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Citation for the original published paper (version of record):
Dharmaraj, M., Lorin, S., Lindkvist, L. et al (2026). Assembly Deviation Simulation of Casted Part Assemblies With The Inclusion of Residual Stress. Procedia CIRP, 145: 218-223.
http://dx.doi.org/10.1016/j.procir.2026.03.133

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ScienceDirect

Procedia CIRP 145 (2026) 218–223

www.elsevier.com/locate/procedia

19th CIRP Conference on Computer-Aided Tolerancing (CAT 2026)

Assembly Deviation Simulation of Casted Part Assemblies With The Inclusion of Residual Stress

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Abstract

Residual stress plays an important role in modern manufacturing, especially with the increasing change of manufacturing environment with mega-casting and additive manufacturing. Advanced manufacturing processes introduce several constraints, and one critical constraint to be predicted and controlled is residual stress, which could affect the geometrical quality during assembly. The stresses might lead to displacement and reduce the deviations of the final product. To ensure this, residual stresses are to be measured, predicted, and controlled throughout part manufacturing and assembly. In this paper, the impact of residual stress on geometrical deviation and variations is investigated through a case study: a small-scale cast bracket structure. A combined approach of casting simulation and variation simulation is applied to quantify the residual stress and to integrate, and identify the influence of residual stress during assembly in geometrical variations. The simulation results emphasize the role of residual stress in the deformations and the tolerances of the assembly and cast parts. This research demonstrates and also contributes methods for the integration of residual stress and geometry assurance to ensure more reliable assemblies in advanced manufacturing.

Keywords: Residual stress; Advanced manufacturing; Mega-casting; Geometry assurance; Variation simulation; RD&T

1. Introduction

In modern manufacturing, geometrical variation is a critical concern in assemblies [1, 2]. It influences the geometrical quality, functional performance and product life. Conventional variation simulation and tolerance analysis methods often neglect the influence of residual stresses introduced during part manufacturing[3]. However, with the advancement of manufacturing processes such as mega-casting and additive manufacturing, residual stresses have become an influential and unavoidable parameter that affects part and assembly deviations.

Residual stress originate from the uneven thermal and mechanical histories during manufacturing processes such as machining [4], casting [5], welding [6] and additive manufacturing [7]. In particular, during casting process irregular cooling rates and solidification in the cast part can result in significant residual stress after manufacturing [8]. Later when such parts are assembled, release or redistribution of residual stresses could lead to unexpected deformations and variations [9]. This could further lead to compromised assembly quality and non-nominal assembly.

Residual stress prediction in manufacturing processes [10, 11, 12] and geometrical variation analysis in assemblies as separate domains [13, 14, 15, 16] have been extensively addressed in industry and academic research. Though there are various numerical methods to predict residual stresses in manufacturing, their influence on geometrical variation during assembly is often neglected. The primary focus in existing studies is either residual stress on part manufacturing or geometrical variations of assemblies. This non-integration often limits the ability to accurately predict assembly deviations. This gap has become increasingly critical for assembled parts produced from modern manufacturing, where residual stresses may get close to yield strength and influence the assembly constraints. Furthermore, advanced manufacturing demands tighter tolerances and high reliability which requires an integrated simulation ap-

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10.1016/j.procir.2026.03.133

proach that considers stress propagation from part manufacturing into assembly.

Variation simulation is widely used within geometrical assurance to predict the part deviations that propagate into assemblies which could influence the final geometrical quality. It provides early design decisions related to tolerance allocation and assembly strategy by evaluating the deviation of assembled components from their nominal geometry. However, such simulations assume no stress parts and do not explicitly consider manufacturing induced residual stress which may introduce deviations during assembly. This part and assembly deviations are expected to influence the variation simulation results.

Therefore, this paper addresses the gap by presenting a variation simulation approach that explicitly includes residual stresses in the analysis of cast part assemblies. A cast bracket is used as a case study. Prediction of residual stress distributions from casting simulations and their influence on assembly deformations and geometrical variations are investigated. The assembly deviation with and without the inclusion of residual stresses is compared in the bracket assembly. Though the chosen case study is a small scale model, the objective is to understand and interpolate the influence of residual stress on an assembly and integrate the methodology into a large mega-cast model.

