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RECENT DEVELOPMENTS IN NONCONVENTIONAL MACHINING OF GLASSES: A REVIEW

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ABSTRACT: This article presents a review on some important recent research, development, and innovations related to the nonconventional machining of glass material. Nonconventional machining processes were identified suitable for machining of glass, years ago, and from then to now various technological developments have made nonconventional machining a viable alternate to the conventional machining of glass material. In this article, we have mainly focused on three important nonconventional machining processes, namely, last cutting, ultrasonic machining, and electrochemical discharge machining (ECDM). Novel aspects, effects of process parameters, and salient features are discussed. Mainly, previous five years' work is reviewed. This review finally ends with a conclusion and important future research directions.
KEYWORDS: Glass, ECDM, surface quality, laser, nonconventional machining, ultrasonic

1. INTRODUCTION

Glass is a typical ceramic material that finds applications in various products and devices used in industrial, commercial, scientific, and domestic areas. It is electrically insulated, optically transparent, mechanically amorphous, and chemically stable [1, 2]. But, its fragility and brittleness are problematic. Sods-lime glass (also known as Pyrex), borosilicate glass, float glass, and quartz are some of its important types under the categories of glass ceramics and ordinary glass. Manufacturing and processing glass is challenging. Material removal from glass requires expert processes to get high quality products to fulfill the application requirements. Photolithography and chemical etching are extensively used for glass machining. Long process sequence thereby long fabrication time, involvement of hazardous substances, and high cost are some possible limitations with these two processes. Issues related to surface damage of glass products in diamond turning and micro milling type processes also make glass machining challenging. Nonconventional or modern/advanced processes have been attempted for machining glass material. Specially, thermal and mechanical type nonconventional machining processes such as laser cutting, ultrasonic machining, electrochemical discharge machining, and abrasive waterjet machining processes are found the most suitable to machine glass or fabricate products out of the glass material [3-5]. With time, there have been several research and development efforts to improvise the capability of nonconventional processes to machine glass with improved accuracy, sustainability, and cost effectiveness. In this review article, we have discussed some of the important past five years' work conducted by previous researchers on fabrication of different glass material using nonconventional machining processes. The scope of our review includes laser cutting (LC), ultrasonic machining (USM), and electrochemical discharge machining (ECDM).

Figure 1 presents the working principles of nonconventional machining processes considered in this work, and a brief discussion is given here as below.

As shown in Fig. 1, in LC, a high intensity laser beam is focused on the work surface of glass, which causes rapid heating and subsequent melting and vaporization of the glass material [6]. Various settings of its process parameters help to achieve the cut depth and geometry required. CO2, Nd: YAG, and fibre etc. are some of the lasers used for precise cutting. Power, stand-off-distance, focal position, cutting speed, and gas pressure are some of the important parameters in laser cutting process [7]. The other important category is the laser assisted machining of glass, where assistance of laser is used in turning or milling of glass to facilitate the materials removal etc. This category is out of the scope of this review paper. USM is a mechanical type nonconventional machining process. As shown in Fig. 1, it makes use of abrasive slurry to remove material from the glass workpiece under the influence of a rotating tool which also rapidly travels to-and-fro due to high frequency ultrasonic vibrations [8]. The downward movement of the tool forces the abrasive laden slurry and material removal by chipping-off action after a brittle fracture, takes place. Abrasive grit size, slurry density, ultrasonic frequency, power rating, and tool material and feed rate are some of the important parameters of USM [9]. Ultrasonic assisted machining processes like drilling and milling etc are out of the scope of this paper. ECDM is a hybridized method of electric discharge machining and electrochemical machining [10]. This process has specially been developed for machining of glass and other ceramics. In this process, as shown in Fig.1, electrolytic dissolution due to electrochemical reaction takes place on the tool electrode. The intensive formation of gas bubbles also takes place. It is followed by a spark erosion at the tip of the tool, occurs due to a potential difference between two electrodes, due to which glass bubbles layers breakdown. It generates heat which causes the removal of material from the nonconducting glass. The chemical etching also somewhat contributes to the material erosion during ECDM. Voltage, stand-off-distance, pulse duration, pulse frequency, type of concentration of electrolyte are some of the important parameters of ECDM process [11].

Some research, innovations, and developments in last five years in machine tool systems, process monitoring and control, product measurement and characterization, and process capability enhancement for nonconventional machining of glass, are reviewed in this article.

