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PREDICTION OF RESIDUAL DEFORMATIONS IN PRODUCTS MANUFACTURED BY SELECTIVE LASER SINTERING

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Abstract. *This study addresses the critical challenge of predicting residual deformations in industrial products manufactured using selective laser sintering (SLS) technology. Residual deformations represent one of the primary factors leading to geometric inaccuracies in SLS-produced parts, directly affecting their functional performance and dimensional precision. The research proposes and validates a novel hypothesis that existing prediction models developed for plastic injection molding can be effectively adapted for SLS applications through appropriate conversion factors. Given the absence of specialized tools for SLS deformation prediction in the current market, this approach leverages the mature capabilities of the SOLIDWORKS Plastics software as an alternative solution. The methodology involves creating finite element models of test components, specifying material properties similar to SLS powders, and simulating thermal conditions that mimic the SLS process. Through a comparative analysis of twelve distinct geometries, a significant correlation between predicted deformations and actual measured deformations was established. This coefficient enables reliable translation between simulation results and actual SLS outcomes. The findings demonstrate that technological compensating deformations can be effectively calculated and applied to original triangulation models, substantially reducing geometric deviations in final products. The research bridges the gap between established injection molding simulation techniques and the rapidly evolving field of additive manufacturing, providing a practical approach to enhance dimensional accuracy without requiring specialized SLS deformation prediction software. This research was developed at the Department of "Integrated Technologies of Mechanical Engineering" named after M. Semko of NTU "KhPI".*

Keywords: *technology planning; selective laser sintering; residual deformation; triangulation models; technological compensating deformations*.

1. Introduction

Industrial products manufactured using selective laser sintering (*SLS*) are accompanied by residual deformations [1]. These residual deformations are one of the main reasons for deviations from the correct geometric shape of manufactured products [2].

One effective method for reducing deviations from the correct geometric shape is the application of technological compensating deformations to the original triangulation models [3]. These technological compensating deformations should correspond to the pattern of predicted (expected) residual deformation of the product and be opposite in sign. To perform compensating deformations of the original triangulation models, the values of expected residual deformations of the base surfaces must be determined.

The main parameters of compensating deformation are the deflection arrow and the relative displacement of the deformation curvature center.

No methods for predicting residual deformations in products manufactured through selective laser sintering were found in the literature review. Therefore, making predictions by adapting existing methods from other technologies that share similar features with selective laser sintering presents a significant research challenge.

2. Review of the literature

Residual deformations in *SLS* primarily result from thermal gradients and phase changes during the manufacturing process. Examined residual stresses in *SLS* through a comprehensive study comparing three different assessment methods: neutron diffraction (non-destructive), contour method (destructive), and finite element analysis (theoretical). Their work identified two key mechanisms behind residual stress formation: thermal gradient-induced elastic-plastic deformation during cooling and restricted deformation of top layers by underlying material during melting [4].

Building on thermal gradient mechanisms, investigated how processing parameters affect thermomechanical behavior in *SLS* of polyamide 12. Their research utilized *COMSOL* Multiphysics to simulate the thermo-mechanical phenomena, demonstrating that heat transfer patterns in different polyamide composite powders significantly impact residual deformation patterns [5].

Recent simulation methods have significantly advanced *SLS* deformation prediction. It is demonstrated through finite element analysis that increasing hatch spacing reduces residual stress in AlSi10Mg parts [6]. For industrial applications, it developed an inherent strain multiscale model that cuts computation time from weeks to hours while maintaining accuracy for complex geometries [7]. Similarly, it created a practical multiscale finite element approach for rapid distortion prediction with different scanning strategies, balancing computational efficiency with prediction accuracy [8].

Developed a dimensional compensation algorithm specifically addressing vertical bending deformation in *SLS*-printed *PA12* parts. Their method analyzes deformation patterns using a polynomial regression model in global Cartesian coordinates and implements an inverse transformation on the original *CAD* model. Experimental validation showed that this approach effectively reduced bending deformations in various samples, including automotive components [9].

Taking a different approach, presented a new methodology for predicting and compensating distortion in selective laser melting at component scale. Their innovative approach uses a calibrated analytical thermal model to derive functions that are implemented in structural finite element analysis, reducing computational time while maintaining accuracy. Their method includes both *FE*-predicted distortion compensation and optical *3D* scan measurement-based compensation [10].

