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Design and Evaluation of a Supersonic Assist-Gas Nozzle for Long-Pulse Laser Drilling

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Abstract

Assist-gas dynamics play a critical role in millisecond laser drilling processes, which predominantly rely on melting and melt ejection to govern material removal efficiency and hole quality. State-of-the-art industrial systems typically employ conical, sub-sonic nozzles, which have limitations on gas jet momentum, shear stress, and effective melt expulsion. In this work, a supersonic assist-gas nozzle tip is designed and implemented for laser drilling using a 20 kW quasi-continuous wave fibre laser. The nozzle design is established using one-dimensional gas dynamic analysis to determine the throat and exit diameters, followed by a two-dimensional method of characteristics to define the minimum-length diverging contour. The resulting gas flow behaviour is evaluated through numerical simulations conducted in ANSYS Fluent, examining both the internal nozzle flow and the downstream free jet characteristics. Experimental validation of the gas jet is performed using schlieren imaging to visualise shock structures and jet expansion, together with pressure measurements of the free jet using a pitot tube connected to a manometer. The fabricated nozzle tip is integrated into an existing nozzle assembly, and its performance is assessed through trepanning laser drilling trials on 2 mm thick C263 nickel superalloy, producing 0.8 mm diameter holes normal to the surface.

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Keywords: Computational fluid dynamics (CFD); Drilling; Laser; Supersonic nozzle; Schlieren imaging

1. Introduction

Assist-gas dynamics play a critical role in continuous-wave or millisecond-pulsed laser-based subtractive processes. In reactive fusion processes such as oxygen-assisted cutting and drilling of ferrous and nickel alloys, it provides sufficient oxygen volume to sustain exothermic oxidation reactions [1]. Equally important, the gas jet must efficiently remove molten material from the interaction zone while providing convective cooling to the substrate [2], which is essential for achieving superior hole/cut quality, characterised by a minimal recast layer thickness and reduced heat-affected zone extent [3].

Most industrial laser cutting and drilling systems employ conventional conical (convergent) nozzles, Figure 1a, whose performance limitations have been extensively documented. Under high stagnation pressure conditions typical of industrial operations (5-20 bar), conical nozzles produce under-expanded, turbulent jets characterised by strong shock-wave structures, including oblique shocks and Mach disks [4]. These shock waves cause substantial momentum loss, reduce effective gas velocity at the workpiece surface, and generate unstable flow patterns that impair melt removal efficiency [5]. Furthermore, conical nozzles provide limited radial shear stress over the kerf walls or within the laser-material interaction zone, reducing their capability to displace molten material laterally away from the hole entrance and kerf walls [6]. To overcome these limitations, supersonic (convergent-divergent, or de Laval) nozzle designs have been explored.

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Supersonic nozzles (Figure 1b) have been extensively investigated and validated for laser cutting applications. Work by Marimuthu [7] demonstrated the feasibility of laser-assisted oxygen cutting of thick steel sections, where high-momentum supersonic gas jets enabled cutting of plates exceeding 50 mm thickness. Studies by Man et al. [8] provided detailed characterisation of supersonic versus subsonic gas jet behaviour, demonstrating that properly designed supersonic nozzles produce uniform, parallel flow with minimal shock. More recently, Orazi et al. [9] reported up to 65% reduction in assist-gas consumption when using supersonic nozzles for inert-gas cutting of stainless steel, accompanied by improved cutting speeds and edge quality compared to conical nozzles.

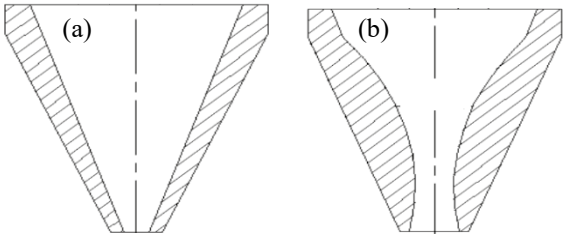


Figure 1. Schematic of (a) Subsonic nozzle and (b) Supersonic nozzle

Despite extensive validation in laser cutting, supersonic nozzle application in laser drilling remains largely unexplored. The only known study is that of Khan et al. [10], which examined nanosecond percussion drilling of 200 μm thick stainless steel using micro-nozzles, application distinct from macro-scale drilling requirements. The broader landscape of laser drilling, particularly millisecond-pulsed drilling [11], which is used extensively across aero-engines, gas turbines, and hydrogen electrolysis, has received limited investigation with respect to the integration of supersonic assist-gas jets..

