Chapter 2
Machining of Glass Materials: An Overview

Asma Perveen and Carlo Molardi

Abstract Being hard and brittle, glass is considered one of the very difficult-to-cut materials. This chapter is primarily concerned about the glass types, properties, and applications as well as associated difficulties in their machining. Following that, this chapter explores various conventional and nonconventional technologies available till today for machining of glass material. Furthermore, it also sheds light on cutting mechanisms of glass materials for both single and multiple cutting edge tools in case of conventional machining. Aspects of tool wear and surface/subsurface damage relevant to glass machining are also discussed.

Keywords Abrasive water jet machining · Discharge · Electrochemical · Glass · Laser · Ultrasonic machining · Ultraprecision · Wear

2.1 Glass and Its Machining

2.1.1 Introduction

In the recent past, to fulfill the request for extreme applications, there have been tremendous interests in improved ceramics and glasses such as, silicon nitride and carbide, alumina, BK7, and soda lime glass materials with unique metallurgical properties. Even if these materials are relatively harder, less heat sensitive and resistant to chemicals, fatigue, and corrosion, such materials impose significant challenges to machining [1]. These materials, known as brittle and difficult to cut, are commonly used not only in the electronic industries but also in the public welfare industries like biomedical and optics [2]. For electronic industries, glass is popular functional material in microelectromechanical system (MEMS) device

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packaging, microelectronic packaging, and microfabricated device like, solid oxide fuel cell for portable electronic device, pump, and reactors [3]. In case of biomedical industry, glass has found its applications in microfluidic device, DNA array, micro-valve, micro-flow sensor, biomedical parts, and biological instrumentations [4]. Glass also acts as substrate for bonding with wafer in semiconductor applications. On top of these areas, glass is also contributing in optics industry for the fabrication of telescope lenses, microscopic slides, optical fiber alignment, and mini-vision system [5, 6]. In addition, it has extensive applications in automotive industry for windscreen, and cockpit windows.

There are various types of glasses available in the market at present. Commercially available glasses can be categorized based on their chemical composition as below:

- Soda lime glass
- Lead glass
- Borosilicate glass
- Aluminosilicate glass
- 96%-silica glass
- Fused silica glass.

Glass is widely used in micro technology system, due to its beneficial and functional properties. Examples can be retrieved from the field of microfluidic devices, used in biotechnical applications [7, 8]. In micro-total-analysis-system (μTas), glass offers several benefits, much more than silicon like optical transparency which is useful as an example for visual inspection, and real time optical detection. The dielectric property of glass can be effectively used to resist strong voltages which are necessary in electrokinetical separation and flow driving. Furthermore, glass presents other interesting properties such as stability to strong temperature gradient and chemical inertness. Such outstanding properties make glass the perfect material to build substrate for DNA arrays. Some of the excellent properties associated with glass materials are quoted as follows [7–10]:

- High hardness
- Homogeneity
- Optical transparency
- Isotropy
- Various refractive indices
- Low thermal and electrical conductivity
- High dielectric strength
- High chemical resistivity.

In the area of machining, advanced working of ceramics and glass materials has earned primary attention. Like most other materials, glass undergoes plastic deformation as seen from indentation test if the depth of cut can be maintained under certain critical value which will avoid brittle fracture [11]. Hence, the possibility to machine hard to cut brittle materials, using ductile strategy avoiding fractures, has become real. This fact leads to the new possibilities of machining brittle materials with optical surface finish by exploiting traditional machining processes which eliminates the necessities of the secondary finishing process. Machining processes like grinding, milling, turning, abrasive jet machining, ultrasonic machining, laser machining have already been quite successfully employed to machine glass. The excellent mechanical properties of these hard to machine materials, i.e., glasses doubtlessly increase their usage in several important applications while opening up the new windows of their applications due to their treatments by ductile machining.

2.1.2 Challenges in Machining of Glass

The family of optical glasses, which are hard and brittle, represents huge challenge to mechanical machining. For optical applications, glass shaping is usually obtained by grinding, followed by a series of polishing processes to remove the damage caused by grinding. However, it is quite challenging to generate favorable microstructure imparting necessary precision characteristics in glass for microfluidics devices. This difficulty to build glass structure is quite evident, among large number of micromachining techniques, both conventional and nonconventional.