This research proposes the integration of residual stress from part manufacturing into a variation simulation domain to determine the impact of residual stress on assembly deviations. The proposed approach provides a base for more realistic and reliable variation simulation of assemblies manufactured with advanced processes.

The rest of the paper is organized as follows. **Section 2** discusses methodology to predict, integrate and evaluate residual stress. **Section 3** introduces the numerical simulation approach and the selected case study. **Section 4** discusses the results of the case study and identifies key insights from the results. **Section 5** concludes the paper with summary and outlines directions of future research with residual stress in consideration.

2. Methodology

The proposed methodology integrates predicted residual stress from casting simulation into geometrical variation analysis during assembly. The approach is carried out in two stages. First stage is the prediction of residual stress using ProCAST [17] and the second stage is the deviations of the assembly in RD&T [18] with an embedded FEA solver. The overall approach enables to investigate the influence of manufacturing residual stress on assembly geometrical variations.

2.1. Residual Stress Prediction on Part

The residual stress distribution in the case study is predicted using ProCAST, a commercial finite element based casting simulation software. The casting process is modeled by defining the part geometry, material properties, casting simulation parameters, and thermal boundary conditions representing the industrial casting. The simulation process involves molten metal flow, heat transfer, solidification and cooling of the cast part. To obtain a realistic residual stress state of the manufactured component, 2 sequential simulations are performed. In the first simulation, the casting process is modeled under mold-constrained conditions to predict residual stress during solidification and cooling. In the second simulation, the cast part is released from the mold to simulate part ejection, allowing stress relaxation and elastic springback.

Thermo-mechanical coupling is applied to compute the residual stress during solidification and subsequent cooling to room temperature. Appropriate thermal and mechanical constraints are applied for the interactions between the cast part, mold, runner and riser during the flow, solidification and cooling in the initial simulation. Furthermore, constraints are modified during part ejection in the next simulation. The resulting residual stress field at the end of the casting process is extracted in specific format and is mapped onto the identical finite element mesh of the part for the assembly analysis. As the mesh is identical during the residual stress data transfer, significant interpolation errors are avoided.

2.2. Residual Stress Integration into Assembly

To evaluate the influence of residual stress on assembly, the predicted residual stress field is imported in to RD&T, a commercial variation simulation and tolerance analysis software. The simulation process involves part deviations, assembly stress, deformation and assembly constraints. The cast part with the exact mesh is modeled as compliant in RD&T and the residual stresses from casting are applied as initial stress conditions. A locating scheme is defined to represent the functional positioning of the parts in the assembly. The locating scheme is implemented through assembly constraints which restrict the relevant degrees of freedom and enable numerical simulation of the assembly. Simulation is then performed to analyze the residual stress interaction with assembly loads and constraints. Assembly simulations are performed with and without the inclusion of residual stress to quantify its contribution to assembly variation.

2.3. Residual Stress Evaluation of Assembly

The impact of residual stress in the assembly is quantified using stress and displacement fields. Comparative analysis of the results identifies the critical areas where residual stress significantly influences assembly geometry. This integrated methodology provides a systematic framework for integrating part residual stress into geometrical variation analysis of assemblies.

This modeling approach ensures that the residual stress introduced during manufacturing process of a part is consistently propagated into the assembly deviation analysis.

3. Numerical Simulation and Case Study

Numerical simulation framework and the selected case study used to investigate the influence of residual stress on geomet-

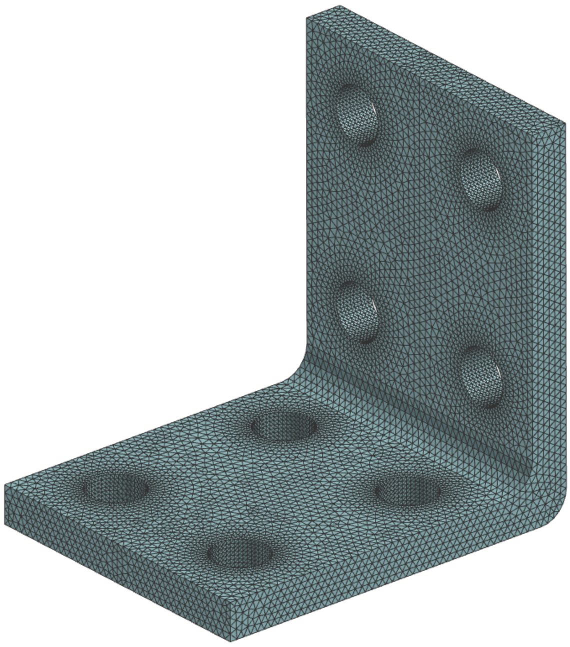

Fig. 1. Finite element model of the Bracket

rical variation during assembly are presented in this section. A cast bracket is chosen as a representative of a small-scale mega-cast part with functional features and relevance in structural assemblies.

