WORKSHOP

ADDITIVE MANUFACTURING. VIBRATIONS. OPTIMISATION.

September 15-17, 2021

Online

InDEStruct · University of Southampton · Vestas aircoil

Day 1: Additive Manufacturing

15 Sept 2021, Wednesday

Additive manufacturing interests at the University of Southampton

Dr Andrew R. Hamilton, *University of Southampton*

09:20-10:00 (UK), 10:20-11:00 (DK) - 16 Sept 2021, Wednesday

In this talk, I will introduce myself, my research interests, and an overview of additive manufacturing capabilities at the University of Southampton. As a process that is suitable for metals and high temperature heat exchanger applications (of interest on the InDEStruct project), I will focus on laser powder bed fusion (LPBF) of metal alloys. I will introduce fundamental processing factors and the effects these have on the properties and performance of the resulting part: Laser interaction and heat transfer into the powder affect the dimensions of the melt pool, which is the basic building block for layer-by-layer deposition of complex shapes. Inherent in the process and due to variability in factors affecting heat transfer, internal pores, defects, and rough surface features form. Rapid solidification and high thermal gradients affect the metallurgical features found in the microstructure. These unique combinations of defects, microstructure, and residual stress contribute to the mechanical properties and performance of the part. The introduction of fundamental process-structure-property considerations will lead into subsequent talks in the InDEStruct workshop that will describe studies of LPBF that aim to characterise the role of defects on fatigue failure initiation and progression; to combine multiple materials within a single LPBF process to extend design freedom and avoid subsequent joining processes; to vary laser scanning process parameters to control local microstructure and properties; to study the effects of as-built microstructures and subsequent heat treatments on high temperature fatigue crack behaviour; and to study surface roughness and radiative heat transfer from as-built surfaces.

Fatigue evaluations of additive manufactured materials in novel heat exchanger design

Khandokar Abu Talha, *University of Southampton*

11:00-11:40 (UK), 12:00-12:40 (DK) - 16 Sept 2021, Wednesday

This project is motivated by the failure of the conventional heat exchanger manufactured by industrial partner Vestas Aircoil. The project aims to exploit the current advancement in metal-based additive manufacturing technology to increase lifetime and enhance efficiency by creating a novel heat exchanger design containing metamaterial structure and evaluate its fatigue behaviour and failure mechanism. Initially, the fatigue behaviour of the 316L SS bend bar is investigated to understand crack initiation, propagation, coalescence mechanism and key parameters affecting them. In parallel to this, a finite element model is developed to predict fatigue life using the strain-life approach. The project currently focuses on the size-scale effect of additive manufacturing on fatigue behaviour. This knowledge would later aid in developing a fatigue lifing technique for the metamaterial structure in a novel heat exchanger.

Effect of heat treatment on fatigue crack growth in IN718/316L multiple-materials layered structures fabricated by laser powder bed fusion

Marie-Salome Duval-Chaneac, *University of Southampton*

12:40-13:20 (UK), 13:40-14:20 (DK) - 16 Sept 2021, Wednesday

Multi-material specimens were produced in layered architecture by Laser Powder Bed Fusion (L-PBF) process, combining 316L stainless steel to IN718 in a single operation. Specimen were heat treated (HTed), the heat treatment was tailored specifically for the combination of 316L and IN718 multi-material specimens. It was found that from medium to high values of stress intensity factor ($\Delta K > 20 MPa\sqrt{m}$) the near tip crack driving force, is less controlled by the effect of multiple-layer architecture than the effect of instrinsic microstructure strengthening. The fatigue crack propagation behaviour was put in perspective with each alloys tensile properties, microstructure analysis and fractographic analysis.

High temperature fatigue crack growth behaviour in additively manufactured Inconel 718

Diego Martinez de Luca, *University of Southampton*

13:20-14:00 (UK), 14:20-15:00 (DK) - 16 Sept 2021, Wednesday

Inconel 718 (IN718) finds application in jet engines or gas turbines components due to its excellent high-temperature mechanical performance and corrosion resistance. Additive manufacturing (AM), offers a relatively new route for processing superalloys with the possibility of producing components: faster and cheaper with significant design freedom. There is, however, a lack of knowledge regarding fatigue properties of AM components due to the wide range of processing variables, and the resultant defect distribution and residual stresses.

