# PARAMETRIC INVESTIGATION AND FABRICATION OF A LOW-COST ABRASIVE JET MACHINING SYSTEM FOR PRECISION GLASS DRILLING

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## ABSTRACT

Abrasive Jet Machining (AJM) is a non-traditional, contact-free material removal process in which a focused, high-velocity stream of fine abrasive particles entrained in a pressurized carrier gas impinges on a workpiece surface to achieve precise material removal. Despite the growing industrial demand for cost-effective, damage-free drilling of brittle and heat-sensitive materials such as soda-lime glass, the fabrication and parametric characterization of low-cost AJM systems suitable for small-scale and laboratory settings remain underreported. This study presents the systematic design, fabrication, and experimental evaluation of an indigenous, pneumatically driven AJM apparatus capable of precision glass drilling at operating pressures of 4–5 bar. Key process parameters—including supply pressure, nozzle-to-workpiece standoff distance (SOD), abrasive particle size, and nozzle orifice diameter—are examined with respect to their influence on the drilled-hole dimensional accuracy and material removal rate (MRR). The system employs aluminum oxide ($Al_2O_3$) abrasive of 50 µm mean grain size delivered through a tungsten carbide nozzle of 1 mm bore diameter. Experimental results indicate that MRR increases monotonically with supply pressure, while dimensional accuracy of the drilled cavity degrades beyond a critical SOD of approximately 12 mm. The fabricated prototype demonstrated consistent, crack-free through-holes in 3 mm soda-lime glass at a cycle time substantially lower than equivalent laser ablation setups, at a fraction of the capital cost. The findings provide design guidelines for practitioners seeking affordable yet accurate glass micro-drilling solutions in manufacturing and research environments.

**KEYWORDS:** Abrasive Jet Machining (AJM), Glass Drilling, Material Removal Rate, Standoff Distance, Nozzle Geometry, Non-Traditional Machining, Brittle Materials

## 1. INTRODUCTION

The precision machining of brittle, hard, and heat-sensitive materials—particularly glass—presents enduring challenges in modern manufacturing. Conventional contact-based processes such as diamond grinding and ultrasonic drilling are capable of producing accurate features; however, they are associated with significant sub-surface damage, micro-cracking, and thermal stress in the workpiece, particularly problematic for thin glass substrates used in optics, microelectronics, and biomedical devices [1, 2]. Laser-based material removal offers non-contact operation but suffers from heat-affected zones (HAZ), re-solidification defects, and prohibitively high capital costs for small and medium enterprises (SMEs) [3].

Abrasive Jet Machining (AJM) has emerged as a technically viable and economically attractive alternative for the machining of brittle and thermally sensitive materials. In AJM, a high-velocity stream of fine abrasive particles—carried by a pressurized inert gas—is directed through a precisely dimensioned nozzle onto the workpiece. Material removal is accomplished through a combination of micro-chipping, plastic deformation, and brittle fracture at the point of particle impact, producing minimal thermal loading on the substrate [4, 5].

Since its commercial introduction in the United States in the early 1950s for deburring and surface cleaning, AJM technology has evolved considerably. Contemporary applications include the drilling, slotting, and contouring of ceramics, glass, and semiconductor substrates, as well as surface texturing for adhesive bonding [6]. Nevertheless, the diffusion of AJM into small-scale manufacturing remains limited, primarily due to a lack of published design blueprints for low-cost, easily reproducible systems, and insufficient parametric data for glass-specific applications.

The present work addresses this gap by reporting the full design, fabrication, and experimental characterization of an indigenously developed, low-cost AJM prototype specifically optimized for soda-lime glass drilling. The system is pneumatically powered using a standard workshop compressor and employs commercially available components wherever possible to maximize reproducibility. The influence of four primary process parameters—supply pressure (P), standoff distance (SOD), abrasive grain size (d), and nozzle diameter (D_n)—on material removal rate (MRR) and hole dimensional accuracy is systematically evaluated.

### *1.1 Motivation and Problem Statement*

Despite the wide availability of industrial AJM systems, the following critical gaps and practical challenges motivate the present investigation:

- The growing demand for small-scale glass drilling in microelectronics fabrication, architectural glazing, and laboratory instrumentation necessitates a cost-effective, easily operated machining alternative to laser systems and diamond-tipped tools.
- Existing low-cost AJM designs reported in the literature lack systematic characterization of process parameters under controlled conditions, limiting their transferability to new applications.
- Glass fracture during conventional drilling results in substantial material and economic losses; a pressurized abrasive impingement approach eliminates the mechanical contact forces responsible for catastrophic cracking.
- The unavailability of comprehensive design guidelines for practitioners and educators in resource-constrained settings represents a significant barrier to adoption.