3.1. Case Study

A small-scale bracket which is commonly used in structural assemblies is considered as a case study. The bracket geometry is 100 * 100 * 8 *mm* in dimension and has 8 bolt holes as shown in Figure 1 which makes it sensitive to residual stress-induced deformation. Such components are representative of industrial cast parts where dimensional accuracy and assembly robustness are critical.

The bracket is manufactured using a casting process, where non-uniform cooling and constrained solidification introduce residual stresses. These stresses remains in the part and may be released or redistributed when assembled. Therefore, the selected case study provides a suitable model to analyze the interaction between manufacturing-induced residual stress and assembly-induced deformation with minimal computational effort.

3.2. Casting Simulation Setup

The casting process of the bracket is simulated as pre-ejection and post-ejection simulations using ProCAST. The thermo-mechanical modeling framework implemented in ProCAST has been validated in previous studies [19, 20] through comparison with experimental measurements of temperature distribution, casting deformation, and residual stress distribution. Based on these validated methodologies, the current study uses proCAST to identify residual stress fields and propagate them into assembly analysis.

The casting configuration used in the study represents a gating system that is intended to generate a thermo-mechanical response during solidification and cooling. The objective of the casting simulation is to obtain a residual stress distribution that can be imported or interpolated into assembly deviation simulation. This methodology forms a base for future mega-casting simulations with industrial standard gating system and setup.

In pre-ejection simulation, the cast simulation model includes the bracket, mold configuration, runner, riser and the associated material properties. The material of the bracket is aluminum casting alloy (EN AC-AlSi7Mg0.3) and the corresponding thermo-mechanical material properties are used in the simulations. The model is meshed for finite element and has 747,111 elements and 130,601 nodes. Thermal boundary conditions are defined to evaluate the heat transfer between the molten metal and the mold. Mold constraints are imposed to represent realistic casting conditions. After filling, the molten metal is allowed to solidify and cool down to 300 Celsius inside the mold before ejection.

Thermo-mechanical coupling is applied to predict the residual stress during solidification and cooling. Once the bracket is cooled till 300 Celsius, the bracket is ejected from the mold to allow elastic springback. Therefore, in post-ejection, the cast simulation model excludes the mold and includes the thermal and stress fields from the previous simulation. The mesh topology remains the same for the simulation. However, the number of elements and nodes reduces to 153,936 and 33,997, respectively, due to the exclusion of mold. The thermal and mechanical boundary conditions are set for the cast and again a thermo-mechanical simulation is performed until the bracket reaches ambient temperature. The nominal mesh, deformed mesh and residual stress field of the bracket are exported in a compatible format to be used in the assembly simulation.

3.3. Assembly and Variation Simulation Setup

The bracket with the identical mesh that has 153,936 elements from ProCAST is modeled as a deformable component in RD&T environment and is assembled with an identical bracket. The assembly methodology in RD&T environment has been validated with previous studies [3, 13, 14, 21] and has been implemented in several automotive industries. The two brackets are spot welded at four locations. The spot welds are modeled as kinematic constraints to represent the joining between the two brackets. Thermal and mechanical effects of welding process such as weld induced residual stress or thermal distortion are not included in the current study. This assumption is to isolate the influence of casting induced residual stress on assembly analysis. However, this limitation of welding induced stress omission may be considered in future studies to improve the assembly simulation reliability.

