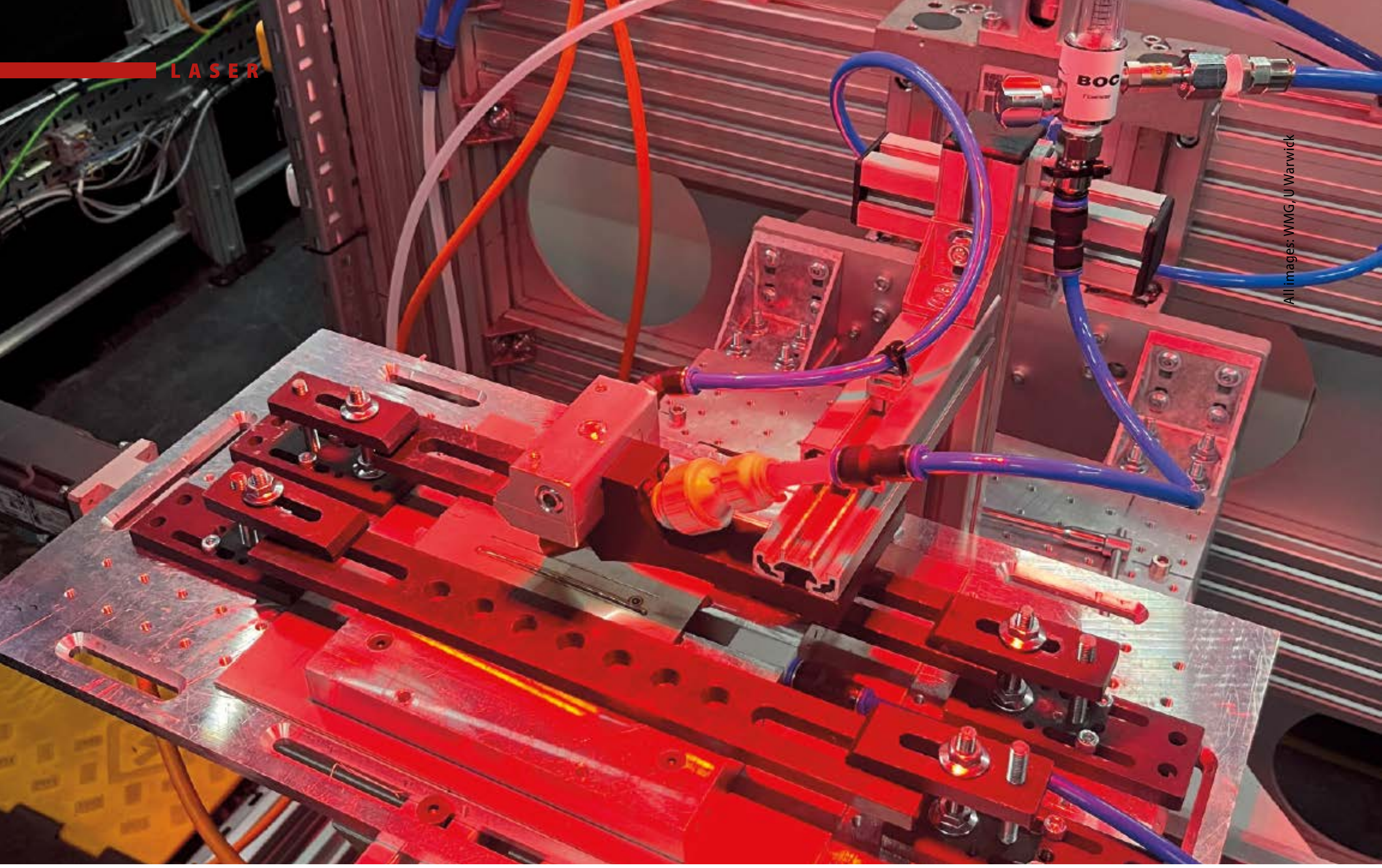

All images: WMG, U Warwick

Energy-efficient deep-penetration laser welding

High-quality single-pass welding of thick-section stainless steel using a dynamic beam laser system

Sharhid Jabar, Yao Ren, and Pasquale Franciosa

Following the launch of the Lasers4MaaS Horizon Europe project, the Laser Beam Welding team at WMG, University of Warwick, has been working closely with partners at the UK Atomic Energy Authority (UKAEA) and Civan Lasers to develop advanced laser welding processes for stainless steels used in fusion power plants. The current focus is on a critical manufacturing challenge for future fusion systems: the reliable and efficient joining of thick-section structural service pipes.