Significant researches have been conducted on micro fabrication technology which mainly involves photolithography, as well as chemical etching methodology. Glass, showing isotropic nature can be wet etched using hydrofluoric acid with a nondirectional strategy. Dry etching by chemical action is also possible in typical SF6 plasma which is hindered due to slow etching rate [12]. Etching techniques involve hazardous problems, since the etching material contains lead or sodium which produces nonvolatile halogen compounds as reaction products. Reactive ion etching, which uses special plasma source, in order to produce high density plasma at low pressure, has been exploited for silicon channels generation. Nevertheless, such techniques are not enough developed to be used in complex glass structures.

Laser machining also offers potential risk of micro-cracking, debris formation, and other damages, because of the high fragility and the poor thermal behaviors of many types of glass [5]. Mechanical machining techniques, such as abrasive jet machining can be used for brittle materials. This technique, which consists of mechanical removal by the use of high-speed jet particles, allows obtaining eroded structure with complex shapes. However, jet machining is hindered due to the rough surface and limited to larger component [13, 14].

Machining of metals to achieve high quality surface finish is relatively easier considering the high ductility. But as the utilization of nonmetallic materials like glass is growing rapidly in manufacturing of precision products ranging from jet engine parts to the mold manufacturing for precision casting, there is an equivalent growth in the demand for ductile mode machining of these materials. This ductile regime cutting has been experimented, mostly using single point process where a single-crystal diamond is employed to remove the brittle material without any fracture. However, generation of asymmetrical features and complex shapes are beyond the capability of turning. With the increasing demand of miniaturization, the challenge of achieving complex shapes and structures on miniaturized devices is also rising. This challenge appeals for versatile machining processes, like milling, to produce such complex shapes. Nevertheless, a multi-cutting edge process creates even more difficult scenario to control the cutting conditions to achieve ductile machining. Brittle materials are machined with difficulties by mechanical cutting process such as milling. The reason can be searched in the damages due to the material removal induced by brittle fracture, leading to a nonuniform surface which requires further polishing. High-speed milling, widely used by industry of metallic mold, is hard to apply in the machining of glass because of the relevant strength and hardness associated with this material. Such technical difficulties highlighted in the above mentioned machining techniques, and the need to reduce the high cost associated with the machining procedures, push the industry to foster newer approaches for machining glass materials [6].

2.2 Cutting Mechanisms

Underpinning knowledge associated with brittle to ductile transition and optimum cutting conditions may offer significant improvement in the machining technology of brittle materials. This section will give an overview of various cutting mechanisms developed over time relevant to glass and prerequisite conditions for ductile mode material removal.

2.2.1 Ductile Mode Machining

Precision applications specific to the tight tolerances have opened up a huge opportunity to explore the new ways and techniques to machine glass materials. The property of ductility indicates the extent of permanent deformation without fracture. The term plastic deformation refers to the ability of the material to shape permanently under loading. All materials have some extent of ductility no matter how brittle they are. So fracture in all materials is preceded by the manifestation of more or less ductility. However, the extent of ductility is diverse for different materials. The scale of consideration is an important factor to assess the plastic deformation probability. Material like glass that is perfectly brittle at macro scale, may exhibit plastic deformation at microscale.

Extensive researches have been pursued over the past two decades, to evaluate the plastic deformation characteristics of brittle materials like glass through indentation, scratching, grinding, and machining. Dolev et al. [15] observed microplasticity phenomenon, where the glass exhibits ductile or plastic behavior, when indented with a concentrated load. Finnie et al. [16], with the help of

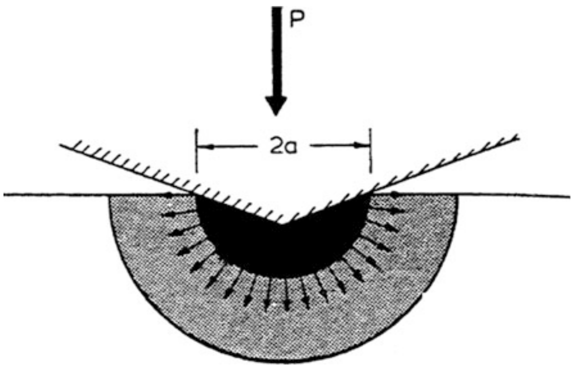

Fig. 2.1 Schematic representation of elastoplastic indentation [18, 19] (Hydrostatics core is depicted as *black* area. Plastic zone is depicted as *gray* color. Elastic matrix is represented by *black arrows*) with kind permission from Elsevier

