates provide the same lay-up [(-45/+45)2(90/0)]S, and approximately the same part thickness (t ≈ 2mm). All L-profiles are produced on a tooling with a nominal angle of 90°. The fibre volume content for all specimens is in the same order of magnitude: *Vf* = 0.50-0.53. The temperature and processing times varied due to the different manufacturers specifications. However for the Momentive RTM system and all prepreg systems the same curing temperature of 135°C is chosen. For each group a slower curing resin system was selected as reference. The RTM-FCER *Momentive Epikote 05475* cured at 135°C shows with an average of 1.39° approximately the same deformation as the reference system *RTM 6* (1.41°) which is cured at a higher temperature of 180°C. A curing at the same temperature for the two systems was not possible according to the recommended manufacturers’ process cycles. Assuming a linear increase of deformation with increasing temperature as shown in section 5.1 curing 180°C would result in a deformation of 2.25° for the *Momentive Epikote 0547.* The resulting spring-in angles of the prepreg systems examined in this study are depicted on the right hand side of Figure 10. The average spring-in angles for the *Mitsubishi PYROFIL #360* and *Hexcel HexPly M77* amount to *φSPI*= 1.42°, *φSPI* = 1.07° respectively. The slower curing reference system *Deltapreg DT120* shows a lower average spring-in of *φSPI* = 0.80°.

It should be noted that both fast curing prepreg systems show noticeable flange warpage. This results in a considerably higher total deformation (*Mitsubishi PYROFIL #360 φTOT* = 2.42°, *Hexcel HexPly M77* *φTOT* = 1.98°). The parts in this study have a nominal thickness of 1.9 mm. These findings are in contradiction to the work of Kappel [13] who only detected warpage phenomena for a part thickness up to 1.5 mm when examining classical aerospace prepregs. This difference may be attributed to geometrical locking between tooling and part. This additional effect which is also relevant for thicker parts is introduced as forced- interaction phenomenon by [13] and needs further investigation. The specimens produced with the reference system *Deltapreg DT120* showed no considerable flange warpage (*φTOT*≈ *φSPI*).

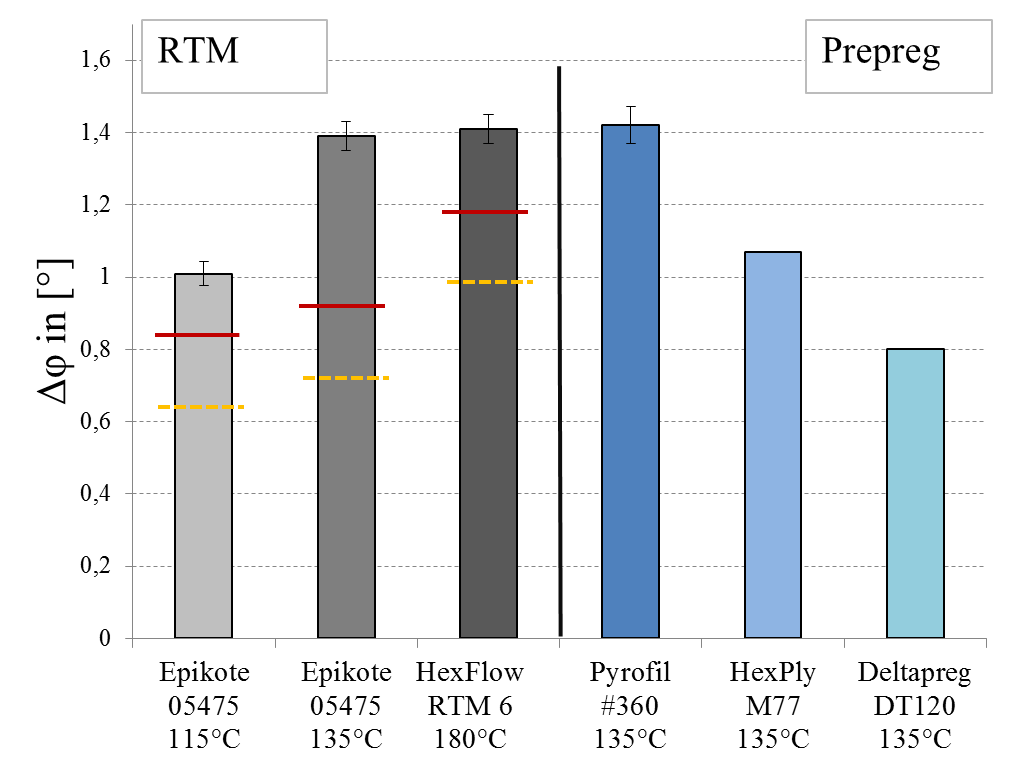


Figure 10: Comparison of different FCER and slower curing reference systems. Yellow dotted line: First analytical approach. Red line: Second analytical approach.

6 Conclusions

An experimental study was performed focusing on fast curing epoxy resins (FCER). The process induced deformations of closed-mould-RTM parts as well as autoclave-fabricated prepreg specimens were investigated. No dependency between cooling rate and spring-in angle of L-profile specimens is revealed. This is in contradiction to the finding of other authors. An increase in process temperature led to an increase of specimen deformation. The relation between the two parameters can be approximated linearly with good accuracy. The different laminate lay-ups examined, showed only a weak influence on spring-in behaviour. This is in accordance with other work since no highly anisotropic laminates were studied.

The two investigated analytical modelling strategies were not able to account for the occurring spring-in deformation quantitatively. The deformations were underestimated by both models. This difference may be attributed to uncertainties in the rheometric measurement of the resins’ chemical shrinkage, which has a large influence on the calculations. However, qualitative conclusions and the investigation of main influencing factors, such as the fibre volume content, were possible with both models.

The occurring deformations for the RTM-FCER as well as the FCER prepregs were slightly higher than for the slower curing reference systems. This behaviour may be attributed to a higher degree of crosslinking between the polymer chains of the resin and a resulting increase of chemical cure shrinkage. Nevertheless, the occurring deformations of the FCER-parts compared to the reference systems is comparably small and lower than expected.

The parts produced in the double-sided tooling setup of the closed-mould RTM process showed no additional flange warpage as deformation besides the classical spring-in. In contrast, the autoclave-fabricated FCER prepreg parts, which were produced on a single-sided tooling, showed considerable flange warpage deformations. The occurring deformations can be attributed to part-tool-interaction. Since comparably thick parts (t = 1,9 mm) were investigated the results are in contradiction to other work.

Generally all results showed a high reproducibility. This finding establishes a promising basis for future prediction approaches.

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