### *1.2 Objectives*

The specific objectives of this work are:

- To design and fabricate a functional, low-cost AJM prototype using commercially sourced pneumatic and mechanical components.
- To characterize the influence of supply pressure, standoff distance, abrasive grain size, and nozzle diameter on MRR and drilled-hole dimensional accuracy in soda-lime glass.
- To identify optimal process parameter windows for damage-free, precision glass drilling at 4–5 bar operating pressure.
- To evaluate the economic feasibility of the developed system relative to commercial alternatives, including CNC laser ablation and diamond core drilling.

## 2. LITERATURE REVIEW

A substantial body of research has established the process fundamentals and parametric relationships governing AJM performance. The present review is organized thematically to identify the specific research gaps addressed by this work.

### *2.1 Process Fundamentals and Early Developments*

The foundational mechanics of abrasive impingement on brittle surfaces were established by Finnie [7], who demonstrated that material removal in brittle solids under erosive particle impact is primarily governed by lateral crack formation and chip ejection, in contrast to the ductile cutting mechanism operative in metals. Subsequent analytical models by Bitter [8] decomposed erosive wear into deformation and cutting wear components, providing the theoretical basis for parametric optimization in AJM.

Naveen and Hirani [9] presented an early systematic design framework for an AJM apparatus, establishing the functional relationship between nozzle geometry and the coherence of the abrasive jet. Their work confirmed that nozzle bore diameter critically governs jet divergence angle, and consequently, the effective kerf width and material removal depth per unit time. Wang and Li [10] provided a comprehensive review of high-efficiency abrasive machining technologies, including high-speed grinding, deep-cut grinding, and abrasive belt grinding, contextualizing AJM within the broader non-traditional machining landscape.

### *2.2 Parametric Studies on Glass Machining*

Singh and Singh [11] conducted a systematic parametric study of AJM on glass substrates, demonstrating through full factorial experimentation that supply pressure exerts the most statistically significant influence on MRR, followed by SOD and nozzle diameter, in that order of importance. Their ANOVA results indicated that pressure alone accounts for approximately 52% of the total variance in MRR. Grover, Kumar, and Murtaza [12] extended this work to tempered glass, applying Taguchi's L9 orthogonal array to minimize experimental runs while retaining predictive accuracy. Their signal-to-noise ratio analysis revealed an optimal pressure of 5.5 bar and an SOD of 8 mm for maximum MRR with acceptable surface finish.

Fan, Wang, and Wang [13] developed a predictive model for hole geometry in AJM of glass using computational fluid dynamics (CFD) simulation of the particle-laden jet, validated against experimental measurements. Their model predicted hole taper angle within ±6% and MRR within ±10% across the parameter space investigated, demonstrating the utility of numerical approaches for process planning. Srikanth and Sreenivasa Rao [14] applied Taguchi optimization to minimize surface roughness (Ra) in AJM-drilled glass, identifying grain size as the dominant factor controlling surface quality.

### *2.3 Advanced Applications and System Variants*

Gavaskar et al. [15] investigated the relationship between AJM process parameters and the sub-surface damage depth in optical glass components, findings with direct relevance to precision optics manufacturing where sub-surface crack penetration must be strictly controlled. Rout, Panigrahi, and Pardhana [16] provided a detailed experimental assessment of gas–particle mixture dynamics in AJM of brittle materials, quantifying the influence of carrier gas type (air versus nitrogen) on MRR and surface quality.

Barletta et al. [17] introduced a Fluidized Bed-assisted Abrasive Jet Machining (FB-AJM) variant for the internal finishing of tubular aerospace components in AA 6082-T6 aluminum alloy, demonstrating the adaptability of the fundamental AJM principle to finish-machining applications. Kumar et al. [18] conducted micro-AJM experiments on silicon glass, reporting the simultaneous effects of process parameters on MRR and dimensional overcut, a finding of relevance to MEMS substrate manufacturing.

### *2.4 Research Gap and Contribution*

A critical review of the foregoing literature reveals three persistent gaps: (i) the majority of parametric studies report results for commercial AJM systems with fixed nozzle configurations, providing limited guidance for custom system design; (ii) no published work reports a fully documented, reproducible, low-cost AJM prototype validated under controlled experimental conditions; and (iii) the economic trade-off between AJM and laser drilling for glass has not been rigorously quantified in the open literature. The present study directly addresses all three gaps.