Most recently, it introduced a data-driven distortion compensation framework for laser powder bed fusion processes. Their approach combines the experimentally calibrated inherent strain method with Gaussian process regression to create compensated geometries. Experimental validation demonstrated impressive results, reducing maximum distortion by up to 82.5% for lattice structures and 77.8% for canonical parts [11].

Material properties significantly impact *SLS* deformation patterns. It found layer thickness directly influences residual stress in Ti6Al4V parts, with thinner layers creating higher stresses despite potential mechanical property improvements [12]. For polymers, it highlighted how material composition affects thermal behavior, noting that understanding segregated filler networks along particle boundaries is critical for predicting deformations in composite materials [13].

Despite advances in *SLS* deformation prediction, several research gaps persist: models for multi-material interfaces as new technologies emerge; integration with topology optimization to create designs inherently resistant to warping; standardized benchmarking protocols; microstructure-informed models incorporating material evolution; and comprehensive studies on applying injection molding simulation tools to *SLS* across diverse geometries and materials.

Recent advances in *SLS* deformation prediction have significantly improved our understanding of the underlying mechanisms and our ability to compensate for these effects. The trend toward integrated approaches that combine simulation, machine learning, and in-process monitoring shows particular promise. However, material-specific challenges and the increasing complexity of *SLS* applications continue to drive the need for more sophisticated prediction methodologies.

Our current research addresses a specific gap in the literature by establishing quantitative relationships between deformation predictions from injection molding simulation software and actual *SLS* outcomes, providing a practical pathway for utilizing existing commercial tools in *SLS* applications.

3. Prediction process in Solidworks plastics

The prediction of residual deformations was conducted using the Solidworks Plastics software package. An example of the system's screen form with the researched product model is presented in Fig. 1.

The workflow begins with the original *CAD* model and progresses through simulation in SOLIDWORKS Plastics, where thermal and mechanical analyses are performed to predict deformation patterns. The visualization of predicted deformations using the *HSV* color scale provides critical insights into potential problem areas before physical manufacturing begins. This process forms the foundation for applying technological compensating deformations to the initial triangulation models.

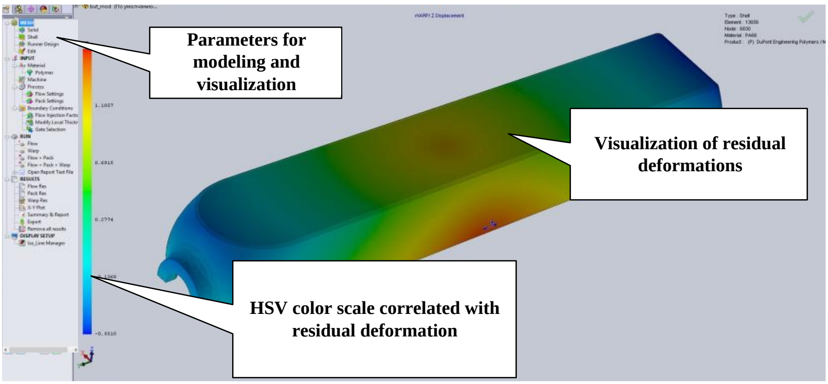

Figure 1 – Workflow for predicting residual deformations in selective laser sintering using Solidworks Plastics

As shown in Fig. 1, the prediction process incorporates several critical elements. The initial verification of the triangulation model ensures surface closure, a prerequisite for accurate simulation. The finite element model construction determines the resolution of the prediction, with element characteristics based on the original triangulation model. Thermal analysis represents the heart of the simulation, where material properties, process parameters (including 230°C processing temperature), and cooling conditions are defined to mimic *SLS* processing conditions. The resulting color visualization (Fig. 1) represents the magnitude of predicted deformations, with warmer colors (red-yellow) indicating larger deformations and cooler colors (green-blue) showing areas with minimal deformation.

To systematically predict residual deformations in *SLS* manufacturing, a structured workflow was developed as shown in Fig. 2. This process diagram illustrates the sequential steps required for accurate deformation prediction in Solidworks Plastics, from initial model verification through to final visualization. Each step in this workflow has been carefully designed to ensure that the simulation accurately reflects the thermal and mechanical conditions encountered during the *SLS* process, despite the software's original intended application for injection molding simulation.

The process diagram presented in Fig. 2 demonstrates the logical progression of steps necessary for effective deformation prediction. Beginning with triangulation model verification ensures that the input geometry is suitable for analysis, with a closed surface that properly represents the intended part. This is followed by the construction of a finite element model with appropriate mesh density to capture geometric features while maintaining computational efficiency.

