Title:
Quantitative Characterization of Warpage for Composite Components

Authors:
Eric J. Martin, emarti58@uwo.ca, Western University, Canada
O. Remus Tutunea-Fatan, rtutunea@eng.uwo.ca, Western University, Canada
Ryan Gergely, ryan.gergely@gm.com, General Motors, USA
David A. Okonski, david.a.okonski@gm.com, General Motors, USA

Keywords:
Warpage metric, composite manufacturing, LFT-D process, reverse engineering

DOI: 10.14733/cadconfP.2021.192-197

Introduction:

Many governments have adopted stringent emissions standards for automobiles in order to reduce the detrimental effects they have on the environment [9]. The reduction of vehicle weight is one avenue to reduce vehicle emissions [7],[13] and composite components can play a key role in many potential solutions [1]. However, there are still many challenges to be overcome when it comes to the widespread use of the composite materials, particularly with respect to the mass production of composite parts and assemblies. One option for composite part fabrication is the long fiber thermoplastic direct (LFT-D) manufacturing process. According to this technology, parts can be produced from individual matrix and fiber components. This approach eliminates the need for a semi-finished product like glass mat thermoplastic (GMT) to be acquired from a material supplier and thus translates into cost savings for the composite part manufacturer [5].

Like many other thermal forming processes, the parts fabricated through LFT-D can experience a significant amount of deformation. Warpage can make parts difficult to incorporate in downstream assemblies. However, despite the importance of this problem, the quantitative characterization of the warpage presented in the surveyed literature is relatively simplistic. While no clear metric for part warpage exists at this time, prior studies have highlighted that part warpage can be reduced by changing molding processing parameters [3],[4],[6],[10],[11]. For many of these studies, part warpage is typically evaluated by the maximum deviation between the nominal and fabricated parts. Nonetheless, while the maximum value of the deviation between the two shapes is indeed important, warpage could be defined in many other ways. One alternative is to evaluate specific regions of the part, particularly those that are involved in subsequent assembly operations. Along these lines, the current study aims to propose alternative metrics capable of evaluating part warpage.

Main Idea:

The main goal of the current study was to propose quantitative warpage metrics that are capable of quantifying part deformation through a unique number. As a possible application example, some of the developed metrics were applied to investigate the effect of various LFT-D processing parameters on the shape of the part. This approach enables the identification of optimum processing conditions that can generate the least warped/deformed shapes. With a warpage metric defined by a unique number in hand, statistical tools were used to evaluate the effect of various process parameters ("input variables") on part warpage ("output variable").

The processing parameters investigated in this study were mold temperature and charge placement as related to the LFT-D fabrication process. After the parts were manufactured, a laser line probe (LLP) was used to collect scans of the top surface of the parts to evaluate part warpage. The scans of the fabricated parts were aligned/registered to their CAD models such that warpage could be determined in a consistent manner (Fig. 1). The name of each warpage metric maintains a strict reference to its geometric definition outlined in the subsequent sections.