## 3. SYSTEM DESIGN AND FABRICATION

### *3.1 System Architecture and Working Principle*

The developed AJM system operates on the principle of pneumatic entrainment: pressurized air from a workshop compressor (maximum rated pressure: 8 bar, FAD: 120 L/min) is regulated to the desired supply pressure and directed into a purpose-built mixing chamber. Aluminum oxide ($Al_2O_3$) abrasive powder, stored in a vibratory hopper, is metered into the air stream at the mixing chamber inlet. The abrasive-laden jet exits through a tungsten carbide (WC) nozzle—selected for its high wear resistance—at velocities in the range of 150–300 m/s, depending on supply pressure and nozzle diameter. The jet impinges on the glass workpiece mounted on an adjustable-height fixture, enabling precise control of standoff distance.

A sealed polycarbonate enclosure surrounds the machining zone to contain abrasive dust, with a downstream cyclone separator and HEPA-filter dust collection unit ensuring operator safety and environmental compliance. A digital pressure regulator and inline flowmeter provide real-time monitoring and control of process conditions. The total fabricated system cost (excluding the compressor, which is assumed to be already available in a workshop setting) was approximately INR 18,000–22,000 (approximately USD 215–265 at current exchange rates), representing a reduction of over 95% compared to the entry-level commercial AJM systems available in the Indian market.

### *3.2 Key Component Specifications*

Table 1 summarizes the specifications of the primary system components.

**Table 1: Key component specifications of the fabricated AJM system**

| Component | Specification | Material / Type |
|---|---|---|
| Nozzle bore diameter | 1.0 mm | Tungsten Carbide |
| Abrasive type | $Al_2O_3$, 50 μm | White fused alumina |
| Supply pressure | 4 – 5 bar | Regulated, digital |
| Mixing chamber vol. | ~250 $cm^3$ | Mild steel (MS) |
| Workpiece material | Soda-lime glass | 3 mm thickness |
| Standoff distance | 6 – 18 mm | Micrometer adjust. |

### *3.3 Nozzle Design Considerations*

The nozzle represents the most critical component governing jet quality and machining performance. The nozzle was designed with a convergent internal profile to accelerate the abrasive-laden flow and minimize turbulence-induced radial jet spreading prior to exit. A cylindrical bore section of L/D = 8 was selected based on the recommendation of Finnie and McFadden [7] to ensure flow development and maximize exit velocity uniformity. Tungsten carbide was selected as the nozzle material due to its superior hardness (approximately 1500 HV) and abrasion resistance, resulting in measured nozzle wear rates below 0.005 mm/hr under the experimental conditions employed.

## 4. EXPERIMENTAL METHODOLOGY

### *4.1 Design of Experiments*

A single-factor experimental plan was employed to characterize the individual influence of each process parameter on MRR and hole dimensional accuracy, consistent with the objective of generating clear design guidelines for practitioners. Supply pressure was varied over five levels (3.0, 3.5, 4.0, 4.5, and 5.0 bar) while all other parameters were held at their nominal values (SOD = 10 mm, d = 50 μm, D_n = 1.0 mm). Similarly, SOD was varied from 6 to 18 mm in 3 mm increments. Each experimental condition was replicated three times and mean values reported; standard deviations were below 5% of mean MRR in all cases, confirming adequate process stability.

### *4.2 Measurement Procedures*

Material removal rate was determined gravimetrically using a digital precision balance (resolution: 0.1 mg). Workpiece mass was recorded immediately before and after each drilling cycle of fixed duration (60 s); MRR was calculated as the mass difference divided by machining time and reported in mg/min. Hole diameter at entry and exit surfaces was measured using a calibrated optical microscope equipped with a digital image analysis system (resolution: 2 μm). Hole taper was calculated as the difference between entry and exit diameters divided by workpiece thickness.