A significant knowledge gap exists regarding the design, evaluation, and experimental validation of supersonic nozzles for millisecond-pulsed laser drilling of industrial-scale components. This paper addresses this gap through systematic investigation on design, simulation, and experimental testing of a supersonic assist-gas nozzle for millisecond-pulsed laser drilling applications.

2. Materials and Methodology

2.1. Nozzle Design Approach

The design process initiated with 1-D isentropic flow theory to establish fundamental geometric parameters, followed by 2-D method of characteristics (MOC) to generate nozzle contour.

The throat and exit area ratios were determined using compressible flow equations for isentropic flow through convergent-divergent nozzle [12]. The design targeted an exit Mach number of 2.0 at the design stagnation pressure of 8 bar, consistent with values commonly adopted in the literature [7, 8] for achieving high-momentum, stable supersonic jets in laser processing. The throat diameter was constrained by the laser beam profile to prevent beam-nozzle interference. With a fibre diameter of 0.1 mm, a collimator focal length of 80 mm, and a focusing lens of 150 mm, the calculated laser beam diameter at the nozzle throat position was 0.81 mm. Consequently, the throat diameter was specified as 1.6 mm to provide adequate clearance. Using the area ratio relationships, the corresponding exit diameter (initial) was calculated as 2.08 mm for the design Mach number.

The divergent section contour was designed using the two-dimensional method of characteristics (MOC) to generate a minimum-length nozzle profile with appropriate exit diameter (final). The MOC approach solves the characteristic equations for supersonic flow. A MATLAB code was used to generate the nozzle contour. The calculation domain extended from the throat (sonic line) to the exit plane, with the maximum expansion angle at the throat.

2.2. Computational Fluid Dynamics Analysis

Computational fluid dynamics simulations were performed using ANSYS Fluent to validate the nozzle design and evaluate internal flow characteristics. The simulations solved the Reynolds-averaged Navier-Stokes equations with the k-ω turbulence model. The governing equations comprised of continuity, momentum conservation, energy conservation and k-ω turbulence model transport equations.

The computational domain encompassed the wider nozzle region, including convergent section (10 mm length), throat region, divergent section (3.26 mm length), and a free flow region (12 mm length) to capture the initial free-jet structure. An axisymmetric formulation was utilized to reduce computational cost while maintaining physical fidelity. Boundary conditions were specified as pressure inlet with stagnation pressure of 8 bar (gauge), stagnation temperature 298.15 K, pressure outlet at 1 bar absolute or 0 bar gauge, no-slip adiabatic walls and axisymmetric boundary condition.

2.3. Experimental Flow Visualization

Schlieren imaging was implemented to visualize density gradients in the free jet emerging from the nozzle exit. The optical setup comprised a high-intensity white LED light source, two 200 mm focal length spherical mirrors arranged in Z-configuration, a knife edge positioned at the focal point of the second mirror, and a Phantom high-speed camera.

Free-jet pressure measurements were conducted using a manometer connected to a pitot tube positioned on the nozzle centreline at various standoff distances from the exit plane. The manometer pitot tube featured a 0.5 mm diameter opening oriented facing the flow to measure total pressure.

2.4. Laser Drilling Experimental Setup

The fabricated supersonic nozzles were integrated into a 150 mm nozzle assembly of the DMG LT50 laser drilling system. Drilling experiments were conducted using an IPG QCW fibre laser operating at 1070 nm and BPP of 4.2 mm.mrad. The optical configuration described in Section 2.1 was employed for all experiments, providing a calculated focused spot diameter of 0.19 mm at the workpiece surface, with the focal plane positioned at the surface. The workpiece material was C263 nickel-based superalloy in 2 mm thick sheet form.

