Composite Structures 140 (2016) 217–229

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Forced-interaction and spring-in – Relevant initiators of process-induced distortions in composite manufacturing

Erik Kappel *

DLR, Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany

ARTICLE INFO

Article history:
Available online 11 January 2016

Keywords:
Layered structures
Process-induced distortions
Autoclave manufacturing
Low-cost tooling

ABSTRACT

Process-induced distortions are still an issue for today's CFRP applications. Nonetheless, cost-reduction is considerably pushed by OEMs. Low cost tools, made from aluminum or steel, offer significant cost-saving potential compared to the state-of-the-art Invar (Ni36) tools. However, their high thermal expansion affects the final part shape detrimentally.

The present paper reports on an experimental pilot study on forced-interaction and spring-in. Distortions of C- and L-profile specimens with unidirectional, cross-ply and quasi-isotropic laminates and thicknesses up to 8.2 mm were manufactured on Invar and aluminum tools. Local and global part distortions were evaluated after manufacturing and compared. The study gives new insight into both acting distortion mechanisms. It quantifies the effect of a high tool CTE on the final part shape, which is of great value for tool and part designers who strive for high-precision composites.

1. Introduction

Increasing production rates are omnipresent in aircraft industries. This process is denoted as ramp-up. It aims for massively increased production rates of for more than 50 aircrafts per month. Rates that high challenge today's manufacturing and assembly processes significantly. This is even exacerbated by the OEM's effort to reduce overall manufacturing costs. It is pursued simultaneously in decades between new aircraft generations. The following two key approaches are identified to serve this aims.

- Improved dimensional control for the manufactured parts enables immense assembly cost reductions, due to less non-adding value shimming operations, thus reduced assembly times.
- Efficient tool compensation (biasing), accounting for process-induced distortions, early on in the design process, in combination with the use of low-cost tooling materials bear the potential of significant cost reduction.

The research presented in this paper addresses the preceding approaches in order to initiate high-precision CFRP manufacturing on low-cost tools. In general, dimensional control of CFRP components is a complex task since the final part shape and its quality is affected by numerous part-, process- and design-specific parameters. Within the present study the tool material as well as the parts' laminates are varied while processing parameters as well as the part dimensions are kept constant.

The paper reports on an experimental investigation on the effect of low-cost aluminum tools on process-induced distortions (PID) of autoclave manufactured C- and L-profiles made from prepreg material. In particular, the widely uninvestigated forced-interaction effect is the focus of the present study. It is the aim to identify and quantify the specific contributions of the three acting distortion mechanisms illustrated in Fig. 1.

Today, Invar tools are the state-of-the-art for high-performance aircraft composite structures. This is mainly due to its extraordinary low coefficient of thermal expansion (CTE) of 2.6 ppm/K [1] which is comparable to CTEs of typical CFRP laminates and due to Invar's excellent durability. However, from a cost point of view Invar is not the optimal choice for all aircraft components for multiple reasons. Its raw material cost exceeds the one of steel for example by a factor of thirteen [2]. Machining of Invar is complex, the availability on the market is rather limited compared to steel or aluminum and the number of trusted tool manufactures for Invar tools in aerospace quality is limited what keeps prices rather high. Moreover, carry-over parts are uncommon in today's aircraft designs. With other words, almost each composite frame or spar and dozens of clips and cleats are unique. Thus, at least one specific manufacturing tool is required for each composite component which equals an immense capital expenditure. The preceding facts

* Tel.: +49 531 295 2398; fax: +49 531 295 2232.
E-mail address: erik.kappel@dlr.de

http://dx.doi.org/10.1016/j.compstruct.2016.01.016
0263-8223/

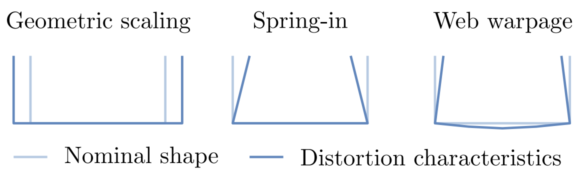

Fig. 1. Observed deformation modes.

underline the demand for low-cost tools since they are a key to reduce CFRP processing costs significantly.

However, low-cost materials, such as steel and aluminum, have disadvantageous properties in terms of comparably high thermal expansion. The effect and the relevance of this shortcoming on the final part shape needs to be understood fundamentally in order to evolve the ability to adapt nominal part geometries accordingly.

Currently, a non-negligible amount of non-adding value operations is necessary to compensate process-induced distortion within the assembly process. Typically shimming is the counter measure of choice which is necessary to enable connecting of CFRP components. As shimming is conducted manually today it is costly and time consuming. Thus, it represents a key-challenge to avoid those shimming operations when striving for very high production rates.

In order to avoid undesired distortions it is common practice that tool geometries have to be modified [3]. This is often done iteratively based on rule of thumb until a satisfying component shape is achieved. However, for new components or simple material changes from one prepreg to another for example, this procedure is costly and risky, in particular when it comes to large composite structures.