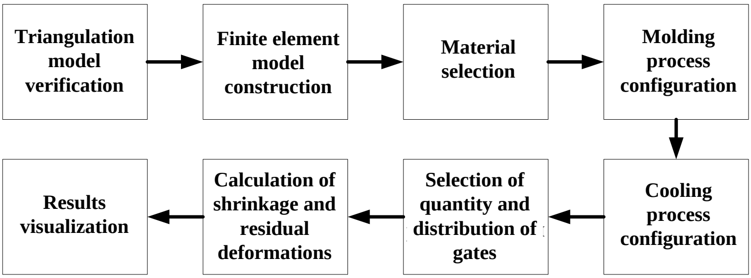

Figure 2 – Schematic diagram of the residual deformation prediction process in Solidworks Plastics

The material selection step is particularly critical, as it establishes the thermo-mechanical properties that govern deformation behavior. For this research, polyamide 66 (*ZYTEL ST801L NC010*) was selected due to its similar characteristics to the *Duraform PA* powder used in *SLS* processing. The process parameters are then defined to simulate *SLS* conditions, including a 230°C processing temperature and appropriate cooling conditions.

The final steps involve the calculation of shrinkage and residual deformations, followed by visualization of the results. This systematic approach enables engineers to predict potential deformation issues before physical prototyping, significantly reducing development time and material waste. Importantly, the established correlation coefficient allows for reliable translation between the simulation predictions and actual *SLS* manufacturing outcomes, making this workflow a valuable tool for industrial applications.

Upon completion of the shrinkage and residual deformation calculations, color visualization of the predicted residual deformations was performed using the *HSV* color scale (Fig. 3).

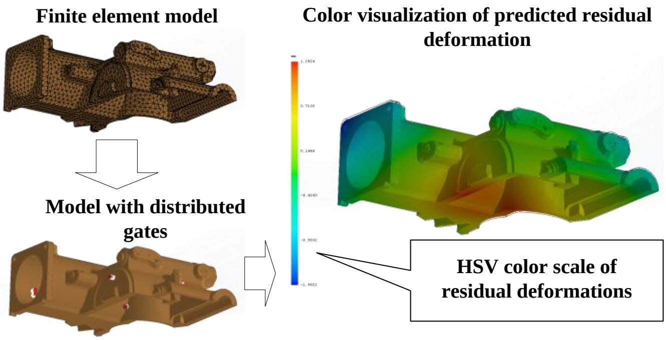

Figure 3 - Visualization of the main stages in residual deformation prediction

The visualization of predicted residual deformations represents a critical component in the analysis process. Fig. 3 illustrates the transformation from a finite element model through to the final visualization of predicted deformations. This visualization process is essential for identifying critical areas prone to dimensional inaccuracies during *SLS* manufacturing, allowing for targeted compensation strategies to be implemented. The visual representation using the *HSV* color scale provides an intuitive understanding of deformation magnitude and distribution across complex geometries.

As demonstrated in Fig. 3, the process begins with the creation of a detailed finite element model that accurately represents the part geometry. This model is then prepared for thermal-mechanical analysis through the strategic placement of gates, which serve as heat input sources simulating the thermal conditions during the *SLS* process. For this study, ten gates were positioned equidistantly to ensure uniform heat distribution, mimicking the gradual cooling experienced in *SLS* manufacturing. This approach eliminates the need for a dedicated cooling system in the simulation, better replicating the *SLS* thermal environment. The final visualization (Fig. 3) employs an *HSV* color scale to represent the magnitude of predicted deformations across the part. Red and yellow regions indicate areas with maximum deformation, while green and blue denote areas with minimal deformation. This color mapping allows designers and engineers to quickly identify problematic features that may require geometric compensation prior to manufacturing.

The ability to visualize deformation patterns before physical production represents a significant advantage, enabling informed decisions about design modifications or compensation strategies.

4. Results and Validation

To validate the hypothesis that injection molding simulation can be adapted for *SLS* deformation prediction, a correlation analysis was conducted between simulated and measured deformations. Fig. 4 presents the empirical relationship between predicted deflection values from SOLIDWORKS Plastics (ΔF_p) and actual measured deflections in *SLS*-manufactured parts (ΔF_c). This relationship is fundamental to the practical application of the proposed methodology, as it establishes a quantitative basis for translating simulation results to expected real-world outcomes.