Preliminary trials were conducted to identify stable and representative drilling conditions for evaluating the supersonic nozzle performance. Based on these initial trials, the laser and

motion parameters were fixed at a pulse duration of 1 ms, pulse energy of 10 J, repetition frequency of 100 Hz, orbital speed of 400 mm/min, two orbital/trepanning passes, and oxygen as the assist gas. Subsequently, gas pressure was isolated as the primary variable and systematically varied in the range of 6-10 bar to assess its influence on drilling performance.

All holes were drilled perpendicular to the surface with a target diameter of 0.8 mm, nozzle standoff distance of 4 mm from the workpiece surface. Drilled holes were characterised using optical microscopy for entrance and exit diameter, and cross-sectional metallography for heat-affected zone, recast and oxide layer. Samples for cross-sectional analysis were sectioned through the hole centreline, mounted in conductive resin, ground to 1200 grit, polished to 1 µm diamond finish, and etched with Kalling's reagent to reveal the microstructure.

3. Results and Discussions

3.1. Design of supersonic nozzle

The supersonic nozzle design was established through one-dimensional compressible flow analysis coupled with two-dimensional method of characteristics (MOC) calculations. For the specified design conditions of 8 bar stagnation pressure and Mach 2.0 exit flow, the throat diameter was fixed as 1.6 mm (constrained by laser beam clearance requirements), and a corresponding exit diameter of 2.08 mm (initial value) calculated from isentropic area ratio relations.

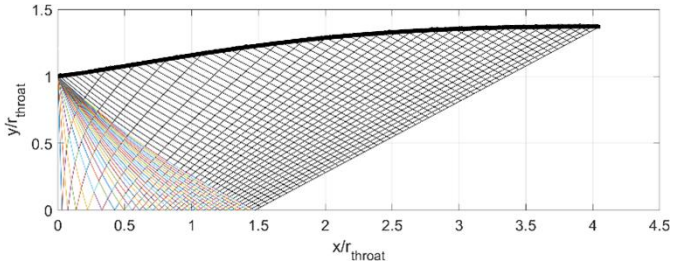
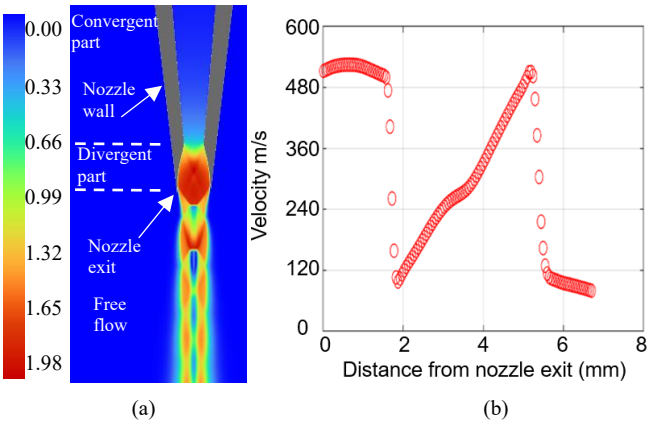


Figure 2. Divergent section nozzle profiles obtained from MOC

Figure 2 presents the divergent section contour generated by MOC for minimum-length nozzle geometry. The profile demonstrates the characteristic smooth expansion from the throat to the exit plane, with the maximum expansion angle positioned at the throat section. The MOC solution achieved an exit area of 3.7 mm², differing by less than 10% from the 1-D prediction (3.4 mm²), confirming the consistency between analytical approaches. Additionally, the exit diameter predicted by the MOC solution is 2.17 mm (final diameter value), compared to 2.08 mm from the 1-D calculation, representing a difference of less than 5%, which further demonstrates close geometric agreement between the two methods The resulting divergent part length of ~ 3.26 mm provides a compact design suitable for integration with the short focal length optical system while maintaining shock-free expansion characteristics essential for uniform gas delivery.