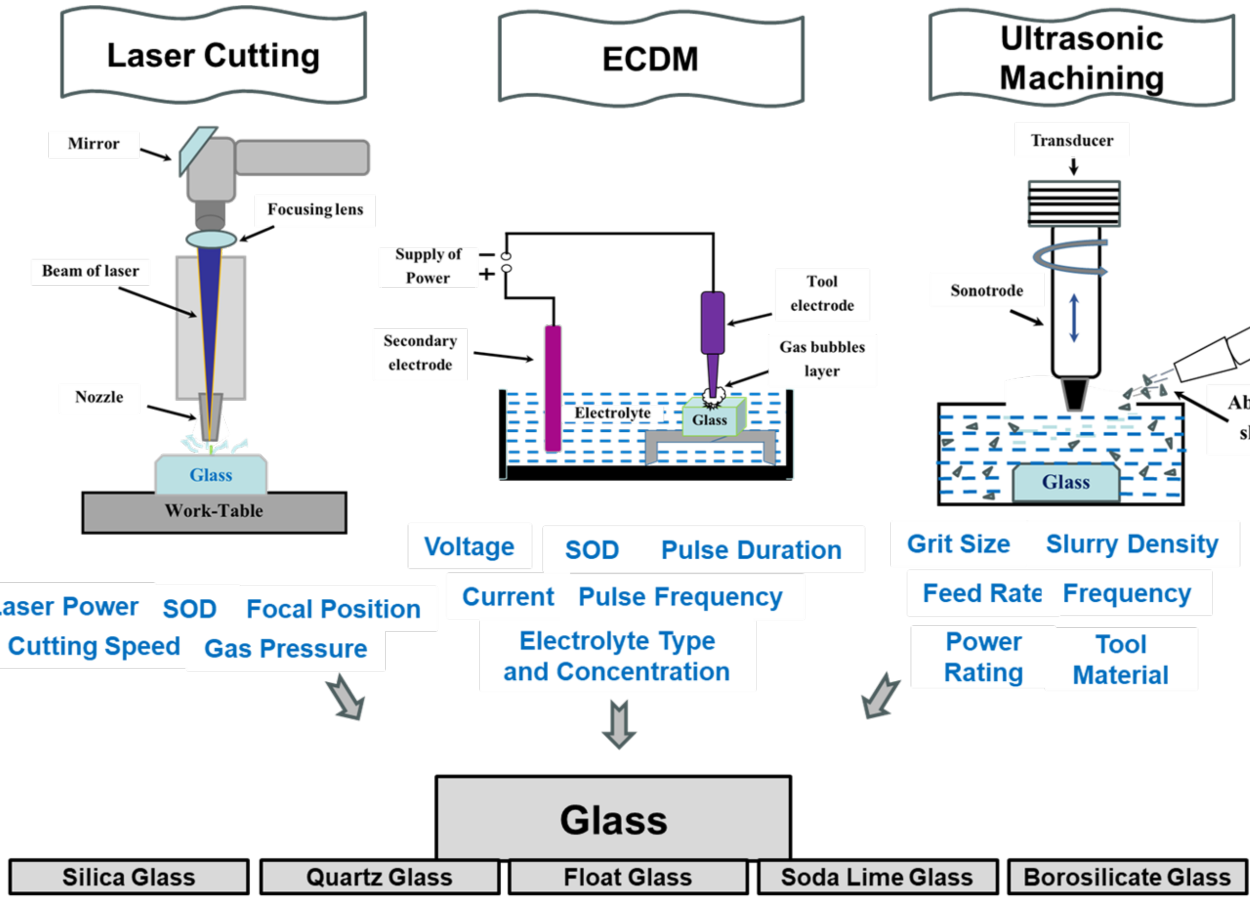

Figure 1. Working principles of various nonconventional machining processes for glass

2. REVIEW OF PAST WORK

Figure 2 illustrates some of the important recent innovations and developments in USM, ECDM, and LC that complemented glass cutting. Table 1 presents a summary of some of the important past work on nonconventional machining of different glass materials. Nonconventional machining of glass was mainly conducted to drill holes or make micro channels or slits. Previous researchers have reported many challenges during their attempts to machine glasses using USM, ECDM, and laser cutting. They developed novel ways to enhance the glass machinability for a better surface quality and process productivity.