The scatter plot in Fig. 4 demonstrates a strong positive correlation between the predicted deformation values from SOLIDWORKS Plastics (Δ_{Fp}) and the experimentally measured deformations in *SLS*-manufactured parts (Δ_{Fc}). The data points, representing 12 different test geometries, show a consistent linear trend that can be expressed by the equation $\Delta_{Fc} = k_p \cdot \Delta_{Fp}$. Through least squares regression analysis, the coefficient k_p was determined to be 1.28±0.08 at a significance level of 0.05.

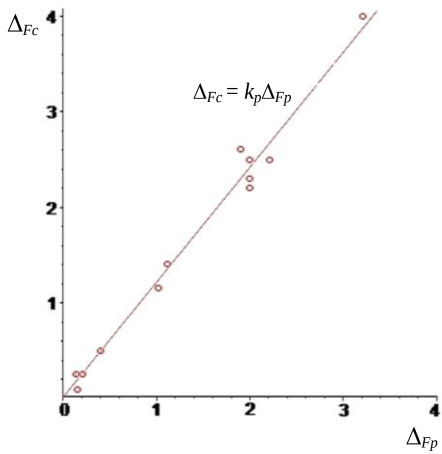

Figure 4 - Correlation between experimental deflection values (Δ_{Fp}) measured on SLS-manufactured parts and predicted deflection values (Δ_{Fp}) from SOLIDWORKS Plastics simulation

This correlation coefficient is particularly significant as it provides a simple yet effective means to convert simulation predictions into practical expectations for actual *SLS* manufacturing outcomes. The value of $k_p > 1$ indicates that real *SLS* parts consistently exhibit larger deformations than those predicted by SOLIDWORKS Plastics, likely due to differences in material behavior and processing conditions between injection molding (for which the software was designed) and selective laser sintering.

The strong linear relationship observed across various geometries validates the core hypothesis of this research: that with appropriate scaling, existing injection molding simulation tools can be effectively repurposed for *SLS* deformation prediction. This finding has significant practical implications, as it enables manufacturers to leverage widely available simulation software for *SLS* applications without requiring specialized and often more expensive dedicated *SLS* simulation tools. The established correlation coefficient serves as a reliable conversion factor that bridges the gap between these two manufacturing domains.

5. Discussion of Results

The experimental investigation conducted in this study has provided significant insights into the prediction and compensation of residual deformations in selective laser sintering manufacturing. Several key findings emerge from the analysis of the results.

The strong linear correlation between predicted deformations from SOLIDWORKS Plastics (ΔF_p) and measured deformations in *SLS*-manufactured parts (ΔF_c) confirms the validity of using injection molding simulation software for *SLS* applications. This cross-technology approach leverages the established capabilities of widely available simulation tools while addressing the specific deformation challenges in *SLS* manufacturing. The consistency of the correlation across 12 different test geometries, with varying complexities and feature characteristics, suggests that this approach is robust and applicable to a range of industrial components.

The determined correlation coefficient ($k_p = 1.28 \pm 0.08$) represents a critical advancement in bridging theoretical predictions and practical outcomes. This coefficient encapsulates the systematic differences between the two manufacturing processes, including variations in material behavior, thermal gradients, and solidification mechanisms. The value of $k_p > 1$ indicates that *SLS* components consistently experience approximately 28% greater deformation than what the injection molding simulation predicts. This quantitative relationship allows for reliable translation between simulation results and expected manufacturing outcomes.

The simulation approach using distributed heat sources (gates) and the absence of a dedicated cooling system successfully replicates the gradual cooling conditions characteristic of the *SLS* process. The thermal simulation results, visualized through the *HSV* color scale, accurately predict the patterns of deformation, even if the absolute magnitudes require scaling through the correlation coefficient. This indicates that the fundamental thermal mechanisms driving deformation in both injection molding and *SLS* have sufficient similarities to enable effective cross-process prediction.

Based on the established correlation, technological compensating deformations can be systematically applied to original triangulation models with confidence. By applying inverse transformations scaled by the factor k_p, manufacturers can proactively mitigate anticipated deformations. This predictive compensation strategy eliminates the need for multiple iterative manufacturing attempts to achieve dimensional accuracy, thereby reducing material waste, energy consumption, and production time.

While the approach has demonstrated high efficacy across the tested geometries, certain limitations must be acknowledged. The correlation coefficient is specific to the material pair used in this study (ZYTEL ST 801 L NC010 in simulation and Duraform PA in *SLS* manufacturing) and would need recalibration for different materials. Additionally, extremely complex geometries with very thin features or sharp transitions may exhibit non-linear deformation behaviors that require more sophisticated modeling approaches.