In this work, the superalloy IN718 manufactured by Laser Powder Bed Fusion (L-PBF) has been characterised focusing on the microstructure, effect of post heat treatment, and dependence of build orientation on fatigue crack growth (FCG). Long crack fatigue tests were conducted on single edge notched samples at 350, and 650 oC in air with load ratio 0.1, using a variety of loading waveforms. Heat treated L-PBF and cast and wrought specimens were compared in terms of fatigue propagation mechanisms. A combination of optical microscopy and scanning electron microscopy (SEM-SEI/BEI, EDS, Alicona MEX) were used to characterise the fracture surfaces.

Investigation of microstructural heterogeneity from laser powder bed fusion process variation and laser re-scanning

Anqi Liang, *University of Southampton*

14:20-15:00 (UK), 15:20-16:00 (DK) - 16 Sept 2021, Wednesday

The implementation of spatially varying processing parameters in laser powder bed fusion (LPBF) can potentially enhance the performance of metal LPBF parts by enabling controlled structure and property heterogeneity in a single manufacturing step. The aim of this study was to assess the microstructural variation of 316L SS by layer-by-layer rescanning using different LPBF processing parameters. A range of parameters were identified by processing single laser scans to investigate the melt pool dimensions, morphology and sub-grain microstructure. Parameters were selected for fusion and densification with initial laser scanning, and different parameters were selected for subsequent rescanning for localised modifications of microstructure and properties. With rescanning, a refinement of the sub-grain cell size from 0.84 mm (initial scanning region) to 0.35 mm (rescanning region) was achieved at high density (99.96%) in 316L SS, enabling potential variations in component hardness after a single LPBF processing step. To fully understand the mechanisms on how process parameters influence the microstructure of LPBF parts and provide a guidance on predicting the microstructure to achieve a microstructural tailoring within a complicated design, an analytical solution, i.e. the Wilson-Rosenthal equation, was adopted. A relationship between linear energy density, cooling rate and microstructure (sub-grain cell size) of 316L SS was established and the predicted cell size in rescanning components shows a good agreement with experimental results.

The effects of processing parameters on roughness of AM 316L Stainless steel.

Christopher Ogunlesi, *University of Southampton*

15:00-15:40 (UK), 16:00-16:40 (DK) - 16 Sept 2021, Wednesday

Laser powder bed fusion allows for the rapid production of parts that may have been two complex or costly to build via traditional subtractive manufacturing. However, due to the unique processing conditions that occur during the build process, as-built parts tend to have high surface roughness compared to machined or cast parts. This can lead to changes in materials properties such as emissivity and may be particularly concerning for internal features which can’t be easily altered with post processing.

The purpose of this study was to understand the how varying the input process parameters of the LPBF process affected certain output factors (responses) of as-built 316L stainless steel (SS) parts which could be related to surface roughness. The input parameters chosen were those that make up the volumetric energy density (laser power, scanning speed, hatch spacing and layer thickness) and build orientation. A definitive screening Design of Experiments method was used to gain as much understanding of the influence of these input parameters on responses with as few experimental runs as possible. Seventeen runs were done, each one varying the input parameters over one of three levels (low, mid and high). Surface texture of the parts was analysed using Focal Variation Microscopy. Finally mathematical models were derived from the statistical analysis to establish the relationships between the process parameters and responses.

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Day 2: Vibrations

16 Sept 2021, Thursday

Waves and finite elements

Prof Dimitrios Chronopoulos*, KU Leuven*

09:10-09:50 (UK), 10:10-10:50 (DK) - 16 Sept 2021, Thursday

Complex, non-isotropic stratified and sandwich constructions are widely used in engineering applications such as in the aerospace and automotive industries, mainly because of their high stiffness-to-mass ratio and the fact that their mechanical characteristics can be designed to suit the particular purposes. Unluckily, this high stiffness-to mass ratio being responsible for the increased mechanical efficiency, imparts as well efficient acoustic radiation. The modelling of the vibrational behaviour of complex composite structures has been a field of extensive study in modern mechanical engineering. The knowledge of the wave propagation characteristics within such a structure seems to provide a key to decode and model its vibrational behaviour.
This presentation will provide a description of the various finite element based approaches nowadays employed in order to compute wave propagation within a periodic structure. Structures of arbitrary complexity, layering and material characteristics can be modelled through the 3D displacement fields used within the FE discretization procedure. The talk will present an overview of the employed theory as well as fundamental results related to:

- The periodicity conditions utilised in order to derive the propagating and evanescent wave mode equations.
- The advantages and disadvantages of formulating the wave propagation problem through a FE approach, compared to an analytical one.
- The pros and cons of the various types in which the FE-based wave propagation problem can be casted.
- The various numerical issues that could occur during the formulation and solution of an FE-based wave propagation problem.
- The FE/WFE hybridisation which results in coupling structures represented in the physical domain to ones represented through their wave space information.

