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Mechanical Performance and Manufacturing Innovations in FFTs and TPMS via Additive Manufacturing and AM-Assisted Casting

predavateljica

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red. prof. dr. Zoran Ren

Priloge: Povzetek in vsebina predavanja

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Talk Summary

This talk is divided into two complementary parts, both focused on the development and testing of innovative lightweight lattice structures using additive manufacturing (AM) and AM-assisted casting.

Part 1 explores Foam-Filled Tubes (FFTs) as energy-absorbing structures. It presents the motivation for studying FFTs, details traditional and hybrid AM–casting manufacturing methods, and highlights current challenges such as incomplete struts and residual investment material. The talk includes Flow 3D simulations that suggest a new hypothesis: defects arising from shrinkage during cooling due to high temperature gradients. Mechanical compression testing results are discussed, showing differences in performance between AM and cast samples, followed by derived mechanical properties like specific energy absorption. The findings emphasize the potential of AM-assisted casting if manufacturing issues are solved, which could be supported by future parametric simulation studies.

Part 2 focuses on tensile fatigue testing of triply periodic minimal surface (TPMS) structures produced by AM-assisted casting. Following quasi-static tensile tests to determine yield strength, high-cycle tensile fatigue tests were performed on diamond and gyroid structures in both solid and sheet configurations. Results include fatigue life data and an assessment of how geometry and topology influence fatigue behavior. These insights inform design strategies for lightweight, fatigue-resistant components.

Together, the two parts illustrate how combining experimental testing and simulation can help overcome manufacturing challenges and advance the development of high-performance, lightweight structural components.

PART 1: Foam Filled Tubes - From AM to AM-Assisted Casting

Abstract

Foam-Filled Tubes (FFTs) are gaining increasing attention for their ability to enhance structural performance by improving energy absorption and strength-to-weight ratio without significant weight penalties, making them of interest in automotive and lightweight engineering applications. This talk explores advanced manufacturing techniques for FFTs, focusing on direct additive manufacturing (AM) and an innovative hybrid approach combining AM with investment casting (AM-Casting).

We present a comparative analysis of these methods, highlighting their respective advantages and limitations. While direct AM allows high geometric precision and tailored properties, it is challenged by high costs and limited material options. The AM-Casting hybrid process offers a potentially scalable and cost-effective alternative, though current challenges such as incomplete struts and residual material defects remain.

Mechanical testing under compression reveals significant differences in performance between cast and AM samples. To understand the root causes of manufacturing defects, we employ Flow 3D simulations of the investment casting process, proposing a new hypothesis that incomplete struts result from shrinkage caused by high temperature gradients during cooling.

Finally, we discuss the potential of AM-Casting for producing high-quality FFTs if manufacturing challenges are addressed, and outline future work involving parametric simulation studies to optimize process parameters. This research contributes to advancing lightweight structural materials with enhanced mechanical performance for industrial applications.

Outline

Introduction

- Briefly introduce foam-filled tubes (FFTs): what they are and why they are relevant.
- Explain the motivation for studying FFTs: enhancement of structural performance (e.g., energy absorption, strength-to-weight ratio) without compromising weight efficiency, particularly important in the automotive industry and lightweight structures.

Manufacturing:

- Overview of traditional manufacturing methods for FFTs (e.g., random foams, stochastic structures).
- Introduction of additive manufacturing (AM): advantages such as design flexibility, geometric precision, and potential for tailored mechanical performance.
- Talk about how AM led to incorporation of TPMS into FFTs
- Presentation of both manufacturing processes used in this study:
    - Direct AM fabrication of FFTs.

    - AM-assisted casting (hybrid approach): AM used to create patterns for subsequent casting.
- Include a short video of the AM–cast process to illustrate the workflow.

Limitations

- Limitations of AM:
    - High cost.
    - Limited choice of printable metals.
    - Resolution constraints affecting fine structural details.
- Limitations of AM-assisted casting:
    - Incomplete or partially filled struts.
    - Presence of residual investment material inside the structure.
- Visual evidence:
    - Present CT scans and SEM images highlighting these defects, porosity, and other observed imperfections in cast samples.

FEM

- Present and discuss Flow 3D simulations of the investment casting process.
- Introduce a new hypothesis for the appearance of incomplete struts: shrinking while cooling due to high temperature gradients.

Mechanical Properties

- Compression testing:
    - AM-manufactured FFTs.
    - Cast FFTs.
- Direct comparison:
    - Discuss differences in load–displacement response.
    - Comment on failure modes and structural integrity.
    - Comment on the potential of AM-Cast if the samples were to come out complete (motivation to further improve the manufacturing process)

Deduced Mechanical Properties (SEA, Plateau and Peak Stress)

- Present and compare key metrics:
    - Specific energy absorption (SEA).
    - Plateau stress.
    - Peak stress.
- Discuss what these results imply for potential applications and design optimization.

Conclusion

- The results highlight both the promise and current limitations of AM-assisted casting (AM-Cast) for manufacturing FFTs.
- Direct AM fabrication provides excellent geometric control and mechanical performance, but is limited by high costs and restricted material choices.
- AM-Cast presents a promising alternative due to its potential scalability and cost-effectiveness.
- Current issues, such as incomplete struts and residual investment material, reduce the structural integrity of cast samples.
- If the AM-Cast process can be refined to produce complete, defect-free samples, it could combine the design flexibility of AM with the cost benefits of casting.
- This improvement would open opportunities for lightweight, high-performance energy absorbers, particularly in automotive and structural applications.
- Therefore, further optimization of the AM-Cast process is well-motivated and could significantly impact the field.
- Additionally, the FEM simulations provide insights that support a new hypothesis: incomplete struts may result from shrinkage during cooling due to high temperature gradients, highlighting areas for targeted process improvement.
- Future work should focus on running a parametric study with simulations of the AM-Cast process to identify the critical process parameters and their optimal values.

PART 2: Tensile Fatigue Testing of TPMS AM-Casting samples

Abstract

Triply periodic minimal surface (TPMS) structures, such as diamond and gyroid types, offer attractive mechanical properties for lightweight applications, as it was discussed in the first part. Now, this part of the talk presents tensile fatigue testing of AM-cast TPMS samples (both solid and sheet-based designs). After quasi-static tensile tests to determine yield strength, high-cycle fatigue tests were conducted under controlled loads. The results highlight differences in fatigue life based on geometry and design, providing insights for designing durable lightweight components.

Outline

Introduction

- We have already introduced TPMS structures, so just reiterate why they are studied (mechanical efficiency, energy absorption, lightweight design)

Manufacturing

- Same process as the AM-Cast FFTs - talk about the challenges of producing sheet samples
- Show design. Types of TPMS tested: diamond and gyroid. Discuss solid vs. sheet

Quasi-static Tensile Testing

- Results: yield strength and initial mechanical response

High Cycle Tensile Fatigue Testing

- Test methodology: load selection based on yield strength
- Comparison of solid vs. sheet designs

Conclusion (Part 2) (To be confirmed or changed according to the results we obtain)

- AM-cast TPMS structures show potential for lightweight fatigue-resistant applications.
- Results help guide design selection and process improvements for better fatigue performance.