The ambition of the project is clear: to harness dynamically shaped, high-power laser beams for autogenous, single-pass welding of thick service pipes, improving keyhole stability and weld quality while keeping laser power as low as possible. Achieving this would mark a major step forward – not only for fusion energy, but more broadly for heavy manufacturing. Looking ahead to future plants, the goal is to develop a representative demonstrator for in-bore laser welding in a confined environment. The primary objective is to show that an integrated welding tool – incorporating effective gas shielding, plume management, and active cooling – can reliably complete the welding process over its required operational duration. Success depends on maintaining consistent weld quality and repeatability without causing critical damage to the tool itself. In this context, keeping laser power low is essential due to the inherent cooling limitations in such constrained environments.

Laser welding is already well established as a core industrial technology, valued for its precision, high processing speeds, and ability to deliver consistently high-quality joints. It is indispensable across sectors such as automotive e-mobility, medical devices, and microelectronics. However, when requirements shift toward deep, single-pass welding of structural metals, the limitations of conventional laser welding become increasingly apparent. Within the current program, single-pass welds of 5 mm thickness in SS316L have already been achieved using a static beam from a multimode laser source. Going deeper introduces new challenges stemming from the beam-quality limitations of conventional high-power multimode fiber lasers, increasing keyhole instability at large penetration depths, and beam attenuation caused by the vapor plume. Success is therefore determined by the integrated system – combining the laser generator, effective top and bottom shielding gas to prevent oxidation, robust plume management, and adequate fixturing.

Recent advances in laser technology are beginning to address these challenges through coherent beam combining (CBC) [1, 2] and optical phased arrays (OPA). Rather than relying on a single high-power multimode source, CBC systems coherently combine multiple single-mode beams, each with inherently high beam quality. Crucially, when combined, these beams retain their single-mode characteristics, producing a laser output with low divergence and a large depth of focus. The final beam diameter is defined by the selected focusing optics, preserving the favorable relationship between focal length, spot size, and depth of focus.

The Lasers4MaaS project has incorporated this technological advancement and systematically developed a dedicated experimental setup, as shown in the image on **p. 20**. In this experimental work, bead-on-plate laser welding was performed on 50 mm × 150 mm SS316L plates, with welds carried out over a length of 120 mm at an industry-standard welding speed of 15 mm/s. The setup employed a CIVAN OPA6 14 kW laser with a 1.5 m prefocusing lens. The system included a SmartMOVE SH30G-ME-LD galvanometric scanning head for accurate beam positioning. The focal plane was set to 1070 mm from the bottom plate of the CIVAN optical head. With Civan's CBC-OPA architecture, beam shapes are generated by overlaying multiple diffraction patterns. Following an incremental approach, we began with the most fundamental shape, corresponding to a single diffraction pattern (**Fig. 1**). It consists of a central Gaussian spot of approximately 136 µm diameter at the 1.5 m prefocusing lens and four main lobes, generated by a single click placed at the center of the shape-generation matrix. This configuration delivered a remarkable ±10 mm depth of focus.

All tests were performed using pure argon shielding gas, delivered to the weld zone at a gauge pressure of 2 bar with flow rates of 30 l/min (top surface) and 10 L/min (bottom surface). Gas was supplied through a specially designed nozzle integrated with the air blade, positioned 70 mm from the process zone. During welding, the laser beam, air blade, and gas nozzle remained fixed while the sample was moved along a precision linear stage to ensure consistent welding conditions.

The results to date are highly encouraging. Welding trials show an almost linear relationship between applied laser power and achieved weld depth across plate thicknesses of 3, 5, 10, and 16 mm

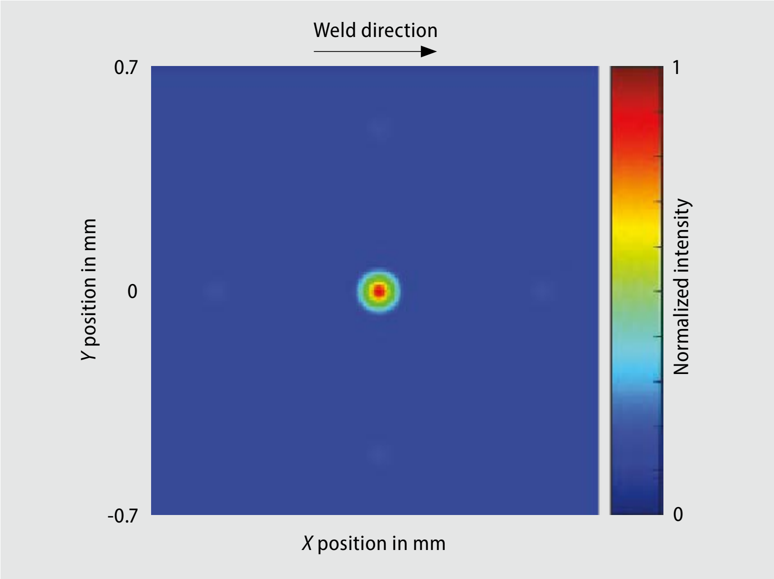

Fig. 1 Tested beam shape for the developed Lasers4MaaS welding setup (image **p. 20**)