3.2. Numerical investigation of supersonic nozzle design



(a) (b)

Figure 3. Numerical simulation results of (a) Mach number and (b) velocity along the nozzle centerline

Figure 3 displays the Mach number contours (a) and velocity of the free-flowing gas (b) gas jet along the centre line. The flow accelerates smoothly from stagnation conditions through the convergent section, reaching sonic Mach 1 at the throat. Continued acceleration in the divergent section produces an exit Mach number of ~1.98.

The simulation reveals substantial boundary layer growth, particularly along the divergent section walls. Despite this viscous effect, the core flow maintains uniform velocity distribution with minimal variation across the central 70% of the exit plane, indicating successful achievement of parallel, shock-free expansion. The downstream free jet exhibits a gradual expansion and velocity decay characteristic of properly expanded supersonic flow.

3.3. Experimental verification of supersonic nozzle design

Figure 4 shows the centreline measured exit gauge pressure for various inlet pressures. The measured pressure increases smoothly, indicating progressive jet development downstream of the nozzle exit, including at the workpiece surface (4 mm) and potentially inside the hole (>4 mm). No abrupt pressure drop is observed within this region, suggesting the absence of a strong normal shock or Mach disk and is consistent with the simulation results in Figure 3, which show sustained supersonic flow and gradual Mach number variation. Results indicate that, at a 4 mm stand-off, the assist-gas jet delivers high momentum to the workpiece without shock-induced pressure losses, supporting efficient drilling process.

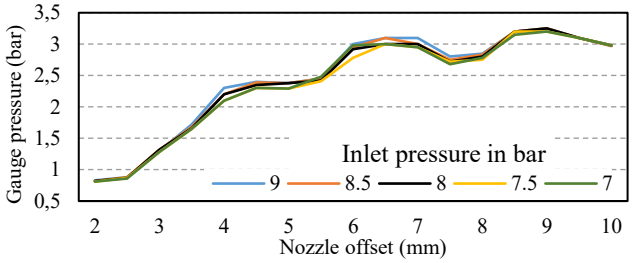


Figure 4. Pressure of the supersonic nozzle gas jet measured using manometer

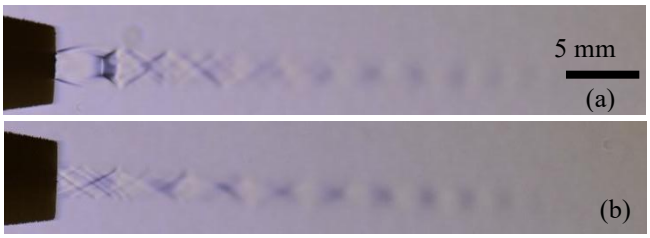


Figure 5. Schlieren imaging of (a) Subsonic nozzle and (b) Supersonic nozzle

Schlieren results (Figure 5) provides direct comparison of gas-jet structure between the subsonic and supersonic nozzle configurations. The subsonic nozzle (Figure 5a) with an exit diameter of 1.6 mm exhibits characteristic features of underexpanded flow: a visible Mach disk, multiple oblique shock, and irregular expansion patterns. These shock waves represent momentum losses and turbulent, unstable flow unsuitable for efficient melt removal.

In contrast, the supersonic nozzle (Figure 5b) produces a clean jet structure with minimal visible shock features when operated at the design pressure of 8 bar. The slight diamond-pattern visible in the near-field (< 4 mm) indicates weak expansion waves characteristic of near-design operation, while the absence of strong shock discontinuities confirms successful shock-free expansion. The jet maintains parallel boundaries extending beyond 10 mm from the exit, demonstrating effective preservation of the uniform core flow predicted by CFD. This stark visual contrast validates the fundamental design objective: elimination of shock-induced losses to maximize available momentum for melt ejection.

3.4. Laser drilling based on supersonic nozzle

Laser drilling trials were carried out on 2 mm thick C263 nickel superalloy to evaluate the performance of the supersonic assist-gas nozzle under industrially relevant millisecond-pulsed conditions. All holes were drilled using a quasi-continuous-wave fibre laser with a target diameter of 0.8 mm, while the assist-gas pressure was varied systematically to assess sensitivity to operating condition.