Auerbach's law, explained that the use of small indenter can exploit the transition from brittle to ductile mode, where the cracking load is having linear proportional relation with the indenter diameter. Lawn et al. [17] quantified the results obtained by indenting soda lime glass with Vickers's Pyramid indenter at different loads (see Fig. 2.1) and reported that cracking is a favorable mechanism above a critical load. Below this point, there are no cracks or fracture. This resulted in a conclusion that significantly lower loads can help to create clear impressions using indenter, however, the possibility of crack initiation increases with increase of load value. Under such controlled environment, possibility of machining glass without any crack in ductile mode has got new dimension. Ductile mode machining can happen in any material so long the deformation keeps in smaller range.

Giovanola and Finnie (1980) performed the first feasible work in order to study the plastic deformation of glass. According to this study, glass can be processed, similar to metal, using ductile phenomenon as long as the cut thickness is kept significantly small [20]. Later on, after a thorough investigation on ductile mode grinding of several ceramics, Bifano [21] stated that the critical undeformed chip thickness, which governs the brittle to ductile transition, is influenced by the intrinsic properties of material like elastic modulus, hardness, and fracture toughness. Blackely (1991) also derived an analytical model using processing parameters of diamond turning in order to evaluate the critical parameters for achieving ductile mode cutting. Figure 2.2 shows a schematic of turning tool with cutting parameters.

This research recommended a critical value of undeformed chip thickness below micron range. According to this model, for achieving ductile surface, it is not necessary that material removal is completely done by ductile mode, rather a combination of ductile brittle mechanism may work well so long the fractured surface remains far from final surface. This situation can be created by using relatively smaller feed rate which keeps the subsurface damage depth far from the critical limit as given in Fig. 2.2 Considering the critical feed rate, the critical undeformed chip thickness, will occur significantly well above the cut surface so that subsurface damage will not be able to reach below the cut surface. As a result, a damage-free surface will be generated even though the brittle fracture will still be

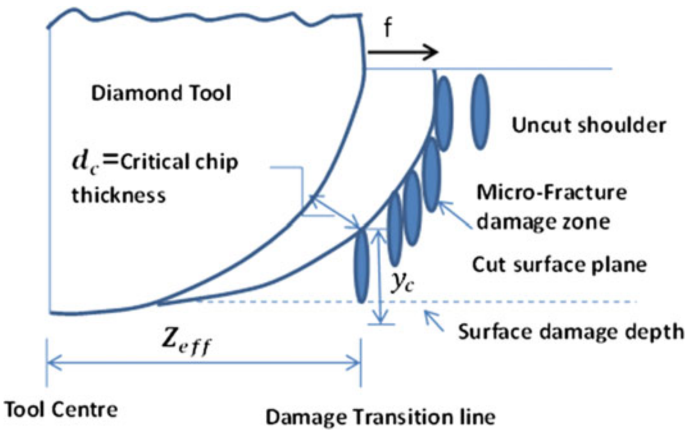

Fig. 2.2 Schematic cutting model for critical depth of cut [11] with kind permission from Elsevier