The assembly locating schemes (3-2-1 method) are modeled with additional arc of spread clamps as shown in Figure 3 to avoid singularity. Contact points are defined between the

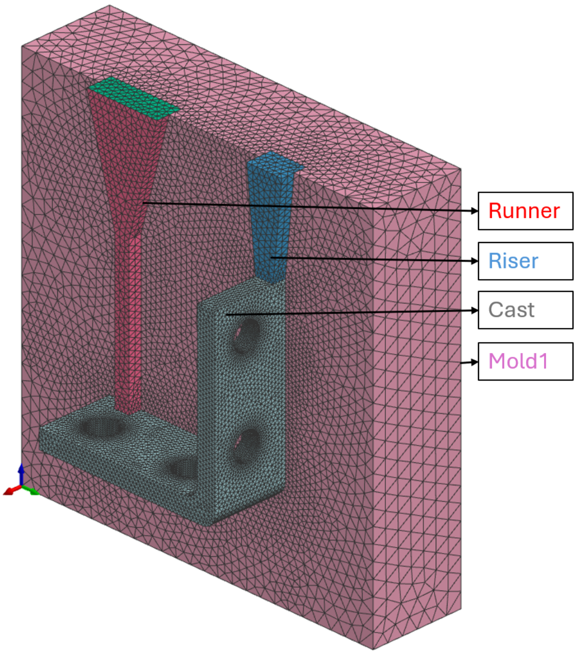

Fig. 2. Finite element model of Bracket with mold, runner and riser

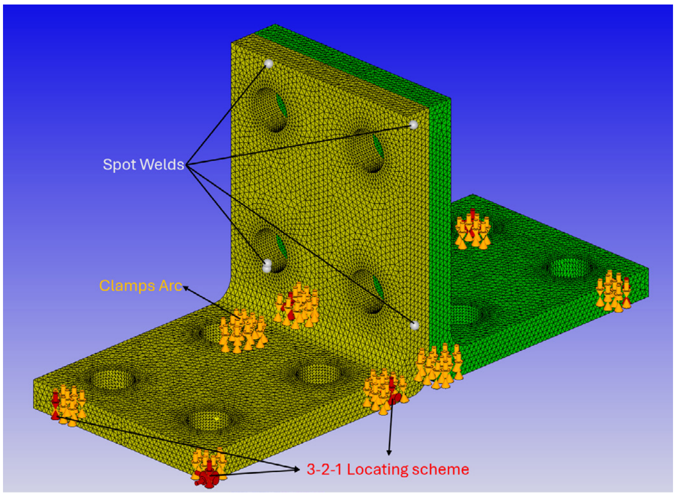

Fig. 3. Assembly of brackets with four Spot Welds

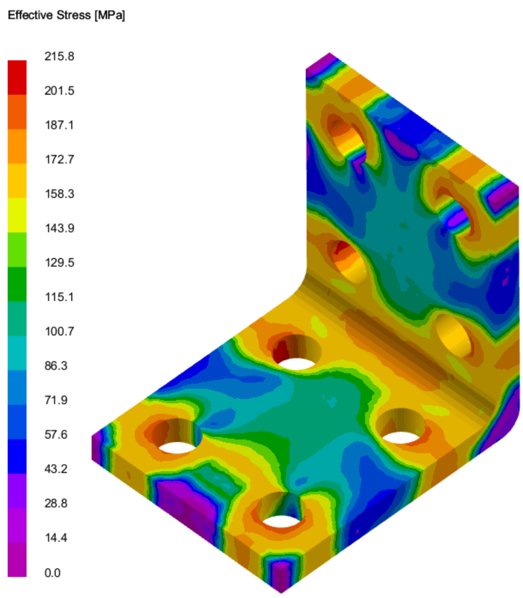

Fig. 4. Post-ejection residual Stress

two brackets to represent the physical interfaces through which forces and constraints are transferred during assembly. The predicted and exported stress field from ProCAST is imported to the exact mesh of the brackets in the assembly.

Results from ProCast, obtained after demolding and cooling to room temperature, were exported to RD&T. Material behavior was modeled using a small-strain elasto-plastic formulation with isotropic hardening and temperature-dependent parameters. The material state was defined at the Gauss points by the stress tensor, accumulated plastic strain, and plastic strain tensor, while the total strain tensor was computed from the displacement field. Temperature and displacement fields were imported at the nodal level.

The imported states were mapped onto two brackets for assembly simulation. One bracket, along with its associated tensor and vector fields, was rotated to achieve the correct fixture orientation. The mechanical solver developed with the proposed methodology predicts the resulting assembly stress and deformations.

4. Results and Discussion

The results of the numerical simulations and the influence of residual stress on geometrical variations during assembly of the cast bracket are discussed in this section. It also focuses on comparing assembly results with and without the inclusion of residual stress.