Ultrasonic machining (USM) that mainly includes rotary ultrasonic drilling of glass in the last five years, has been complemented with technological interventions that facilitated glass cutting with enhanced machinability. These technological interventions mainly include integration of optimization techniques, hybridization with chemical etching, simulation tool implementation [12-22]. These attempts are summarized in Table 1. Some of the selected and most important work are focused on gang drilling of square hole on glass slides [14], intentional coating of Myristic acid type material on Pyrex glass for surface and geometrical property enhancement after ultrasonic machining [16], optimization of ultrasonic drilling of BK-7 glass that resulted in highest productivity and best surface quality [18], machining of float glass using hybrid process of USM and chemical etching to reduce defects and improve surface quality [19, 20]. One of the important investigations reported conducting smoothed particle hydrodynamics simulation for material removal rate and tool wear in ultrasonic micromachining of float glass [21]. The simulation helped to predict and understand the material removal mechanism by studying tool penetration and crack initiation and propagation. The simulation results were also verified by experiments. A recent investigation highlights the development of a novel template-based electrophoretically assisted micro-ultrasonic machine tool for microchannel fabrication on soda-lime glass [22]. The electrophoresis assistance given to the abrasive particles resulted in 4% increment in efficiency of the machining process and 20% reduction in surface roughness of the machined glass.