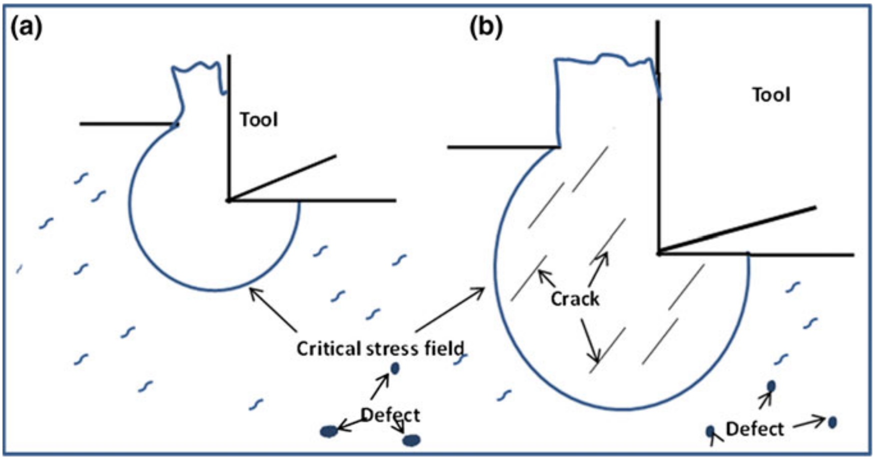

Fig. 2.3 Schematic of defect distribution and chip removal. Stress field generated by **a** small depth of cut **b** large depth of cut [22] with kind permission from Elsevier

there in the machining. Alternatively, higher feed rate causes the critical undeformed chip thickness to occur adjacent to the cut surface. Consequently, damage will propagate beneath the cut surface, contributing in brittle mode machining [11].

Brittle to ductile transition can be alternatively explained by the analysis of cleavage fracture using the existence of defects [22]. Density of defects limits the plastic deformation and the cleavage. Generally, the critical value of fracture is determined by stress field size due to the smaller size of defect density in brittle materials. Figure 2.3 shows the size effects phenomenon. Smaller uncut chip thickness, causing the generation of smaller stress field, avoids the cleavage fracture which in turn shifts the cutting mode from brittle to ductile.

Therefore, there exists two different approaches of material removal, namely brittle fracture and plastic deformation for brittle materials machining. The former one occurs when the cleavage plane coincides with the maximum shear stress plane. The later occurs on the slip plane coinciding with the maximum tensile stress plane. Considering the case where the critical shear stress is overtaken by the tensile stress applied in slip direction, before the occurrence of cleavage, the workpiece undergoes plastic deformation in the small stress field associated with the cut depth. Conversely, when the applied tensile stress, which is normal to the plane of the cleavage, manages to overcome the critical tensile stress before the plastic deformation onset, in such case, the scenario is dominated by the brittle fracture [23].

Cai et al. [24] narrated about another possibility that can help in ductile regime machining. It is the case when the value of uncut chip thickness is significant; in particular, its value is less than the size of cutting edge. Under this circumstance, the cutting force becomes lower than the thrust force in the machining process which squeezes the material beneath the cutting edge and a highly compressive hydrostatic force is prevailed in the regime of chip formation which arrests the propagation of fractures. Therefore, material removal mechanism is dominated by plastic deformation over brittle fracture. Ultraprecision machining using higher negative rake angle tools usually provide enough hydrostatic pressure for inducing plastic deformation. Moreover, careful look into a grinding wheel reveals the fact that grinding grains possessing higher negative rake angle cause the cutting force to reduce half of the thrust force. A deep analysis of ultraprecision technique for brittle materials suggested that higher negative rake angle can be achieved by selecting the value of cut depth less than tool radius. Consequently, plastic deformation or ductile mode machining takes place, which also prevents median cracks initiation because of huge hydrostatic pressure created by the tool edge [25].

2.2.2 Material Removal Mechanism in Glass

Machining of glass in ductile manner could be considered similar as the machining of metal. However, high brittleness arises from the irregularity of atoms structure inside the glass material. On the other hand, atoms inside the metal maintains static regular pattern as indicated by Miller indices contrary to the amorphous material [26]. The status of atomic bond indicates the kind of material removal mechanism involved [27, 28]. Metals, having metallic bonds, generally experience ductile manner machining. Brittle mode machining of glass can cause vertical cracks which results in substantial amount of subsurface damage during loading whereas during unloading it can cause lateral cracks to generate which consequently results in material removal. Nevertheless, choosing very low depth of cut can avoid the situation of brittle mode cutting even for brittle material like glass. Blackley [11] suggested the depth of cut to be below 10 nm in order to machine glass in ductile manner. Therefore, mechanics of material removal involves brittle fracture and plastic deformation in glass. Lateral and median cracks are consequence of brittle fracture created while indenting on brittle substrates. Cutting load and work piece properties govern the brittle mode fracture. On the other hand, plastic deformation is similar to chip formation involving scratching, ploughing, and formation of chips during the grinding process of metal. Theory of ductile mode machining suggests that all materials irrespective of its ductility will experience brittle ductile transition phenomenon below the critical depth of cut for that particular material. Below this critical depth of cut limit, the energy for crack propagation seems to be greater than the energy for plastic deformation which makes the plastic deformation mechanism as predominant [29]. When the grain makes impact on the material during grinding, in the contact region; heat accumulation, caused by the poor thermal dissipation, along with the large compressive stress causes plastic deformation [30]. Therefore, ductile regime machining is influenced altogether by the tool shape, feed rate, and the critical depth. However, clean ductile mode only appears along the tool apex as the actual depth of cut is found to be lower than the critical depth [31]. During turning, material response is governed by the stress field size and value, along with the cutting combination. While investigating the transition between brittle and ductile phenomenon, it has been understood that generated stress field can be arranged in four different zones as given below [32]:

