NEWSLETTER 4

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Modelling and simulation

Overview

Within the MTC, a key group alongside those from Laser processing is the modelling and simulation team. In FLASH, we are building capability by simulating the three laser processes occurring within the combined head, with an objective of integrating design models based on these that reduce the time and cost of new product development compared to typical design cycles by at least half.

These models are laser welding with a case study on hairpin welding with an 8 kW continuous wave laser, laser drilling with a 20-kW millisecond pulsed laser and laser processing with a 400 W nanosecond Water jet guided laser. By simulating these processes, we can estimate the topology (the shape) of each workpiece as it is processed with specific machine settings.

After validation against an equivalent physical experiment, this provides data to COSMOS Thrace describing the input-output sensitivity of the laser processing. They can take advantage of this data to inform their algorithm utilising machine learning, and so the consortium can provide optimisation in manufacturing towards minimising material wastage and energy and the number of defects occurring.

Our first model to be validated simulates hairpin welding, whereby a pair of wires with cut and prepared ends are impacted by a controlled laser to physically melt the copper wires and thus weld them together upon cooling.

Laser processing

A model has been developed in COMSOL Multiphysics that simulates polishing or smoothing of surfaces using Synova's microjet -a water water-guided laser jet, where the surface material is brought just to the melting point and allowed to flow before solidification. This will be further developed to simulate machining, whereby vaporisation occurs and material is removed rather than redistributed. Initially, only the latent heat of melting is considered, but when vaporisation occurs and material is converted from solid to gas, a lot more aspects need to be considered. Latent heat of vaporisation, surface to ambient radiation and the Marangoni effect come into play. These usually have a greater effect, the higher the temperature the material becomes. The Marangoni effect enhances the weld pool (or area where material is being removed) due to the induced flow in the molten material, and without this being carefully considered, the simulation will underpredict the size of the final features in the material.

Laser Welding

Laser welding is one of the most advanced joining techniques in modern manufacturing, but it's also one of the most complex. We are using high-fidelity modelling to understand this process and make it more predictable. This in turn supports industry cut development time and reduce waste.

Why is it so complex?

When a laser interacts with metal, it creates a molten pool that can behave in surprising ways. The depth and shape of this pool depend on many factors:

- **Heat flow and fluid movement** inside the molten metal.
- **Surface tension effects**, which drive circulation in the weld pool.
- **Energy absorption**, which changes with the angle and condition of the surface.

These interactions decide whether the weld is shallow or forms a deep "keyhole," which affects strength and reliability.

Our modelling approach

We've built a simulation using FLOW-3D to replicate laser welding on copper hairpins, a common component in electric motors. The model includes:

- A realistic laser path following an elliptical scan pattern.
- Heat transfer and melt pool behaviour are included and were verified under different power settings
- Key physical effects like recoil pressure (from metal vaporisation) and Marangoni flow.

By adjusting parameters such as laser power and speed, we can predict how the weld pool will form, eliminating the need for repeated physical trials, as demonstrated in Figure 1. Traditionally, measuring weld porosity, which directly impacts the performance of electric motors (the lower the porosity, the better), requires destructive testing.

Our approach allows us to identify conditions that lead to poor weld quality prior to production.

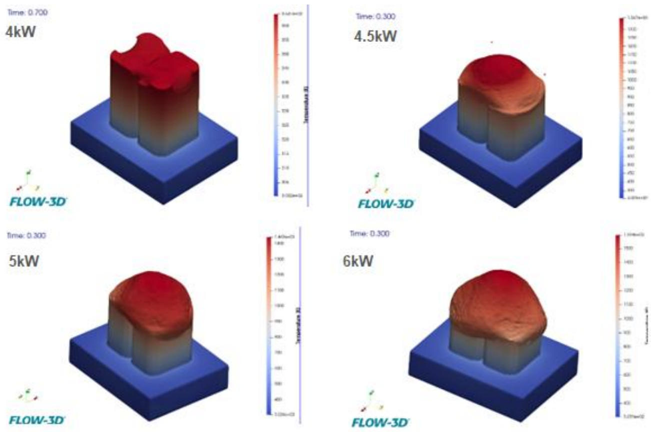

Figure 1: Demonstration of hairpin welding simulations at various laser powers.

Laser Drilling

Laser drilling is a precision material processing technique that utilises a high-energy, coherent laser beam to create holes or cavities in a wide range of materials. The process involves focusing the laser beam onto the workpiece surface, generating sufficient power density to induce rapid heating, melting, and ejection of material in both liquid and vapor phases. Heat transfer within the material occurs primarily through conduction, with convective and radiative mechanisms contributing to the overall thermal dynamics.

A key aspect of this is the interaction between the laser-induced thermal effects and the assist gas dynamics, particularly within subsonic and supersonic nozzles. These gas flows significantly influence material removal efficiency, hole quality, and process stability.

We are focused on advancing the understanding of gas dynamics in laser drilling, with a particular emphasis on supersonic nozzle configurations. Our goal is to model and optimise these dynamics to support the development of high-performance nozzle designs and improve overall drilling outcomes.

Key Activities

1. Literature Investigation: We begin by exploring the current state of research to identify technological advancements, knowledge gaps, and foundational theories in nozzle design, compressible flow modelling, and laser-material interactions.
2. Nozzle Design & Gas Dynamics Modelling: Building on this foundation, we design supersonic nozzles and develop detailed models to accurately capture compressible flow behaviour, enabling seamless integration with laser interaction simulations.
3. Laser Drilling Process Simulations: Using multi-physics modelling, we simulate the thermal, fluid, and material interactions in coupon-level laser drilling scenarios to establish a robust baseline for further analysis.

Our Modelling Approach

To investigate and optimise gas dynamics in laser drilling, we employed a computational fluid dynamics (CFD) approach using ANSYS Fluent. This enabled high-fidelity simulation of compressible gas flows within both subsonic and supersonic nozzle geometries. The models are designed to capture key physical phenomena, including shock structures, boundary layer effects, and flow separation, which are critical to understanding assist gas behaviour during drilling.

These flow simulations are integrated with multi-physics models that incorporate thermal conduction, phase change, and laser-material interactions, allowing us to simulate realistic drilling scenarios. By coupling fluid dynamics with heat transfer and material response, we can evaluate the influence of nozzle design and operating conditions on process efficiency and hole quality.

This modelling framework provides a powerful toolset for virtual experimentation, design optimisation, and predictive analysis.

