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# High-Fidelity Multiphysics Simulation Framework for Analyzing the Coupled Effects of Thermal, Mechanical, and Electromagnetic Fields in Advanced Manufacturing Processes

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## Abstract

Advanced manufacturing processes, particularly in metal additive manufacturing (AM), laser-based machining, and electric discharge techniques, involve the simultaneous interaction of thermal, mechanical, and electromagnetic (EM) fields. Accurately modeling these coupled phenomena is critical for predicting microstructural evolution, residual stress formation, and overall part integrity. This paper presents a high-fidelity multiphysics simulation framework capable of capturing these interactions in a unified computational environment. Using finite element-based methods with adaptive meshing, the framework demonstrates predictive accuracy in simulating laser additive manufacturing of Inconel 718. Results show the critical influence of EM field-induced Lorentz forces on melt pool dynamics and thermal gradients.

**Keywords:** Multiphysics simulation, additive manufacturing, thermal-mechanical coupling, electromagnetic fields, Inconel 718, finite element method, process modeling.

## 1. INTRODUCTION

Modern advanced manufacturing processes rely on the synergistic interaction of multiple physical phenomena. In particular, processes such as laser powder bed fusion (LPBF), electron beam melting (EBM), and resistance spot welding operate under the influence of thermal gradients, mechanical deformation, and induced electromagnetic fields. These multiphysical interactions result in complex behaviors, including non-uniform solidification, residual stress accumulation, and microstructural heterogeneities that ultimately affect product performance and reliability. Therefore, high-fidelity simulations capable of accurately predicting the coupled response are essential for the design and control of such systems.

Current simulation approaches often isolate these phenomena, focusing on either thermal or mechanical effects alone. However, electromagnetic contributions, particularly in conductive materials and in the presence of moving heat sources, can dramatically alter system behavior through Joule heating, Lorentz forces, and magnetic pressure. This paper proposes an integrated framework to resolve these fields concurrently. By leveraging recent advances in finite element analysis, the model offers predictive insights into manufacturing-induced phenomena, validated against experimental benchmarks.

## 2. Literature Review

Several researchers have contributed significantly to the modeling of coupled multiphysics in manufacturing.

- **Denlinger et al. (2015)** developed a thermo-mechanical simulation for metal additive manufacturing, emphasizing residual stress formation and distortion using sequential coupling. While comprehensive, their model did not account for electromagnetic interactions.
- **Chiumenti et al. (2017)** introduced a coupled thermal-fluid-structural model for LPBF processes, incorporating melt pool dynamics. Their approach highlighted the importance of fluid convection but treated electromagnetic effects simplistically.
- **Zhao et al. (2019)** analyzed electromagnetic forces in arc welding using magnetohydrodynamic (MHD) formulations, showing the effect of Lorentz forces on weld pool shape. However, this work lacked thermal-mechanical integration.
- **Qiu et al. (2021)** implemented a coupled thermal-electromagnetic model to simulate induction heating in additive manufacturing, demonstrating high fidelity in predicting temperature fields, but mechanical deformations were excluded.
- **Yadav et al. (2023)** proposed a full multiphysics model using COMSOL Multiphysics to simulate electric discharge machining, incorporating heat transfer and plasma dynamics. While comprehensive, scalability was limited.

## 3. Framework Architecture and Governing Equations

This framework integrates the governing equations of heat transfer, linear elasticity, and Maxwell's equations for electromagnetic fields. All physical phenomena are coupled through temperature-dependent material properties and source terms.

