WATER-SPRAY ASSISTED LASER DRILLING (SALaD): INSIGHTS

PRIYANKA GHOSH ET AL.*, THE MANUFACTURING TECHNOLOGY CENTRE

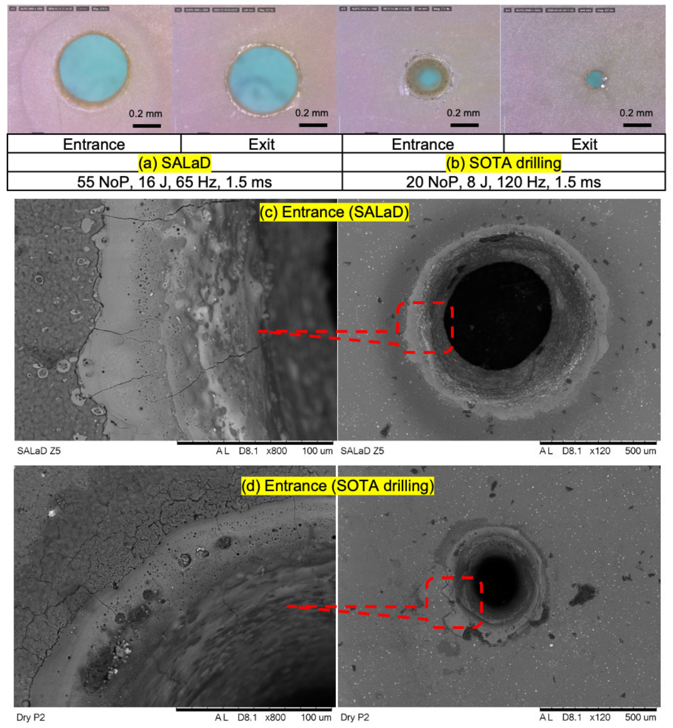

Figure 1: Comparison of hole characteristics of SALaD vs SOTA processes

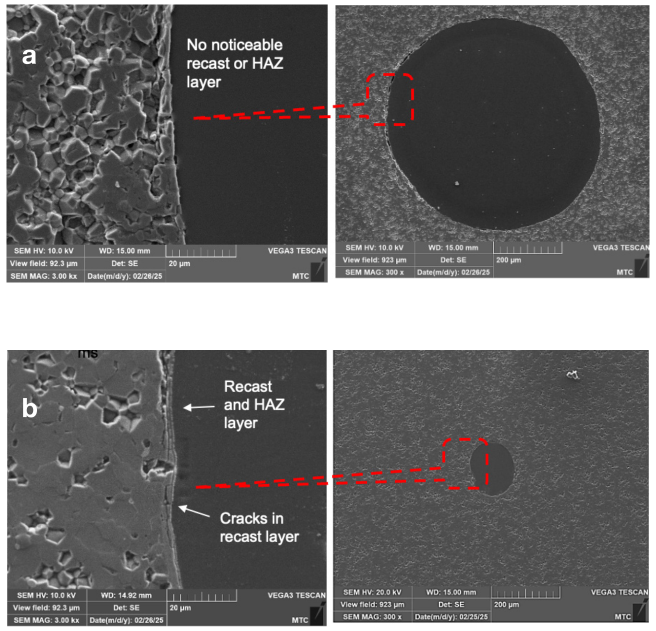

Figure 2: Transverse cross section of a) SALaD and b) SOTA laser drilling; 55 NoP, 16 J, 65 Hz, 1.5 ms

INTRODUCTION

A critical manufacturing requirement for aluminium nitride-based devices is the drilling of through-holes with diameters ranging from ~100 μm to several millimetres. There is a clear gap in existing laser drilling technologies for achieving both high-speed and high-quality drilling of brittle materials like aluminium nitride (AlN). To address this technology and knowledge gap, the proposed study will develop and investigate a coaxial water-spray assisted millisecond fibre laser drilling approach.

EXPERIMENTS

The water-spray assisted laser drilling (SALaD) experiments were conducted on commercially available AlN ceramic substrates with a thickness of 0.6 mm. A high-power quasi-continuous wave (QCW) ytterbium-doped fibre laser system (YLS-2000/20000-QCW) was used. The focal spot diameter for this configuration was 125 μm (approx.). A commercial coaxial laser drilling head (Precitec) was modified to incorporate a water-spray delivery system. The original nozzle tip was re-engineered to allow injection of pressurised water. Compressed air, ranging from 1-5 bar, and oxygen assist gas, supplied at a controlled pressure (1-7 bar), mixed with the water at the nozzle tip, was used, resulting in atomisation and formation of a fine water spray.