4.1. Residual Stress After Casting and Ejection

The ProCAST simulations provide distinct residual stress states before and after bracket ejection. In pre-ejection simulation, with mold-constrained cooling the deformation of the bracket is restricted, which results in a distributed residual stress field. After ejection, the mold constraints are removed and the subsequent cooling to ambient temperature leads to stress redistribution as in Figure 4 and elastic deformation of the part. The post-ejection residual stress has higher localized stress levels with maximum von Mises stress increasing from 184.2 *MPa* before ejection to 215.8 *MPa* after ejection. The post-ejection stress field represents a realistic condition of the cast bracket and is used for variation simulation in RD&T.

4.2. Assembly Stress

The influence of residual stress on assembly is evaluated by comparing the displacement and stress results from assembly simulations performed with and without residual stress of the part. In the assembly simulation without residual stress, the maximum von Mises stress is 160.2 *MPa* as shown in Figure

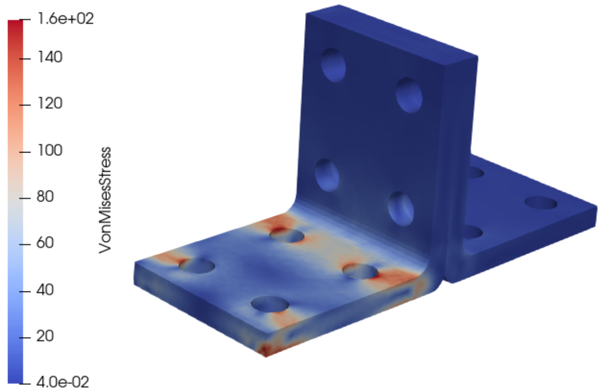

Fig. 5. Assembly stress without inclusion of part residual stress

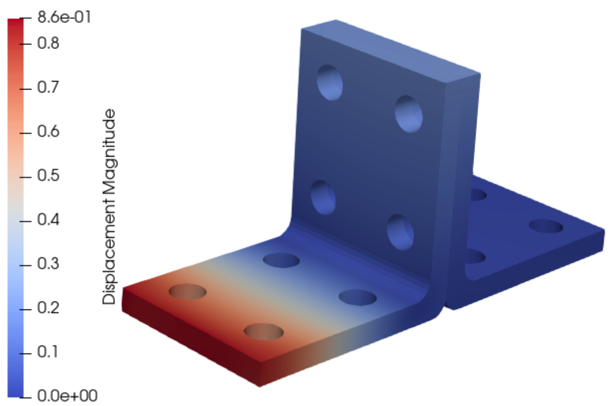

Fig. 6. Assembly displacement without inclusion of part residual stress

Table 1. Comparison of assembly stress and deformation with and without residual stress

	Assembly stress (MPa)	Deformation (mm)
With RS	340	1.1
Without RS	160.2	0.86

5. The maximum displacement is 0.86 *mm* and is localized near one corner edge of the bracket as seen in Figure 6 as it is driven mainly by assembly-induced constraints and loading.

The inclusion of residual stress from casting simulation shows the clear difference in both stress and displacement distribution. The maximum von Mises stress increases significantly to 340 *MPa* as shown in Figure 7. The maximum von Mises stress exceeds the nominal yield strength of the aluminum alloy indicating possible plastic deformation locally and strain hardening. In addition, the maximum displacement increases to 1.1 *mm* and is no longer restricted to one corner but is widely distributed across the bracket geometry as seen in Figure 8. This indicates the influence of residual stress alters the structural stiffness and load redistribution during assembly, which increases global deformation.

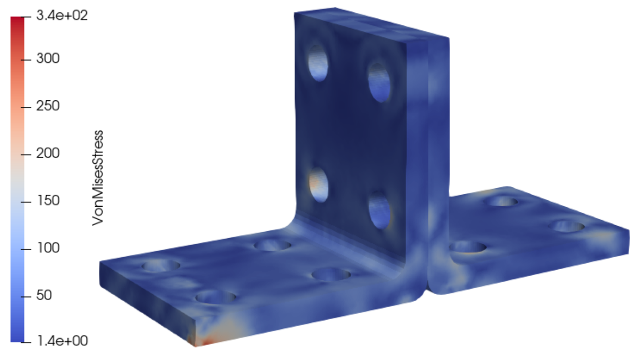

Fig. 7. Assembly stress with inclusion of part residual stress

The comparison shown in Table 1 clearly demonstrates that residual stress contributes to an increase in maximum von Mises stress and displacement values and also a distributed deformation. The observed increase in geometrical deviation shows the sensitivity of assembly behavior to residual stress originating from the casting or any modern manufacturing process. Therefore, ignoring residual stress during assembly deformation could fail to capture the realistic assembly deviation of cast parts. As geometrical variation is driven by these deviations, variation simulation outcomes would be realistic if residual stresses are taken into account for the simulation.