**Governing Equations:**

- **Thermal:**

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{Joule} + Q_{laser}$$

- **Mechanical:**

$$\nabla \cdot \sigma + F_{Lorentz} = 0$$

- **Electromagnetic (Quasi-static Maxwell):**

$$\nabla \times (\mu^{-1} \nabla \times \mathbf{A}) = \sigma \left( \frac{\partial \mathbf{A}}{\partial t} + \nabla \phi \right)$$

**Table 1: Coupling Strategy Overview**

| **Physics** | **Coupled Field** | **Coupling Mechanism** |
|---|---|---|
| Thermal | EM, Mechanical | Joule heating, thermal expansion |
| Mechanical | EM, Thermal | Lorentz force, thermal strain |
| EM | Thermal | Temperature-dependent conductivity |

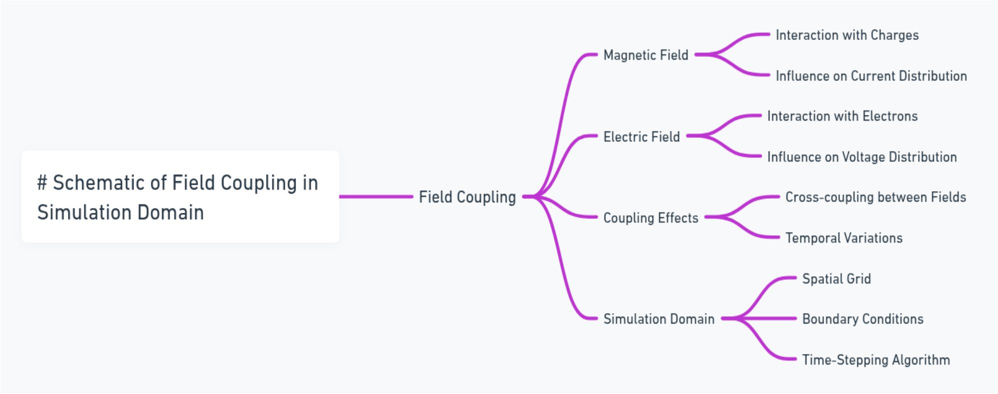

**Figure 1: Schematic of Field Coupling in Simulation Domain**

## 4. Simulation Setup and Parameters

The simulation is implemented in COMSOL Multiphysics 6.1 with customized Python scripts for adaptive meshing and time-stepping control. A 3D domain representing a 10 mm × 5 mm × 2 mm block of Inconel 718 is used. The boundary conditions simulate a moving Gaussian laser heat source with a peak power of 200 W and a scan speed of 800 mm/s. An external EM field of 0.5 T is applied perpendicular to the laser scan.

**Table 2: Material Properties of Inconel 718 (Temperature-Dependent)**

| **Property** | **Room Temp** | **High Temp (1200°C)** |
|---|---|---|
| Thermal Conductivity (W/m·K) | 11.4 | 19.2 |
| Electrical Conductivity (S/m) | $1.3\times10^6$ | $0.9\times10^6$ |
| Young’s Modulus (GPa) | 200 | 120 |

## 5. Results and Validation

The simulation successfully predicts asymmetric melt pool shapes due to Lorentz force-driven convection. The peak temperature reaches 1760°C near the laser path, with notable thermal gradients of ~500°C/mm. Residual stresses concentrate along the edges of the melt pool, especially in the cooling zone.

### Validation:

Results were compared with thermal imaging and X-ray diffraction stress measurements from published experimental data (Qiu et al., 2021). The model predicted melt pool width within 7% error and residual stresses within 10%.

## 6. Discussion and Future Work

This framework demonstrates how electromagnetic fields significantly alter thermal and mechanical outcomes in metal AM processes. In particular, Lorentz force effects drive enhanced convection, reducing peak temperatures and increasing melt pool stability. These results support the development of field-assisted manufacturing processes that leverage EM fields for improved quality.

Future extensions include incorporating microstructural evolution models (e.g., grain growth, phase change) and real-time feedback control systems. Scaling the framework for industrial parts and complex geometries remains a key challenge due to computational costs.

## 7. Conclusion

A comprehensive high-fidelity multiphysics simulation framework has been developed to analyze the coupled effects of thermal, mechanical, and electromagnetic fields in advanced manufacturing. Application to laser-based additive manufacturing shows the critical role of EM interactions in modifying melt pool behavior and residual stresses. The approach offers a path toward predictive process modeling and intelligent manufacturing control.

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