Compared to developing dedicated *SLS* simulation software or conducting extensive empirical testing, the proposed approach offers significant advantages in terms of accessibility, computational efficiency, and integration with existing design workflows. The method reduces the barrier to entry for predicting *SLS* deformations, making high-quality additive manufacturing more accessible to a broader range of industrial applications where dimensional accuracy is critical.

This analysis demonstrates that adapted injection molding simulation offers a viable and effective pathway for predicting and compensating for residual deformations in *SLS* manufacturing. The established correlation coefficient provides the necessary bridge between simulation and reality, enabling manufacturers to leverage existing software tools to enhance the dimensional accuracy of *SLS*-produced components.

6. Conclusions

The hypothesis regarding the possibility of predicting residual deformations in products manufactured by selective laser sintering using approaches developed for plastic injection molding has been validated. The established correlation between Solidworks Plastics predictions and actual *SLS* deformations demonstrates that existing simulation tools can be effectively adapted for *SLS* applications.

The proposed methodology for predicting residual deformations includes triangulation model verification, finite element model creation, material selection, process parameter definition, and simulation of deformations using distributed heat sources to replicate *SLS* thermal conditions.

The methodology enables the determination of critical parameters for technological compensating deformations, including the deflection arrow and the relative displacement of the deformation curvature center, which can be applied to original *CAD* models to improve dimensional accuracy.

The approach offers significant practical advantages for industry, including:

- utilization of widely available simulation software instead of specialized SLS deformation prediction tools;
- reduction in material waste and production time by decreasing the need for iterative physical prototyping;
- improved dimensional accuracy of final *SLS*-manufactured components.

This research addresses a significant gap in the field of additive manufacturing by providing a practical, accessible approach to predicting and compensating for residual deformations in *SLS*-manufactured parts. The established correlation coefficient serves as a valuable bridge between injection molding simulation and *SLS* manufacturing reality, enabling more accurate production of complex components with reduced trial-and-error iterations.

Future work should focus on extending this approach to a wider range of materials, investigating more complex geometries, and potentially integrating the methodology with topology optimization to develop designs inherently resistant to deformation during the *SLS* process.

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ПРОГНОЗУВАННЯ ЗАЛИШКОВИХ ДЕФОРМАЦІЙ ВИРОБІВ, ВИГОТОВЛЕНИХ ЗА ДОПОМОГОЮ СЕЛЕКТИВНОГО ЛАЗЕРНОГО СПІКАННЯ

Анотація. *Дослідження розглядає критичну проблему прогнозування залишкових деформацій у промислових виробах, виготовлених за допомогою технології селективного лазерного спікання (SLS). Залишкові деформації є одним з основних факторів, що призводять до геометричних неточностей у деталях, виготовлених за допомогою SLS, безпосередньо впливаючи на їх функціональні характеристики та точність розмірів. Дослідження пропонує та підтверджує нову гіпотезу про те, що існуючі моделі прогнозування, розроблені для лиття пластмас під тиском, можуть бути ефективно адаптовані для застосування SLS за допомогою відповідних коефіцієнтів перетворення. Враховуючи відсутність спеціалізованих інструментів для прогнозування деформації SLS на сучасному ринку, цей підхід використовує відомі можливості програмного забезпечення SOLIDWORKS Plastics як альтернативне рішення. Методологія включає створення моделей скінченних елементів тестових компонентів, визначення* *властивостей матеріалу, подібних до порошків SLS, та моделювання теплових умов, що імітують процес SLS. Завдяки порівняльному аналізу дванадцяти різних конструкцій виробів було встановлено значну кореляцію між прогнозованими деформаціями та фактично виміряними деформаціями. Цей коефіцієнт забезпечує надійне перетворення між результатами моделювання та фактичними результатами SLS. Результати дослідження демонструють, що технологічні компенсуючі деформації можна ефективно розраховувати та застосовувати до оригінальних моделей тріангуляції, що суттєво зменшує геометричні відхилення в кінцевих виробах. Дослідження усуває розрив між усталеними методами моделювання лиття під тиском та адитивного виробництва, забезпечуючи практичний підхід до підвищення точності розмірів без необхідності спеціалізованого програмного забезпечення для прогнозування деформації виробів одержаних методом SLS. Дослідження виконувались на кафедрі «Інтегрованих технологій машинобудування» імені М.Ф. Семка НТУ «ХПІ».*

Ключові слова: *технологічна підготовка; селективне лазерне спікання; залишкова деформація; моделі тріангуляції; технологічні компенсуючі деформації.*