Figure 6a summarises the influence of assist-gas pressure on thermal affected zone thickness and the hole wall taper, for fixed laser and motion parameters (1 ms, 10 J, 100 Hz, 400 mm/min orbital speed, two orbits). At low pressures (5-6 bar), the thermal affected zone remains relatively low and the magnitude of hole wall taper increases, indicating insufficient melt expulsion and prolonged thermal interaction within the hole. As the pressure is increased towards the nozzle design condition, the wall taper improved. At 8 bar, corresponding to the design stagnation pressure of the supersonic nozzle, the thermal affected zone reaches ~30-35 µm, while the hole taper reduces to ~negative 0.65°. Further increase in pressure beyond the design condition leads to a deterioration in drilling quality. At 9-10 bar, the thermal affected zone increases markedly, and the magnitude of taper rises again, suggesting less stable melt ejection conditions. The observed negative taper is likely attributable to enhanced exothermic reactions at the lower region of the hole, driven by the greater gas momentum delivered by the supersonic nozzle. This also suggests that the supersonic nozzle may be better suited to processing thicker materials, which typically present challenges when using conventional nozzles.

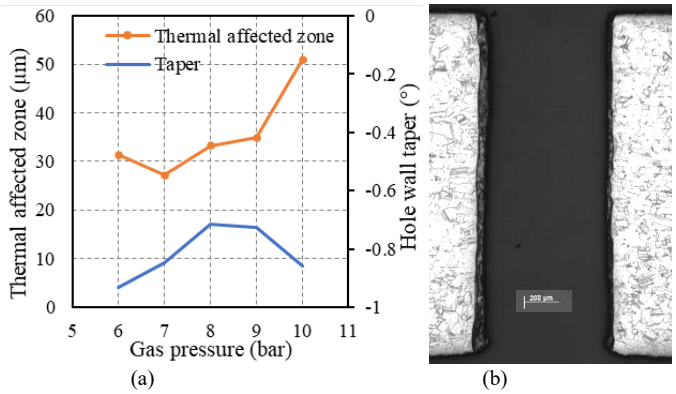


Figure 6. (a) Effect of gas pressure on drilling quality; (b) Cross sectional metallography image of a typical hole (1 ms, 10 J, 100 Hz, 400 mm/min, 2 orbits, 8 bar O_2)

Figure 6b presents a cross-sectional metallographic image of a representative hole drilled at the optimal condition of 8 bar oxygen pressure. The hole exhibits a uniform profile through the full 2 mm thickness, with minimal wall divergence and no evidence of localised constrictions or collapse. The combined thermal layer, comprising recast material, oxide layer and any heat-affected zone, is limited to less than 35 µm along the hole wall. No cracking or resolidified globules are observed, indicating stable melt removal during the multi-orbit drilling process. The consistent wall morphology and limited thermal damage are in line with the high-momentum, near-parallel gas jet delivered at the nozzle design condition, supporting efficient melt ejection while avoiding excessive heat accumulation.

4. Conclusions

This work successfully designed, simulated, and experimentally validated a supersonic assist-gas nozzle for millisecond-pulsed laser drilling applications. The nozzle design, established through 1-D gas dynamics and 2-D method of characteristics, achieved a minimum-length geometry (throat diameter 1.6 mm, exit diameter 2.17 mm) suitable for laser-based beam delivery systems.

CFD simulations confirmed shock-free internal expansion with supersonic nozzle exit velocity reaching Mach ~2. Experimental validation demonstrated superior performance compared to conventional subsonic nozzles, eliminating Mach disks formation and shock-induced momentum losses, as confirmed by manometer and schlieren visualization.

Laser drilling trials on C263 nickel superalloy established optimal operating conditions at the design pressure of 8 bar, producing high-quality 0.8 mm diameter holes with minimal thermal damage (<35 µm), and clean entrance/exit morphology. Pressure variation studies confirmed the importance of operating at design conditions, with both under-pressure (inadequate melt removal) and over-pressure (shock formation, flow instability) degrading hole quality.

The validated supersonic nozzle design provides a robust platform for enhancing the millisecond laser drilling process, offering improvements in melt ejection efficiency and process stability compared to subsonic assist-gas delivery systems.

Acknowledgements

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