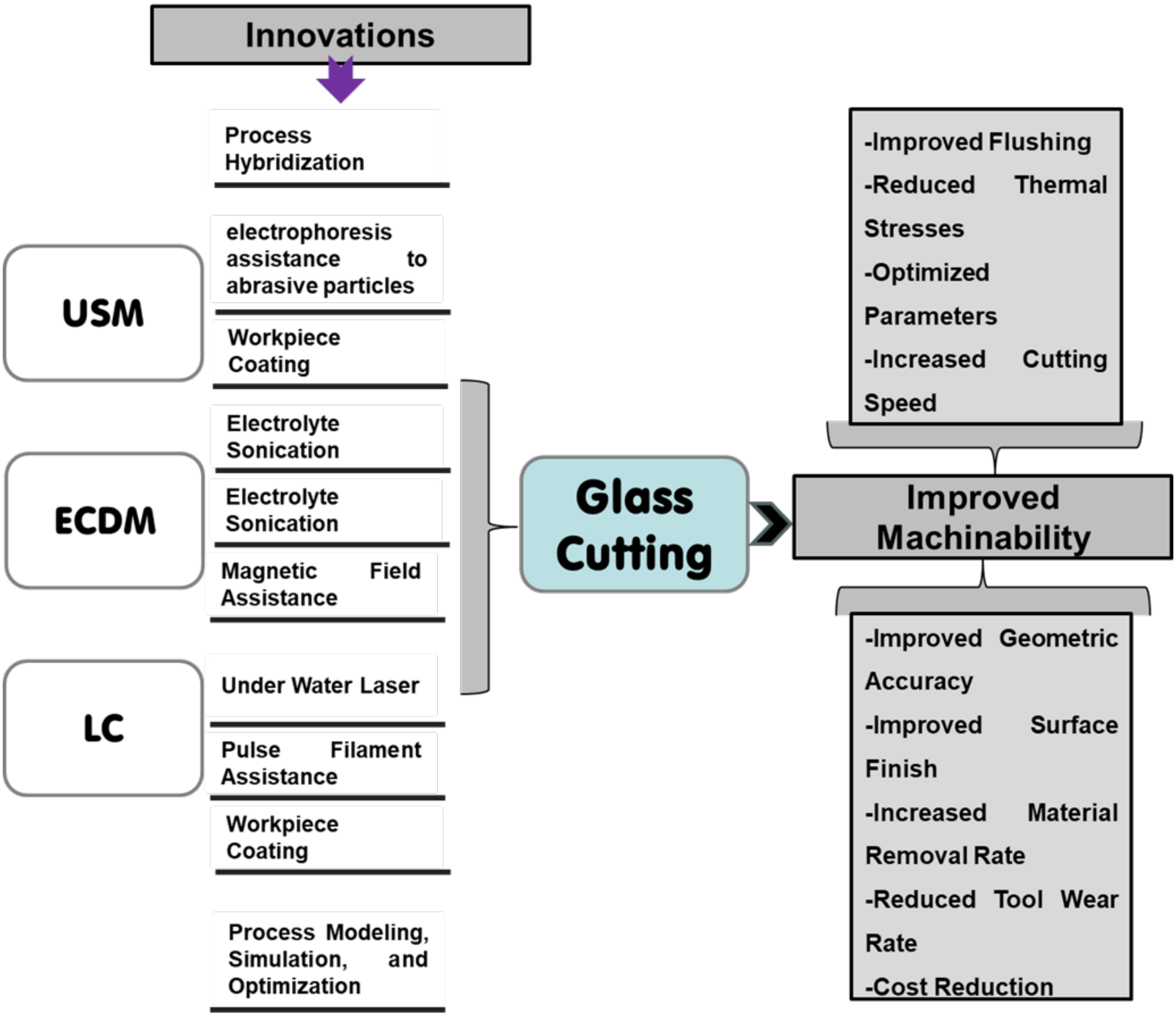

Figure 2. Recent innovations and developments in nonconventional machining for improved glass cutting

Table 1. Summary of important past work on nonconventional machining of glass

Reference	Glass material type	Experimental details	Key Findings
Ultrasonic Machining			
[12]	BK-7 Glass	Effect of USM parameters on cutting quality during hole drilling in glass	The best quality of cutting achieved with 1.32 µm roughness, 3 µm cylindricity.
[13]	Quartz	Study on influence of tool feed rate and power on machinability	Low tool feed rate found desirable for geometric accuracy.
[14]	Glass slides	Gang drilling of square holes	Fine abrasive particles, high slurry flow rate and tool feed rate are desirable for the enhanced machinability of glass in terms of material removal rate and hole's surface quality and geometrical accuracy.
[15]	Glass slide	Slot cutting using SS tool by ultrasonic drilling	-Low overcut can be achieved with low values of power, abrasive size, and tool feed rate.
[16]	Pyrex	Study on influence of coating on characteristics of micro-channel	Myristic acid has been found as the most suitable coating material for Pyrex to get good surface quality and geometrical accuracy.
[17]	Quartz	Investigation on Parameter effect and their optimization	-Low tool feed rate and high rotational speed facilitated material removal by plastic deformation, while their opposite values caused brittle fracture-based machining. -Optimized MRR-0.2135 mm^3/s and roughness- 0.3685 µm achieved.
[18]	BK-7 Glass	Ultrasonic drilling process optimization	-Tool feed rate found as the most influential factor -Utility concept based multiperformance optimization resulted in the best values of MRR 0.3729 mm^3/s and surface roughness 0.293 µm.
[19,20]	Float Glass	Study of hybrid USM and chemical etching (under hydrofluoric acid) on hole drilling	-The hybridization could reduce the drilled hole entrance chipping and improve surface integrity. -5% concentration of hydrofluoric acid generated <1 micron roughness.
Electrochemical Discharge Machining			
[23]	Silica glass	Taguchi L27 and GRA optimization for overcut, tool wear, and MRR.	-Voltage is the most influential parameter. -Optimum parameter combination 45V voltage, electrolyte concentration- 25 wt.%,

			stand-off-distance- 1.5 mm, pulse frequency- 400 Hz, pulse-on time- 45 µs) -Good quality of the machined surface.
[24]	Soda lime glass	Study on the influence of abrasive mixed electrolyte.	-Improved MRR and depth of machining with Al_2O_3. -Overcut reduced due to SiC.
[25]	Soda lime glass	Study on effect of voltage and duty factor	High voltage and duty factor increased the HAZ and thereby deterioration of the work surface.
[26]	Borosilicate glass	Study of MRR and roughness of glass	-Successful fabrication of micro holes equipped with 0.8 microns average roughness. -1.5 mm/min MRR
[27]	Borosilicate glass	Investigation of electrolyte sonication on performance of ECDM	Improved flushing of machined material.
[28]	Borosilicate glass	Simulation and experimental studies	There was a good agreement found between simulation and experimental results. MRR and width overcut increased with increase in voltage, pulse-on time, and electrolyte concentration.
[29]	Borosilicate glass	Investigation on wire electrochemical discharge machining under mist flow	Higher mist flow rate produced better surface integrity with low heat affected zone and thermal cracks, due to improved flushing and spark stability.
[30]	N BK-7 glass	Study on drilling of glass	25% improvement in MRR and 7.6% reduction in tool wear rate. High range of machining parameters is suitable to obtain better quality characteristics
		Laser Cutting	
[35]	Glass	Micromachining by CO_2 laser	-Successful fabrication of microchannels -Low speed for better roughness
[36]	Optical Glass	CO_2 laser micromachining of preheated Glass	-high power, low speed, and high passes for high tolerance microchannels.
[37]	Soda-Lime Glass	Influence of infrared femtosecond laser under films of water, Sodium Chloride, Potassium Hydroxide.	Potassium hydroxide identified as the best solution for laser machining of glass
[38]	Crown Glass	CO_2 Laser	-Successful drilling of cylindrical holes (min diameter- 150 microns and min length- 109 micron.
[39]	Borosilicate Glass	CO_2 Laser Cutting	Increase in laser power affects productivity proportionately and