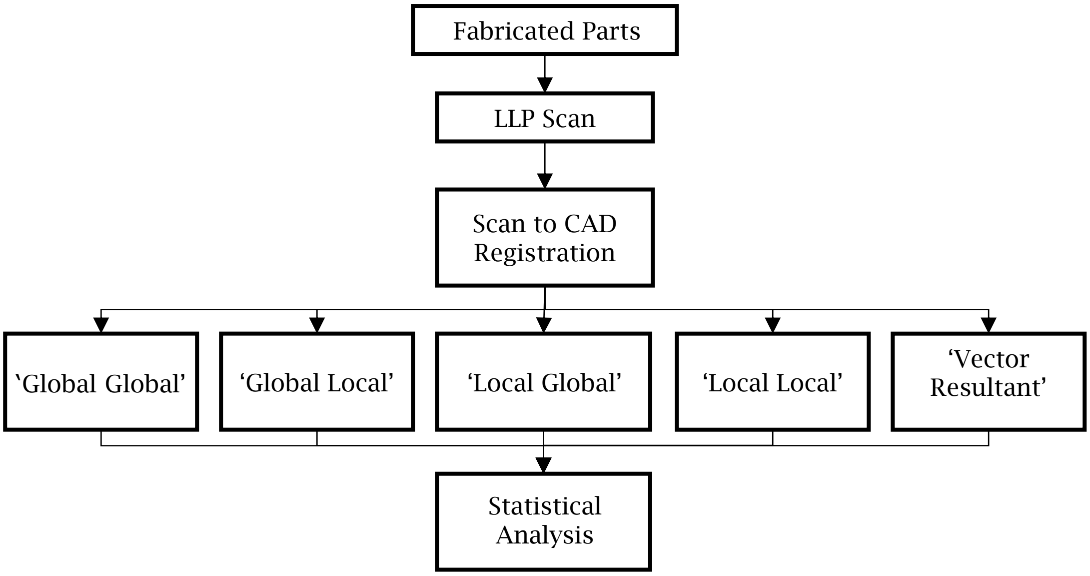
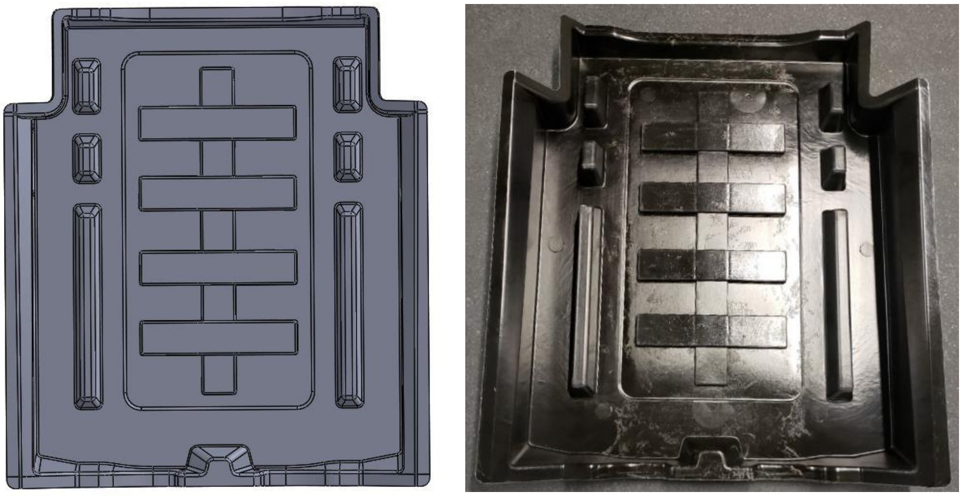


Fig. 1: Study workflow.

The part molded in this study was a demonstrator part, a seatback outer (SBO, Fig. 2). The dimensions of the bounding box of the sample part are 540 x 480 x 98 mm whereas its thickness was approximately 3 mm.



(a) (b)

Fig. 2: Seatback outer (SBO) representations: (a) CAD model, (b) physical part.

Warpage Metrics:

Background

Part warpage can be defined in a number of different ways. In a typical reverse engineering (RE) setup, part warpage is often evaluated using a color map of the deviation calculated as the Euclidian distance between the nominal CAD model and its distorted counterpart. If multiple physical parts are to be compared against the same model, then a robust registration procedure must be used. The majority of commercial systems rely on variants of iterative least mean square approaches for this purpose. However, regardless of the method used, once the parts are aligned, the distances between the scanned part and the CAD model are determined across the entire surface. Since the result of RE is a tessellated geometry, deviation is commonly calculated at each vertex of the mesh. To facilitate reading and interpretation of the warpage pattern between pairs of physical parts, each facet of the mesh is usually colored according to the distance to the reference geometry. This primarily qualitative approach is ineffective when attempting to identify the optimal processing conditions for part fabrication. This is because most statistical tools require numerical values for the variable regarded as the main output (sometimes called the target objective) of the process.

As indicated above, the most common measurement used to describe part warp is the maximum deviation between nominal and scanned geometries. An example of this approach was presented by Song et al [12] in their analysis of the compression molded composite components. The same metric has also been used elsewhere [2],[4]. However, the question that arises is whether this metric adequately represents the parts and can be used in a more complex analysis of the manufacturing process and processing parameters. While in some situations this simplified warpage metric might be sufficient, a metric that combines multiple measurements over the entire part or at specific areas of interest could provide more valuable insights.

Data Acquisition and Mesh Alignment Procedure

To ensure the quality of the data collected, parts were covered with white talk powder. The part was then laid down on a flat granite table and scanned in a free state (i.e.; no clamps) condition in order to avoid the introduction of additional deformations through clamping. The raw data acquired was passed through several filtering operations and a triangular mesh was generated at the end of the process.

The mesh of the scanned component was then aligned to the CAD model by means of a best-fit procedure relying on the classical 'iterative closest point' (ICP) best-fit algorithm [8]. Heuristic searches have identified the central (and largely less warped) area of the part as the most appropriate region to be included in the best fit alignment procedure (Fig. 3).

Fig. 3: Area constituting the target of the alignment procedure.

Definitions
Five warpage metrics were developed and used to assess the effect of processing conditions on part deformation. All five metrics were essentially reduced to a single numerical value calculated as the average of the absolute value of deviations. The difference being that each metric considers a different set of measurement points/vertices. In the naming of the metrics presented below, the first word in the group of two refers to the measurement zone for which the metric was calculated – over the entire part ('global') or just a smaller region of interest ('local'). The second word refers to whether all vertices in the measurement zone are included in the calculation ('global') or just a limited subset of them ('local'). In the present study, the 'regions of interest' were the areas that are important for downstream manufacturing operations, namely, the two long lateral flanges presented in Fig. 2.

