

PROCEEDINGS

Design-to-Process Framework Addressing Thermal-Mechanical Effects in Advanced Manufacturing

Chen Wang^{1,*}, Pan Wang¹, Chen-Nan Sun¹, Andi Haris¹, Wang Qi¹, Hui Huang¹, Yi Wen Cheah¹, Zi An Wu¹ and Wern Sze Teo¹

¹Singapore Institute of Manufacturing Technology (SIMTech), Agency for Science, Technology and Research (A*STAR), 636732, Singapore

*Corresponding Author: Chen Wang. Email: wang_chen@a-star.edu.sg

ABSTRACT

Enhancing sustainability in advanced manufacturing demands first-time-right production, minimal post-processes, and precise dimensional control across diverse near-net shape processes. Because of heating and cooling involved, geometric inaccuracies are widely reported, such as the thermal distortions and part shrinkage during additive manufacturing, as well as wrinkles and spring-back of composites in either thermo-stamping process or in-situ polymerisation processes [1,2]. It is challenging to mitigate, in design stage, imperfections from forming processes that inherent to complex thermal-mechanical behaviors of materials and factors from process conditions. In this study, we proposed a design-to-process framework to integrate distortion prediction with part design, thereby shortening the trial-and-error manufacturing cycle. The framework was developed and validated based on different process cases by integrating tailored distortion and warpage prediction methods.

The first case study introduced a design-to-compensation methodology for the electron beam powder bed fusion process [1]. By obtaining the pre-compensated geometry in the design for manufacturing workflow, the framework considered thermal-gradient induced nonlinear shrinkages, improving as-built dimensional conformance. The effectiveness of the design-to-compensation method was validated in shrinkage prediction and fabrication of a large-format component with the maximum dimensional error at 0.018%.

In the second case, a supervised learning approach was conducted to predict warpage of beam component fabricated by laser powder bed fusion [3]. The warpage was affected by geometrical factors and non-uniform distributed process-induced residual stress. To overcome simulation limitations, the robustness of multi-variable machine learning algorithms was compared to capture warpage profile in the giving process conditions. The methodology shows potential for predicting warpage behavior in other residual-stress-dominated processes, such as composite overmoulding and in-situ polymerization [4,5].

In the third case, we explored feasibility of developing cylindric couplers for joining metal and FRTP composite pipelines through in-situ polymerization [5]. Resin flow front modelling facilitates the coupled prediction of thermal-mechanical interactions and infusion dynamics during in-situ polymerisation of composite couplers. By simultaneously resolving exothermic heat generation, viscosity evolution, and cure-induced stress development within the consolidating preform, the approach identifies critical defect precursors prior to physical manufacture. This predictive capability enables systematic virtual optimisation of process parameters, ensuring controlled flow front progression and polymerisation shrinkage, thereby improving structural integrity and repeatability of the final component.

Finally, we applied the virtual manufacturing tool to capture key defects before mold-trial. A thermo-stamping model was developed with AniForm software to predict forming of large-scale composite components made from woven carbon fiber fabrics reinforced thermoplastic (PAEK) [2]. The simulation enabled the optimal choices of the gripping configurations and laminate layups to minimize wrinkling defects of the deformed component. Validated with experimental observations, we demonstrated that pre-identification of key process configurations via process



modelling saves design-to-process time and production development cost associated with manufacturing trial iterations.

Finally, we applied the virtual manufacturing tool to capture key defects before mold-trial. A thermo-stamping model was developed with AniForm software to predict forming of large-scale composite components made from woven carbon fiber fabrics reinforced thermoplastic (PAEK) [2]. The simulation enabled the optimal choices of the gripping configurations and laminate layouts to minimize wrinkling defects of the deformed component. Validated with experimental observations, we demonstrated that pre-identification of key process configurations via process modelling saves design-to-process time and production development cost associated with manufacturing trial iterations.

In summary, the series of work highlights a versatile design-to-process framework that accelerates product development by leveraging predictive insights of process-induced distortions into design stage. By customizing prediction methods, it advances scientific understanding of coupled thermo-mechanical interactions in different high temperature forming processes. From a sustainable perspective, facilitating first time right manufacturing reduces material waste and carbon footprint of above-mentioned intensive processes.

KEYWORDS

Sustainable and advanced manufacturing; distortion prediction; process modelling; geometric compensation; thermo-mechanical interactions

Funding Statement: This research is supported by the Agency for Science, Technology and Research (A*STAR) under its Career Development Fund (CDF) Grant No. C210112043 and Polymer Matrix Composites Programme Grant No. A19C9a0044. The work is also supported by the National Research Foundation (NRF), Singapore, and A*STAR under the RIE2025 Urban Solutions and Sustainability (USS) Low-Carbon Energy Research (LCER) Programme, Grant No. U2311D4004, and the Manufacturing, Trade and Connectivity (MTC) Programmatic Grant Advanced models for Additive Manufacturing (AM2), Grant No. M22L2b0111.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

References

1. Wang, C., Sun, C. N., Zhang, L., Feih, S., & Wang, P. (2024). Improving component dimensional accuracy in electron beam powder bed fusion by addressing nonlinear deformations with 3D compensation strategies. *Virtual and Physical Prototyping*, 19(1), e2430319.
2. Haris, A., Cheah, Y. W., & Teo, W. S. (2024). Thermoforming simulation of a carbon fiber-reinforced PAEK composite stringer. *Solid State Phenomena*, 357, 113–118.
3. Wang, C., Sun, C. N., Chang, T., Liang, X., Ma, N., & Wang, P. (2026). Orientation-dependent residual stress governs anisotropic warpage in laser powder bed fusion stainless steel: experimental analysis and predictive modelling. *Additive Manufacturing*, 121, 105158.
4. Shanmugam, L., Cheah, Y. W., Ho, K. H., Rajan, B. K., Tan, C. C. L., Haris, A., & Wang, C. (2024). Flexural behaviours and heterogeneous interface fracture in overmoulded multi-material thermoplastic composites. *Composite Communications*, 52, 102152.
5. Wang, Q., Wu, Z. A., Su, Z., Pitchai, P., Muhammad, R., Yek, A. W. M., Huang, H., Teo, W. S., Wang, C., & Haris, A. (2025). Feasibility of developing fiber-reinforced thermoplastic composite couplers for hydrogen transmission pipelines. *Proceedings of the 24th International Conference on Composite Materials (ICCM-24)*, Baltimore, USA.