The anisotropic material properties of carbon/epoxy composites and current process cycles, utilizing elevated temperatures and high pressure, are the sources for these distortions. Albert and Fernlund [4] introduced the distinction between intrinsic and extrinsic sources for PID. Former ones, driven by the composite's constituents fiber and resin, are typically denoted as spring-in (less often springback).

Extrinsic sources summarize all affectations of the part during processing from outside. The bagging arrangement in combination with typical single-sided tool concepts for example, is reported to have an effect on PID, since a gradient of fiber volume fraction can be induced due to resin flow [5–7]. However, the tool is believed to have the strongest impact on the final part shape. Comprehensive studies on the warpage effect verify this [8,10,11]. Warpage represents a frictional locking between the part and the tool which is emphasized by the acting autoclave pressure. Experimental studies on flat, symmetric and/or unidirectional laminates show similar trends where warpage of a part w depends in its length L and its thickness t. Twigg et al. [10] found the relation $w \propto L^3/t^2$ while Kappel et al. [11,12] found $w \propto L^2/t$. The studies show that tool-surface roughness as well as the type of prepreg at hand significantly affect warpage distortions [11]. A study on circular curved specimens of comparable thickness show that spring-in distortions exceed warpage distortions significantly [13]. Nonetheless, it is common sense that warpage is of limited relevance for real-life CFRP structural components in aerospace applications since laminates typically have multi-angle stackings with thicknesses above 1.6 mm.

When complex CFRP components such as Z-, C-frames or I-shaped stiffeners are manufactured more complex double-sided tool concepts are necessary to assure the required tight dimensional tolerances. When low-cost tool materials with their high thermal expansion should be used to manufacture those kinds of structures this leads to additional challenges. The thermal mismatch leads to form closure between the part and the tool which can be denoted as geometrical locking as well. This effect has been demonstrated and briefly experimentally verified by Potter et al. [8]. The relevance for real-life composite structures cannot be elaborated based on this single study. Kappel et al. [13,15] could show that a certain fraction of the observed PID of an integral CFRP box structure, with a cross-ply laminate of 3 mm thickness, is induced by the tool. Since the laminate is forced to the tool by autoclave pressure the effect has been denoted as forced-interaction [13].

The research presented in this paper pursues the aim to develop an initial understanding of the forced-interaction effect. An experimental pilot study on C- and L- profiles, manufactured on an Invar and an aluminum tool, is performed. Spring-in and forced-interaction distortions are inspected to investigate whether both effects superpose or interact each other.

2. The forced-interaction effect

Forced-interaction is an extrinsic effect which can induce considerable distortions in CFRP structures. It is driven by the tool's CTE since distortions occur when the tool CTE exceeds the laminate's CTE. A principle sketch of the acting mechanism is given in Fig. 2.

The acting autoclave pressure forces the laminate to stay on the expanding tool surface while it expands. Sliding of the laminate stack on the tool-part interface is hindered due to form closure. Normal forces, acting on the angled flanges, are aligned parallel to fibers in the web area. This circumstance represents the main difference to the earlier investigated warpage effect. It is believed to be the reason of an increased stress-introduction.

In preliminary experiments it has been observed that the web area of C-profile specimens warps away from the tool when they are manufactured on an aluminum male mold. This is observed even for laminate thicknesses of 3 mm, which is in contrast to distortions due to warpage [10,11]. This deformation behavior can only be explained with a residual stress distribution that is inhomogeneous in through-thickness direction. According to Eq. (1) this results in a corresponding bending moment M_b which is responsible to the observed distortions.

$$|M_b| = \left| b \cdot \int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma(z) \cdot z \cdot dz \right| > 0 \tag{1}$$

As indicated above there is experimental evidence that even thicker laminates are affected by forced-interaction. However, a funded assessment of the effect's relevance demands for a quantification of the the stress-gradient magnitudes. The following section comprises an analytical estimation of the acting stress gradients based on the available set of experimental data.

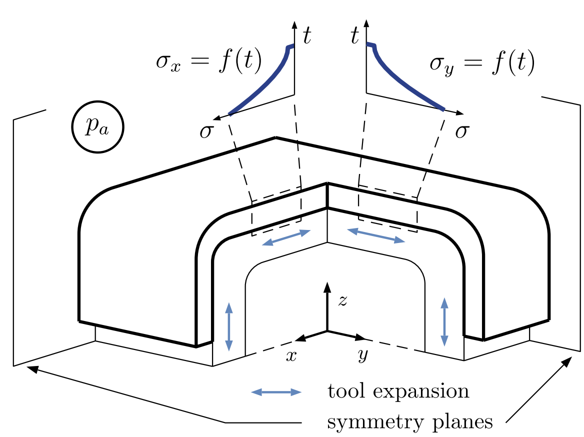

Fig. 2. The forced-interaction mechanism induces through-thickness (t) stress gradients $\sigma_i = f(t)$ which lead to considerable PID.