Key process parameters including spray conditions, number of pulses, pulse energy, and pulse duration were systematically varied to investigate their influence on SALaD of AlN, including hole morphology, material removal, and process consistency. Comparative analysis with state-of-the-art (dry) laser drilling was also performed to understand and benchmark the improvements achieved using the proposed technique. A large volume of data was collected, and multiple analyses were conducted, which can be assessed in the full research publication [1].

RESULTS AND DISCUSSION

A comprehensive optimisation trial was conducted for the dry, state-of-the-art (SOTA) drilling process, and the final optimised parameters (20 NoP, 8 J, 120 Hz, 1.5 ms) were used to enable a representative comparison. Figures 1 and 2 provide a comparative assessment of hole characteristics produced using the SALaD technique versus the SOTA drilling approach. The optimised SALaD configuration employed 55 pulses at 16 J, 65 Hz, and a pulse duration of 1.5 ms, while the SOTA drilling condition used 20 pulses at 8 J, 120 Hz and 1.5 ms.

As seen from Figures 1a and 1b, the SALaD process produces holes of larger diameter and minimal taper. The entrance diameter for percussion-drilled holes is approximately 0.65-0.80 mm, whereas the SOTA laser drilling produces holes in the range of 0.20-0.25 mm. The plasma-assisted material removal also contributed to the improved hole characteristics observed with SALaD.

In addition to size, SALaD exhibits noticeably less spatter, cleaner edges, and reduced thermal artefacts. The scanning electron microscope (SEM) images in Figures 1b and 1d reveal that the dry-drilled holes exhibit a relatively thick spatter layer and visible cracks within the spatter. In contrast, the water-assisted holes are significantly cleaner, with minimal spatter (Figures 1a and 1c).

Cross-sectional SEM images (Figure 2) further emphasise the benefit of SALaD compared to the SOTA dry laser drilling in terms of the thermal damage. In Figure 2b, a visible recast layer approximately 10-20 μm thick lines sidewalls, accompanied by a layer of heat affected zone (HAZ) extending into the substrate. In several locations, microcracks were observed over the recast. Conversely, the recast layer was negligible in the SALaD sample (Figure 2a), and no visible HAZ or microcracking was present. The material interface remained sharp and clean up to the very edge of the hole, demonstrating that the water mist effectively reduces thermal accumulation, enables better melt ejection and prevents thermal damage of the base material.