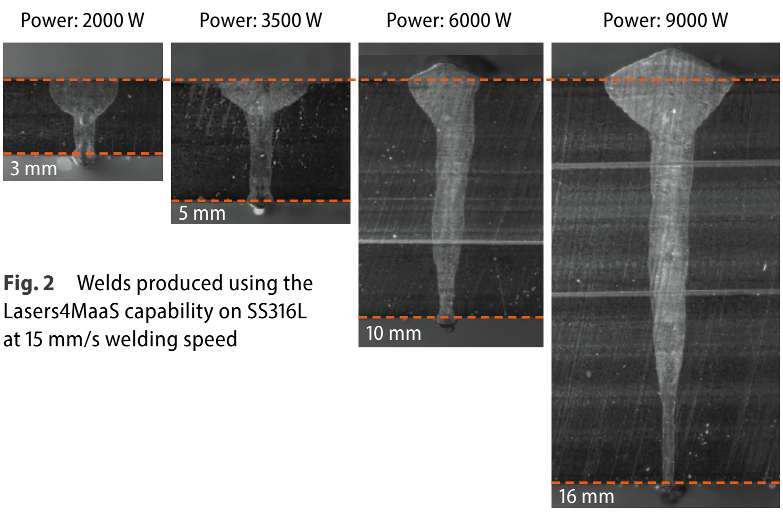

Fig. 2 Welds produced using the Lasers4MaaS capability on SS316L at 15 mm/s welding speed

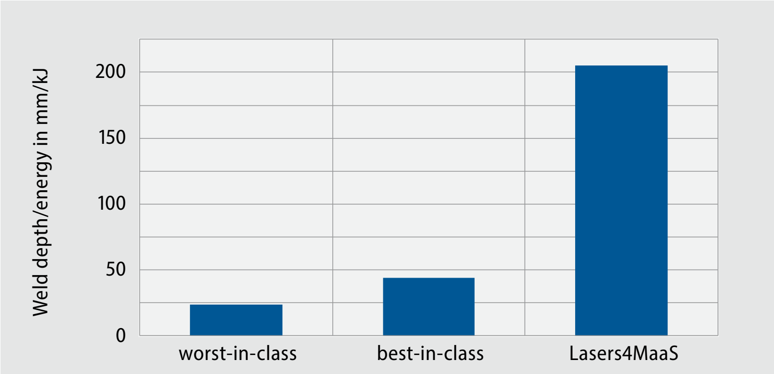

Fig. 3 Comparison of Lasers4MaaS with best- and worst-in-class results reported in the public domain. The reference data were extracted from the Scopus database and filtered using the keywords "316L", "fiber lasers" and "cw lasers", retaining only studies that reported weld depths greater than 5 mm. To ensure comparability across different experimental conditions, the energy input was calculated by multiplying the total laser power by the interaction time and subsequently normalizing it by the achieved weld depth.

(**Fig. 2**). Benchmarking these results against published literature further highlights the potential of the developed welding capability. As summarized in **Fig. 3**, the present work demonstrates particularly strong performance in terms of energy required per unit depth of weld penetration. Overall, the system performs exceptionally well compared with studies involving similar material thicknesses and processing conditions. This advantage is directly linked to the system architecture, which outperforms conventional high-power multimode laser systems in both penetration capability and energy efficiency. From a sustainability standpoint, the results are especially promising, with further optimization underway using more advanced dynamic beam shapes.

By breaking the long-standing trade-off between high power and beam quality, the project is demonstrating deep, stable, and energy-efficient welding of demanding materials such as 316L stainless steel. For fusion power plants, this capability supports the manufacture of robust, high-integrity structures essential to future energy systems. Beyond fusion plants, the same technology holds transformative potential for sectors such as shipbuilding and heavy industry, where thick-section joining, productivity, and efficiency are increasingly critical to meeting sustainability targets.

*

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