According to the aforementioned naming conventions, the 'global global' metric was calculated over the entire part and included all of the vertices in the mesh. By contrast, the 'local local' metric was calculated by including only vertices located in certain regions of interest *and* by including only a limited subset of them. The other two possible metrics included a limited subset of vertices that were distributed over the entire part surface ('global local') and all vertices within certain regions of interest ('local global'). The biggest drawback of these four warpage metrics is that all deviations are calculated in a direction that is normal to the deformed part surface. If the part is characterized by large distortions, this method of calculating deviations can lead to inaccuracy in the part warpage metric. As such, two issues can arise. First, some vertices will yield null Euclidian distance evaluations if the algorithm is unable to find/intersect the target reference mesh within the analyzed solid angle (typically of small/very small steradian magnitudes). Second, each particular point on the part can be distorted in a broad spectrum of directions relative to its nominal position in space (covering large solid angles), not only in a direction normal or quasi-normal to the nominal surface. Therefore, valuable warpage detail will be inevitably lost.

To address this drawback, a fifth warp metric – termed 'vector resultant' – was developed by measuring distances between a set of points that could be identified by features on the part on both the undeformed and deformed part data. The biggest drawback of this approach was that, for this study, it was completely manual and thus time intensive and prone to human interpretation. As a result, fewer vertices were included in the 'vector resultant' metric compared to the other four metrics. Nonetheless, through judicious selection of the measurement points, the 'vector resultant' metric can yield meaningful results for evaluation of part warpage.

All five of the part warp metrics were initially applied to a set of parts made through the LFT-D process. Within the limited scope of the present abstract, only the 'global global' and 'local local' metrics were selected and applied to two studies in which one process variable was changed.

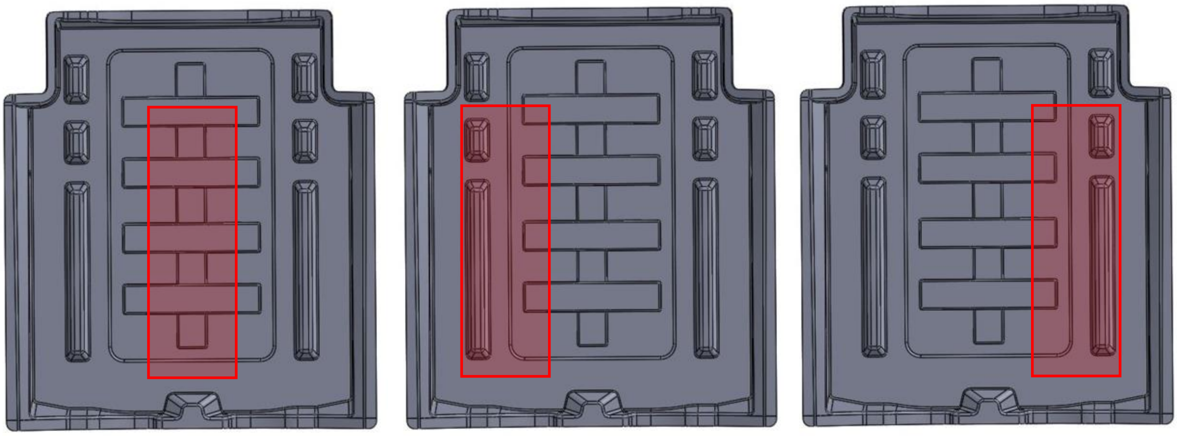
<u>Applications of Warpage Metrics:</u>

Effect of Mold Temperature on Warpage
A molding trial was performed in which mold temperature was varied between two setpoints: 100˚C and 150˚C. For each mold temperature, ten parts were made, and warpage was analyzed (20 parts in total). The results obtained showed a minimal difference between the warpage of the two sets (obtained for 100˚C and 150˚C) when evaluated with 'global global' or 'local local' metrics. A t-test was used to evaluate statistical significance. This suggests that mold temperature does not have a differentiable effect on the part warp under these molding conditions.

Effect of Charge Placement on Warpage
A second molding trial was performed in which only the charge placement was varied between three different conditions: left, right, and center (Fig. 4). For each charge placement, nine parts were made and their 'global global' or 'local local' warpages were determined (27 parts in total). ANOVA was used to evaluate statistical significance. The results suggest that charge placement does not have a differentiable effect on part deformation for the investigated molding conditions.