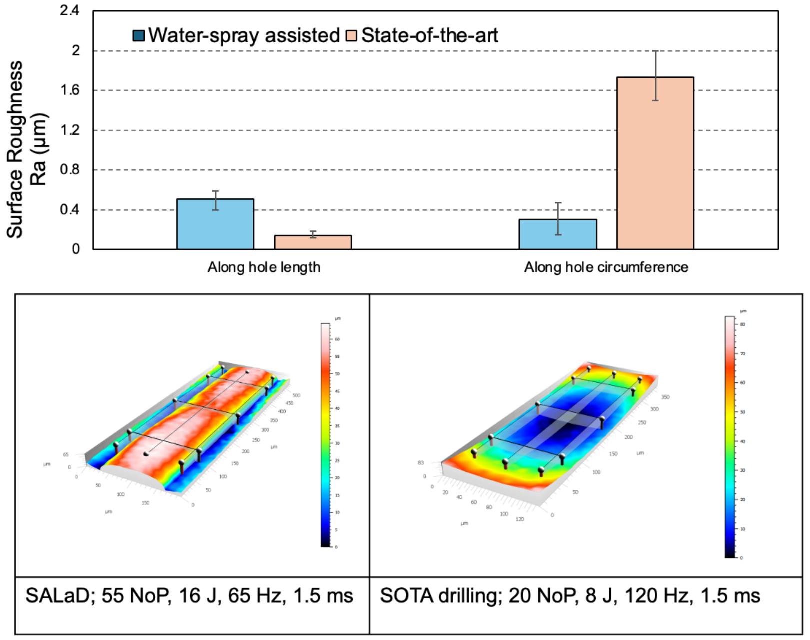

Figure 3: Comparison of surface roughness of SALaD vs SOTA driled hole

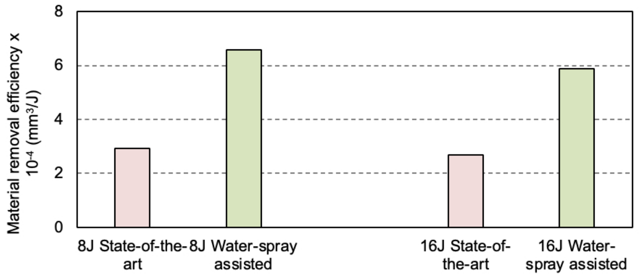

Figure 4: Comparison of material removal efficiency (8 J at 40 NoP, 65 Hz, 1.5 ms, 6-4 bar; 16 J at 35 NoP, 105 Hz, 1.5 ms, 6-4 bar)

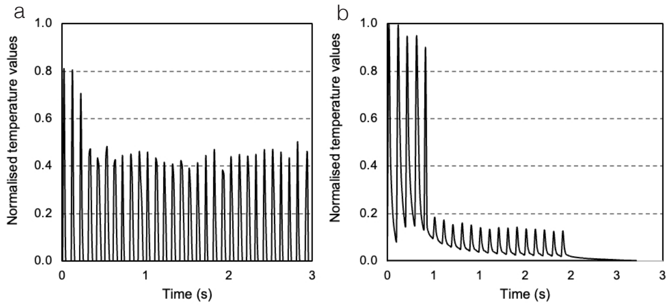

Figure 5: Thermal camera results of a) SALaD and b) SOTA laser drilling

The introduction of a coaxial water-spray into millisecond fibre laser drilling of AlN ceramics fundamentally transforms the process dynamics, yielding significant improvements in hole quality, thermal regulation, and process repeatability. SEM images confirmed the absence of subsurface damage and recast in the SALaD condition, while surface roughness measurements (Figure 3) showed more uniform roughness values (~0.4 μm Ra) compared to the dry-drilled case (1.6 μm Ra), in the lateral direction. In addition, SALaD method removes more material per unit of energy compared to the SOTA drilling method. Figure 4 reveals that the SALaD process consistently achieves higher material removal volumes per joule of input energy. Despite the higher number of pulses used in the SALaD process, the cumulative removal volume is substantially higher, indicating that each pulse remains productive over a longer drilling cycle.

Furthermore, the cooling action of the mist stabilises the process zone temperature, thereby preserving laser absorption efficiency over multiple pulses. In contrast, the SOTA dry process tends to suffer from cumulative thermal build-up, leading to increased plasma shielding and reduced laser-material coupling efficiency over time. The superior per-joule removal observed in the SALaD trials is therefore attributed not merely to thermal suppression, but to a dynamic synergy between evaporative cooling, impulsive melt expulsion, and consistent absorption conditions across the drilling cycle.

The temperature history plot reveals a distinct difference between the two processes. Figure 5 shows high temperatures for the first few (~5) pulses (corresponding to high material removal), followed by a significant drop (~80%) around pulse number 6 (after drilling the hole), and then a gradual reduction until pulse number 20 (due to laser interaction with the hole walls), after which no noticeable temperature is observed. In contrast, the SALaD process shows peak temperatures for the first three pulses (corresponding to high material removal) and then maintains relatively higher temperatures throughout all 25 recorded pulses. The relatively higher temperatures observed on subsequent pulses (from the fourth pulse) are more indicative of the plasma plume temperature rather than the material temperature.

SUMMARY

This study has demonstrated that integrating a coaxial water-spray delivery system into a millisecond fibre laser drilling configuration markedly enhances the machinability of brittle ceramics such as aluminium nitride. The introduction of a fine, coaxially aligned water mist into the laser-material interaction zone serves multiple roles: it provides localised evaporative cooling, promotes symmetrical melt ejection, and significantly mitigates thermal damage mechanisms including recast layer formation, spatter deposition, and microcracking.

ACKNOWLEDGEMENT

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REFERENCE

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*** Kiran Pick, Sundar Marimuthu (MTC)**

Priyanka.Ghosh@the-mtc.org
www.the-mtc.org

Priyanka Ghosh is an a ward-winning engineer, pioneering various laser-based manufacturing activities at the MTC, and is a Visiting Fellow at London South Bank University.