The main objective of the talk will be to aid the attendants to differentiate between the various ways in which the FE wave propagation problem can be formulated as well as choose the approach that best fits their needs.

Long-term variations in structural dynamics: tracking and compensation with a damage diagnostics perspective

Prof Luis David Avendaño-Valencia, *University of Southern Denmark*

09:50-10:30 (UK), 10:50-11:30 (DK) - 16 Sept 2021, Thursday

Structures experience through their operational lifetime significant variations in their vibrational response characteristics. These variations stem from natural deterioration and damage accrual, effectively degrading their operational performance slowly and steadily in the long term. Concurrently, Environmental and Operational Variability (EOV) introduces substantial fluctuations in the dynamic characteristics of the structure. While EOV-driven variations are harmless to the structural performance in the short term, in the long term may lead to noteworthy differences in the accumulated fatigue in contrast to the level expected at the design phase. Moreover, the innocuous EOV-related variations in the structural dynamics can easily mask harmful variations due to damage and will hinder the effectiveness of vibration-based damage diagnosis algorithms.
In this talk we will discuss methods to cope with the changing dynamic characteristics stemming from EOV in the identification and tracking of dynamic (modal) characteristics of a structure, within a damage diagnosis perspective. These methods combine well-known system identification tools with machine learning techniques, to deal, in an implicit or explicit form, with the changing structural dynamics. Implicit methods use solely the vibration characteristics (temporal and multivariate) to cope with EOV-driven variations. Otherwise, explicit methods correlate operational variables with vibration characteristics to compensate EOV-driven variations in a cause-effect manner. We will analyze both classes of methods, their characteristics, and main examples, followed by their application in the construction of damage diagnosis algorithms.

Hopefully, this talk will give newcomers and savvy SHM and OMA practitioners a broad perspective on the hurdles and state-of-the-art methods for dealing with long-term vibration monitoring data, and serve as a guide for the design of their own vibration-based SHM algorithms.

Digital Twin

Dr Claus Ibsen*, Vestas aircoil*

10:50-11:30 (UK), 11:50-12:30 (DK) - 16 Sept 2021, Thursday

TBC

Continuum model and effective medium approaches to dynamics of tube-fin assemblies

Kevin Jose*, University of Southampton*

12:30-13:10 (UK), 13:30-14:10 (DK) - 16 Sept 2021, Thursday

Heat exchanges are used widely and often consist of a set of tubes in parallel. These tubes are fitted with fins along their length spaced regularly, which couples them elastically, to improve their thermal performance. There is a need to ensure that the lowest natural frequencies of the tube-fin systems are kept above the frequency band of the base excitation, to increase fatigue life. Because the tube-fin assembly consists of 100s-1000s of components, FEM based modal analysis is computationally expensive at initial stages of design search, which inevitably requires running codes for a very large number of parametric combinations. Here, a Rayleigh quotient-based approximation to estimate the lowest few natural modes of the system is developed. The approach makes use of an ansatz consistent with the geometry of the problem, with only a few undetermined degrees-of-freedom that are resolved variationally. The method affords computational efficiency that does not scale with the number of components, and hence is suitable for repetitive design evaluations and optimisation. A Python based GUI is also developed for deployment in industry.

Vibration testing in an industrial setting: from experimental to operational modal analysis

Milena Bavaresco, *University of Southampton*

13:10-13:50 (UK), 14:10-14:50 (DK) - 16 Sept 2021, Thursday

Experimental modal analysis (EMA) is a known, well-established process to estimate the modal parameters of a system. It relies on having specific environmental conditions and controlled input to the structure under test. Industrial structures, especially ones which are very large or difficult to access, may pose a challenge to comply with these requirements. In those cases, methods based on ambient vibrations and output-only data may be beneficial. Such methods belong to the field of operational modal analysis (OMA).

In this seminar, I will present the main aspects of an OMA procedure based on cross-correlation functions: data acquisition, relevant tools for data processing and outcomes. Experimental results from simple to complex structures are given where EMA and OMA results are compared. Special focus will be given to transitioning from EMA to OMA and to the related advantages and challenges.