<u>Conclusions:</u>
The main goal of the current study was to develop several quantitative part warpage metrics. To demonstrate their practical utility, some of these metrics were subsequently used to gain insight on the

effect of various LFT-D processing parameters on the shape of the part. Certainly, part warpage metrics can be defined in many ways and the current study has outlined just some of such possibilities. Among them, two ('global global' and 'local local') were selected and applied to two separate studies in which one processing parameter was changed: first mold temperature, then charge placement. While neither of the two processing parameters was found to have a statistically significant effect on part warpage, the newly developed metrics provide alternatives to investigate correlations between manufacturing process parameters and the deformation of the resulting parts.



(a) (b) (c)

Fig. 4: Analyzed charge placement locations: (a) center, (b) left, and (c) right.

Future extensions of this work will be focused on the application of the newly developed part warp metrics in a multidimensional DoE involving the modification of several LFT-D processing parameters.

Acknowledgements:

The work presented in this study is the result of the collaboration between Western University (London, Canada) and General Motors (Warren, USA). Partial financial support was also provided by Natural Sciences and Engineering Research Council (NSERC) of Canada, Ontario Centers of Excellence (OCE), and General Motors of Canada.

References:

[1] Beardmore, P.; Johnson, C. F.: The potential for composites in structural automotive applications, Composites science and Technology, 26, 1986, 251-281. http://doi.org/10.1016/0266-3538(86)90002-3

[2] Kim, H. K.; Sohn, J. S.; Ryu, Y.; Kim, S. W.; Cha, S. W.: Warpage reduction of glass fiber reinforced plastic using microcellular foaming process applied injection molding, Polymers, 11, 2019, 360. http://doi.org/10.3390/polym11020360

[3] Kitayama, S.; Miyakawa, H.; Takano, M.; Aiba, S.: Multi-objective optimization of injection molding process parameters for short cycle time and warpage reduction using conformal cooling channel, The International Journal of Advanced Manufacturing Technology, 88, 2017, 1735-1744. http://doi.org/10.1007/s00170-016-8904-x

[4] Kitayama, S.; Onuki, R.; Yamazaki, K.: Warpage reduction with variable pressure profile in plastic injection molding via sequential approximate optimization, The International Journal of Advanced Manufacturing Technology, 72, 2014, 827-838. http://doi.org/10.1007/s00170-014-5697-7

[5] Krause, W.; Henning, F.; Tröster, S.; Geiger, O.; Eyerer, P.: LFT-D: A process technology for large scale production of fiber reinforced thermoplastic components, Journal of Thermoplastic Composite Materials, 16, 2003, 289-302. http://doi.org/10.1177%2F0892705703016004001

[6] Kurtaran, H.; Erzurumlu, T.: Efficient warpage optimization of thin shell plastic parts using response surface methodology and genetic algorithm, The International Journal of Advanced Manufacturing Technology, 27, 2006, 468-472. http://doi.org/10.1007/s00170-004-2321-2

[7] Lewis, G. M.; Buchanan, C. A.; Jhaveri, K. D.; Sullivan, J. L.; Kelly, J. C.; Das, S.; Taub, A. I.; Keoleian, G. A.: Green Principles for Vehicle Lightweighting, Environmental science & technology, 53, 2019, 4063-4077. http://doi.org/10.1021/acs.est.8b05897

[8] Li, Y.; Gu, P.: Free-form surface inspection techniques state of the art review, Computer-Aided Design, 36, 2004, 1395-1417. http://doi.org/10.1016/j.cad.2004.02.009

[9] Liu, C.; Greene, D. L.: Vehicle Manufacturer Technology Adoption and Pricing Strategies under Fuel Economy/Emissions Standards and Feebates, The Energy Journal, 35, 2014,

[10] Liu, F.; Zeng, S.; Zhou, H.; Li, J.: A study on the distinguishing responses of shrinkage and warpage to processing conditions in injection molding, Journal of applied polymer Science, 125, 2012, 731-744. http://doi.org/10.1002/app.35564

[11] Mohan, M.; Ansari, M. N. M.; Shanks, R. A.: Review on the effects of process parameters on strength, shrinkage, and warpage of injection molding plastic component, Polymer-Plastics Technology and Engineering, 56, 2017, 1-12. http://doi.org/10.1080/03602559.2015.1132466

[12] Song, Y.; Gandhi, U.; Sekito, T.; Vaidya, U. K.; Vallury, S.; Yang, A.; Osswald, T.: CAE method for compression molding of carbon fiber-reinforced thermoplastic composite using bulk materials, Composites Part A: Applied Science and Manufacturing, 114, 2018, 388-397. http://doi.org/10.1016/j.compositesa.2018.09.002

[13] Ward, J.; Gohlke, D.; Nealer, R.: The Importance of Powertrain Downsizing in a Benefit - Cost Analysis of Vehicle Lightweighting, JOM, 69, 2017, 1065-1070. http://doi.org/10.1007/s11837-017-2330-x