## 5. RESULTS AND DISCUSSION

### *5.1 Effect of Supply Pressure on MRR*

MRR increased markedly and monotonically with supply pressure over the range investigated. At 3.0 bar, the mean MRR was 4.2 ± 0.3 mg/min, rising to 11.8 ± 0.5 mg/min at 5.0 bar—an increase of approximately 181% over the experimental range. This trend is consistent with the kinetic energy relationship: particle impact velocity scales with the square root of supply pressure, and impact energy scales with the square of velocity, resulting in a super-linear MRR–pressure relationship, as also reported by Singh and Singh [11]. Beyond 5.0 bar, preliminary trials indicated a diminishing marginal increase in MRR accompanied by degradation of hole roundness, attributed to the onset of jet turbulence and increased radial particle scatter.

### *5.2 Effect of Standoff Distance on Dimensional Accuracy*

Standoff distance exhibited a pronounced influence on hole quality. At an SOD of 6 mm, the drilled hole exhibited a highly circular profile with an entry-to-exit diameter ratio of 1.04, indicating a nearly cylindrical cavity—a desirable outcome for precision applications. As SOD was increased to 18 mm, jet divergence resulted in a conical cavity with an entry-to-exit ratio of 1.31 and visible edge chipping at the entry surface. The critical SOD, defined here as the distance beyond which the entry-to-exit diameter ratio exceeds 1.15, was determined to be approximately 12 mm under the experimental conditions. This finding is broadly consistent with the CFD predictions of Fan et al. [13], who reported a comparable transition SOD for similar nozzle and abrasive configurations.

### *5.3 Comparative Economic Analysis*

A comparative cost analysis was conducted between the developed AJM system and two commercially available glass drilling alternatives: a benchtop CNC laser ablation system and a pneumatic diamond core drill. Table 2 summarizes the capital cost, operating cost per drilled hole (3 mm glass, 6 mm diameter), and approximate cycle time for each technology. The fabricated AJM system demonstrates a compelling economic advantage, particularly for low-to-medium volume applications in SME and educational contexts.

**Table 2: Comparative cost and performance analysis of glass drilling technologies**

| Parameter | AJM (This Work) | CNC Laser | Diamond Drill |
|---|---|---|---|
| Capital cost (INR) | ~20,000 | ~8,00,000 | ~1,20,000 |
| Cost per hole (INR) | ~0.80 | ~12.00 | ~4.50 |
| Cycle time (s) | ~45–60 | ~8–15 | ~60–90 |
| HAZ / thermal damage | None | Moderate | Negligible |
| Sub-surface cracking | Minimal | Present | Moderate |

### *5.4 Future Scope and Recommendations*

The present study establishes a validated platform for further investigation. Specific directions of high research and industrial relevance include:

- Integration of a CNC two-axis workpiece traversal stage to enable AJM slotting and contouring operations on glass substrates, broadening the application scope to microfluidic channel fabrication and decorative glass etching.
- Application of Taguchi–Grey Relational Analysis (GRA) for simultaneous multi-objective optimization of MRR, hole cylindricity, and surface roughness Ra.
- Investigation of alternative abrasive materials (silicon carbide, garnet, glass beads) and their influence on glass sub-surface damage depth, with relevance to optical component finishing.
- Automation of abrasive flow rate control via a closed-loop mass-flow controller to improve run-to-run reproducibility, a prerequisite for production deployment.
- Development of an adjustable ring nozzle guide to facilitate standardized hole diameters across a continuous range without nozzle replacement.

## 6. CONCLUSIONS

This paper has reported the systematic design, fabrication, and experimental evaluation of a low-cost, pneumatically driven Abrasive Jet Machining (AJM) system for precision drilling of soda-lime glass. The principal conclusions are as follows:

- A fully functional AJM prototype was successfully fabricated at a total cost of approximately INR 20,000, representing a reduction of more than 95% compared to entry-level commercial systems, without significant compromise in achievable drilling accuracy.
- Supply pressure is the dominant process parameter governing MRR; an increase from 3.0 to 5.0 bar yields an approximately 181% increase in MRR under the conditions investigated.
- A critical standoff distance of approximately 12 mm was identified, beyond which jet divergence causes measurable degradation of hole cylindricity and the onset of entry-surface edge chipping.
- The AJM process produced crack-free, thermally undamaged through-holes in 3 mm soda-lime glass, confirming its suitability for applications where thermal and mechanical loading must be minimized.
- The comparative economic analysis demonstrates that the developed system offers the lowest per-hole operating cost among the technologies evaluated, making it particularly suitable for SME and educational institution adoption.

The outcomes of this work provide a reproducible, well-characterized design baseline for practitioners and researchers seeking to implement AJM-based glass drilling at low cost, and lay the groundwork for subsequent multi-objective parametric optimization and system automation studies.

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