4.3. Discussion

In conventional assembly variation simulations, the parts are considered as stress-free. However, modern manufacturing processes may introduce significant residual stress that influence the deformation behavior of components during assembly. In this work, residual stresses predicted from casting simulation using commercial software using proCAST are integrated into assembly deviation analysis performed with a new methodology implemented in the research module (non-commercial) in RD&T. The objective is to understand the influence and impact of manufacturing-induced residual stress in assembly stress and deviations.

The results confirm that residual stress is an important contributor to assembly stress and deformation. Therefore, including residual stresses increase the accuracy in variation simulations of the assembly. The proposed approach by using the post-ejection residual stress state as input to RD&T ensures a physically realistic representation of the manufactured part. Though, the results are demonstrated with a small-scale bracket as case study and casting as a manufacturing application, the methodology is generic and applicable to other large mega-cast parts and advanced manufacturing processes. The results emphasizes the importance of linking manufacturing process simulation with geometrical assurance to improve assembly quality.

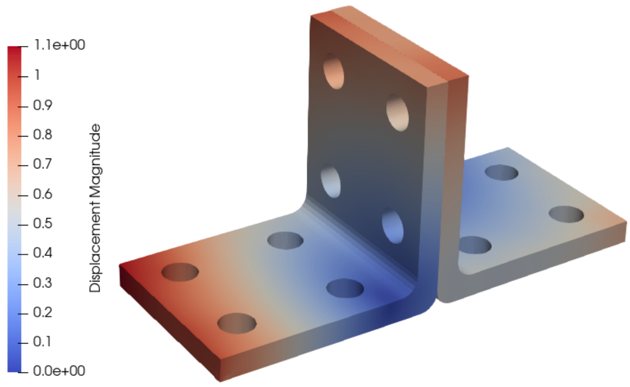

Fig. 8. Assembly displacement with inclusion of part residual stress

5. Conclusion

A variation simulation approach for cast part assemblies that explicitly includes residual stress field is presented in this paper. A bracket is chosen as a case study. The residual stresses predicted from a manufacturing process such as casting were integrated into an assembly variation simulation environment. The results demonstrate that residual stress significantly influences assembly stress, deformation and geometrical deviations. The inclusion of casting-induced residual stress resulted in increased and more widely distributed stresses, as well as higher global displacement in the assembly. The results indicate that residual stress is essential when evaluating geometrical deviations in cast part assemblies. These findings emphasize that residual stress should be considered as an important factor in variation simulation to improve the prediction accuracy of assembly variations.

Although the case study chosen in this study focuses on a relatively small bracket component, the primary objective is to demonstrate an integrated simulation framework that integrates casting induced residual stress into assembly deviation simulations. The methodology to include the interpolation of the residual stress field from casting to assembly analysis is scalable and applicable to mega-castings where the residual stress effects may significantly influence assembly deviation due to mega-casting process parameters.

The research shows that neglecting residual stress in variation simulation approaches could underestimate the deformation and variation in assemblies. This can be avoided by integrating the proposed methodology in geometrical assurance workflows. This integration also helps to achieve more realistic assemblies. Furthermore, the proposed methodology provides a base for future research on integrating manufacturing process effects into assembly variation analysis.

The research will be further extended with real-time mega-cast parts, medium-scale parts, large-scale parts, and other advanced manufacturing processes. Furthermore, future work will focus on extending the proposed framework into manufacturing and assembly parameter optimization with residual stress influence.

Acknowledgment

This work was carried out at the Wingquist Laboratory within the Area of Advance Production at Chalmers University of Technology and supported by Sweden's Innovation Agency (VINNOVA). The support of the project Gromcap (grant ID 2023-00802) is gratefully acknowledged.

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