Structural life estimation using frequency response analysis

Kevin Jose & **Khandokar Abu Talha,** *University of Southampton*

15:10-15:50 (UK), 16:10-16:50 (DK) - 16 Sept 2021, Thursday

A way to estimate fatigue life of structures using frequency response calculations is presented. Specifics of carrying out frequency response calculations in an industrial context including integration of sensor data are covered. The stress response data from hotspot analysis is used as an input for rainflow count technique which calculates the accumulated damage during operation. The total accumulated damage, in combination, with material fatigue lifing data is used then to estimate the total lifetime of the structure. The method presented here can be useful in early design phase as well as in structural health monitoring and predictive monitoring.

Day 3: Optimisation

17 Sept 2021, Friday

Topology optimisation of fluid-thermal systems: heat sinks and heat exchangers

Dr Joe Alexendersen, *University of Southern Denmark*

09:10-09:50 (UK), 10:10-10:50 (DK) - 17 Sept 2021, Friday

Topology optimisation is a powerful tool for the simulation-based design of physical structures. In contrast to size and shape optimisation, it can explore a vast design space due to a large design freedom. When applied to multiphysics problems such as conjugate heat transfer, the computational cost and complexity of the models require extra attention. This can be tackled by using large scale parallel computations on supercomputers to reduce wall clock time or by deriving simplified physical models to alleviate the computational cost. This talk will discuss these aspects in the context of applications in fluid-thermal systems, such as heat sinks and heat exchangers.

Leveraging multiple fidelities within design optimisation

Dr David Toal, *University of Southampton*

10:10-10:50 (UK), 11:10-11:50 (DK) - 17 Sept 2021, Friday

Engineers face continual pressure to deliver better performing designs in a reduced time frame for their business to react to customer demand and remain globally competitive. Leveraging multiple levels of fidelity within a design optimisation framework has been demonstrated to offer both an improvement in final design performance and a reduction in the overall optimisation cost. The following presentation reviews recent advances in this area and demonstrates how varying both geometric and simulation fidelity can be advantageous on a variety of problems.

Shape Transference for Surface Detail Reconstruction

Honorio Salmeron Valdivieso, *University of Southampton*

12:00-12:30 (UK), 13:00-13:30 (DK) - 17 Sept 2021, Friday

Reverse engineering processes often encounter difficulty capturing small, highly localized, surface information. Partly due to insufficiently automated frameworks for handling such geometric data during the shape reconstruction pipeline. It could be the case if a manufactured device was 3D scanned for lifecycle management, with interest in surface imperfections such as coating wear off. We have developed a tool for blending surface patches with arbitrary irregularities into a base shape. The approach aims to transfer small surface features by using a multi-resolution scheme and rigid deformations. Automating this process enables the inclusion of outsourced surface information in designs, including samples prepared in mesh handling software, or raw scan information.

Multi-objective optimisation of a corrugated tube for heat exchanger

Atul Singh, *University of Southampton*

12:40-13:10 (UK), 11:10-11:50 (DK) - 17 Sept 2021, Friday

Engineering systems have various parameters in their design that affect their performance. Changing these parameters, or a combination of them, becomes an optimisation challenge where an efficient design should be found out within the restraint of a fixed computational budget. Moreover, these performance metrics used to evaluate a design are themselves competing in nature, where changing one parameter could lead to an unwanted change in the overall objective of the design and evaluating such change for all such combinations would be infeasible in an engineering context. The current presentation discusses the multi-objective optimisation of a corrugated tubes of a heat exchanger to increase heat transfer, reduce the pressure drop, and aim to discuss the method to achieve the same.

Aerofoil shape parameterisation via an adversarial auto-encoder

Tom Bamford, *University of Southampton*

13:25-13:55 (UK), 14:25-14:55 (DK) - 17 Sept 2021, Friday

Current aerodynamic design processes suffer from expensive optimisation procedures, in part due to the requirement to search large design spaces. Recent advances in deep learning, and more precisely the development of high-quality generative models such as Generative Adversarial Networks (GANs) and Variational Auto-Encoders (VAEs), has opened new possibilities for shape parameterisation and aerodynamic design. Whilst the focus of work in this area so far has primarily focused on generative aerofoil design via coordinate-based shape representations, aerofoil generation via image-based shape representation is yet to receive much attention. The aim in this talk is to rectify this by investigating aerofoil shape generation via signed distance field geometry representations.