			increase in speed inversely. -Coating on glass workpiece enhances the machinability due to the absorption of more laser power.
[40]	Soda Lime Glass	CO_2 Laser Cutting	-Crack propagation is the major cutting mechanism which occurs due to thermal stresses generate by rapid heating cooling -Low scan speed and laser power suggested for better cut quality
[41]	Soda Lime Glass	Microchannels fabrication by Ultraviolet picosecond laser	-Offset with double bidirectional scanning is preferable to attain the best geometry on the workpiece.

Electrochemical discharge machining (ECDM) that constitutes both ECM and EDM was developed for machining of nonconducting material like glass. Some important recent investigations indicate the capability of this process mainly for ease of machining of silica, soda-lime, and borosilicate glass [23-30]. The innovative strategies incorporated in last five years mainly include sonication of electrolyte for improved flushing of the debris particles [27], application of simulation tool for ease of understanding of the process mechanism [28], use of wire as an electrode and therefore known as wire ECDM for cutting borosilicate glass under mist flow for minimizing thermal effects [29]. All investigations reported carefully select the voltage and pulse parameters, as they affect the most. Recently innovated sacrificial layer ECDM conducted on glass wafer bonded borosilicate glass and improved properties of the machined hole were achieved due to minimization in adverse thermal effects [31]. Nanoparticles from a borosilicate workpart were generated using an indigenously developed ECDM setup [32]. The assistance of magnetic field was also brought into existence during electrochemical spark drilling of a soda-lime glass slide [33]. It was possible to obtain stable sparking due to the formation of low size gas bubbles influenced by magnetic field. A unique textured wire-ECDM was attempted on borosilicate glass [34]. The localized electric field intensification due to textured wire resulted in micro-slits fabricated with better geometrical accuracy at optimum combination of parameters.

Laser cutting (LC) of glass has mostly been conducted using CO2 laser, on soda-lime glass, and for fabrication of microchannels [35-41]. Low scanning speed and laser power have been recommended to obtain the high quality of the machined surface of glass. Some novel strategies like machining under water and films of chemicals [37, 42], surface coating of the glass workpiece [39], combination of offset and double direction scanning [41], have been attempted by various researchers to facilitate laser machining of glass.

Besides these strategies, finite element analysis-based simulation tool has also been used to predict and better understand the thermal aspects and crack propagation mechanism of glass cutting by lasers [43]. A recently investigated technique named ultrashort pulsed filamentation has been proved beneficial to glass cutting as it generates small heat affected zone [44]. It uses a specially designed optic in Nd:YAG laser machining. One of the latest research projects also include cutting of Gorilla glasses (sods-lime) by a pulse filament assisted femtosecond laser with promising future use for commercial applications [45]. Some research is also conducted to extend the applications of Laser cutting for machining solar glass to facilitate the photovoltaic industry [46, 47].

3. CONCLUSION

Some recent developments in nontraditional machining of glasses have been presented and discussed in this review article. The important conclusion points are highlighted below:

- Ultrasonic machining of glass is a viable alternative to other processes, since it can cut holes and slits on glass with good accuracy. Its hybridization with processes like chemical etching can improve the process productivity for a better machinability.

- Creating multiple holes at a time in glass is also possible with ultrasonic drilling.
- In ECDM, improved flushing due to mist flow assistance and electrolyte sonication, is a novelty to obtain better machinability for glass. Voltage and duty factor are the most influential factors.
- Laser cutting of glass has been extended to many applications. The most important factors to consider are power and scanning speed. Under water laser, assistance of pulse filament, ultrashort pulse, and finite element analysis, have been found effective.
- Advancement in nonconventional machining process simulation is also very important to bring innovation and novelties for improving the surface quality and geometric accuracy of the machines glass and productivity of the processes.
- Process optimization for machinability enhancement of nontraditional machining of glasses is an important aspect. The application of machine learning and other soft computing-based techniques require future attempts to establish the field further.
- Sustainability analysis of the nonconventional processes for machining of glass is yet another important future research avenue.

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