Master Thesis

Title

Analysis of microstructure and its effect on the tribo-mechanical properties of L-DED processed LTT-based Fe-C-B-Cr-X tool steels

Introduction

Laser Directed Energy Deposition (L-DED) is a rapidly advancing additive manufacturing (AM) technique known for its high material deposition rate and flexibility, making it attractive for various industrial applications. However, when processing tool steels via L-DED, cracks and porosity may arise due to rapid solidification and must be scientifically addressed. Some alloys are more prone to such defects, and additional potential causes may include process parameters if not studied properly. While chemical composition and optimizing process parameters can help, alloy design strategies such as the Low Transformation Temperature (LTT) approach offer a more effective solution by reducing residual stresses through delayed martensitic transformation.

A fundamental understanding of the solidification behavior and microstructural evolution of LTT-based Fe-C-B-Cr-X tool steels are essential for their successful implementation in L-DED. This project investigates how variations in L-DED parameters influence microstructural features—such as hard phases including borides and carbo-borides, and retained austenite—and their subsequent impact on tribo-mechanical properties, namely wear resistance, hardness, and toughness. The insights gained will contribute to optimizing L-DED processing conditions and advancing alloy design for additive manufacturing processes.

Scientific and technological questions

- How do L-DED process parameters influence solidification behavior, defect formation, and microstructure evolution in LTT-based Fe-C-B-Cr-X tool steels?
- What correlations exist between L-DED processing conditions (laser power, scan speed, powder feed rate, exposure time, and energy density) and the resulting wear properties and hardness?
- To what extent do thermodynamically predicted solidification behaviors align with experimental observations?
- How does sample geometry affect microstructure formation in terms of porosity and cracks in thick and thin sections?

Methodology

The project combines computational modeling and experimental validation to examine the relationship between process parameters, microstructure, and tribo-mechanical properties. In the computational approach, Thermo-Calc is utilized to select the Fe-C-B-Cr-X alloy system based on the LTT strategy. The martensitic transformation temperatures (Ms) are predicted to ensure reduced residual stresses and minimize cold cracking.

For experimental procedures, L-DED samples are fabricated using X50CrMoB10-2-1 powder with the controlled addition of pure elements to produce geometries with thick and thin sections under different process parameters on mild steel substrate plate. The microstructure is analyzed using light and scanning electron microscopy (SEM) to evaluate defects such as cracks and porosity. The phase identification using X-ray Diffraction (XRD), or synchrotron XRD.

Grain size, hard phase volume fraction, and phase composition are further characterized using electron back scattered diffraction (EBSD), energy dispersive X-ray spectroscopy (EDX). Residual stresses are measured using the Stresstech X-ray diffraction device, with a particular focus on retained austenite content and internal stress distributions. Tribo-mechanical properties are evaluated through scratch testing to determine wear resistance, while microhardness testing assesses hardness variations across different microstructures followed by 4-point bending test.

Work packages

WP1: Literature review and training (Month 1)

The initial phase involves a comprehensive review of relevant literature in the domains of L-DED, additive manufacturing, boron-alloyed tool steels, and LTT steels. The literature search focuses on identifying previous studies regarding the influence of process parameters on solidification behavior. Research databases such as Google Scholar, Elsevier, Springer, and Wiley are utilized. Additionally, this phase includes hands-on training on Thermo-Calc, experimental techniques, and data analysis tools to ensure familiarity with key methodologies.

WP2: Computational methods (Months 2)

This phase focuses on performing CALPHAD simulations using Thermo-Calc to predict the Ms temperature based on built-in models in the software and other empirical models such as Andrews and Ishida's equations. Phase stability is examined under equilibrium and Scheil-Gulliver solidification models to predict the formation of hard phases and phase transformations during solidification.

WP3: Experimental fabrication and characterization (Months 3-4)

The experimental phase involves the fabrication of L-DED samples under varying process conditions, including laser power, scan speed, exposure time, powder feed rate, and in-situ admixing of additional powders (if required). The dilatometry of the L-DED-produced samples is to be conducted with various cooling rates and holding times. A minimum of 50 samples will be produced, followed by an immediate assessment of porosity and cracking after metallographic preparation using OM and SEM. Based on the optimized parameters, selected samples with varying thick and thin sections will undergo thorough characterization, including microstructural analysis using SEM, chemical composition assessment via EDX, and phase identification using XRD or Synchrotron XRD. Additionally, EBSD may be employed to analyze grain structure and phase distribution. To evaluate mechanical performance, residual stress measurements, wear resistance testing, microhardness, and 4-point bending flexure tests will be conducted.

WP4: Data analysis (Month 5)

This phase involves comparing computational predictions with experimental results to assess deviations and refine model accuracy. The correlation between microstructural features and processing parameters is established, with a focus on optimizing process parameters to minimize porosity, residual stresses, and cold cracking. The results are critically evaluated to identify potential discrepancies between Thermo-Calc simulations and experimental outcomes, leading to adjustments in modeling assumptions or experimental conditions.

WP5: Reporting and presentation (Month 6)

The final phase is dedicated to data interpretation and discussion. The interactions between processing parameters and their effects on microstructure and mechanical properties are systematically analyzed. The findings are compiled into a scientific report, which discusses key insights and potential applications of the developed methodologies in research and industrial applications. The project culminates with a final presentation and possible publication of results in academic journals.

Expected outcomes

- Identification of optimal L-DED parameters for LTT-alloys.
- Improved understanding of the relationship between processing conditions, microstructure, and residual stresses.
- Insights into tribo-mechanical properties, including wear resistance, hardness, and toughness properties.
- Development of recommendations for minimizing porosity and cold cracking in AM processes.

Resources required

- Software: Thermo-Calc
- Equipment: Metallography, Dilatometer, L-DED system, SEM, EBSD, XRD, Stresstech X-ray diffraction device, scratch tester for wear, nanoindenter.
- Materials: LTT-based tool steel powders.

Project summary

This project investigates the microstructure and tribo-mechanical properties of LTT-based boron-alloyed tool steel in the Fe-C-B-Cr-X system processed via L-DED. The research aims to identify optimal L-DED parameters to mitigate porosity and cold cracking—key challenges in AM. A combination of computational modeling and experimental validation is employed to evaluate the impact of alloy composition and process parameters on residual stresses, microstructural evolution, and retained austenite formation. The findings contribute to improving alloy design strategies for AM applications and optimizing L-DED processing conditions for enhanced material performance. The results will be submitted for publication in a peer-reviewed journal to advance scientific and industrial knowledge in the field.