1. Zone I: Chemical/temperature effect on top of mechanical action removes materials in this region (Machining unit below 10^{-6} mm).
2. Zone II: The material behaves as an ideal crystal without any dislocation. Initiation of dislocation appears just prior to brittle fracture which leads the crystal to next zone (Machining unit between 10^{-6} and 10^{-4} mm).
3. Zone III: This zone exhibits plastic deformation. Typically, cracks appear in this stage (Machining unit between 10^{-4} and 10^{-2} mm).
4. Zone IV: Crack/brittle mode is dominating at this region (Machining unit above 10^{-2} mm).

Therefore, it can be comprehended that, material removal occurs due to erosion/chemical action while using extremely small depth of cut, then it follows plastic deformation/microfracture, depending on the conditions.

2.3 Machining of Glass

2.3.1 Conventional Machining

2.3.1.1 Turning

Single point diamond turning (SPDT) is an ultraprecision cutting technique to generate nano surfaces with submicrometer level of form accuracy while product manufacturing [33]. The capability of machining optical substrates, for operation in infrared and visible region, has given widely acceptance to SPDT process as a fabrication technology for optics [34]. In the recent past, the availability of high-precision turning machines with nano-level tool positioning accuracy was considered to be a prerequisite for machining brittle materials in ductile mode. As mentioned earlier, there is this critical value of feed rate and depth of cut for every material which should not be exceeded; otherwise it will cause the ductile mode to switch into brittle mode and initiates several different crack systems (as shown in Fig. 2.2) [11]. A study on ultraprecision turning of optical glass ZKN7, conducted by Fang et al. [35] reported that undeformed chip thickness with the size of sub-micrometer level can produce mirror finish (R_a = 14.5 nm) with ductile mode cutting. The force generated during ductile mode cutting of ZKN7 glass is found to be around 1 N, however, the growth of shear stress continues until it becomes too enormous to cause speedy tool wear, due to the submicron size of undeformed chip thickness.

Previously, ultraprecision machine tools, providing high accuracy and stiffness, was used mainly to conduct ductile mode machining because of the difficult situation arises from the smaller cutting depth and lower feed rate. Research performed to investigate ductile machining of glass proved to be not so practical due to the high wear rate of tools. Therefore, more researches on vibration assisted turning of brittle materials were undertaken with a hope to elevate this critical value [36,37,38] and the results suggested the promising capability of cutting fragile materials by ultrasonic vibration in ductile manner. Although, specially controlled vibration assisted machining was able to offer mirror finish on soda lime glass, the mechanism behind this vibration assisted machining was not well established back then. Tool wear was still quite large compared with that in the conventional machining of soft metals. Therefore, Wang et al. [39] performed another study to examine the cutting process of glass by varying the impact of vibration in a diamond tool and suggested that the ratio of the cutting speed associated with the workpiece and the maximum vibration speed of the tool is a key factor to determine the critical depth of cut. In cutting, assisted by ultrasonic vibration, the reduction of cutting force is influenced by the combination of dynamic friction and aerodynamic lubrication. The increasing tendency of critical depth of cut is influenced by the cutting force reduction. Chalcogenide glass used for infrared imaging purpose has been attempted to machine recently using diamond turning and experimental result reported the change in the cutting mechanics to ductile mode at uncut chip thickness of 1 micron [40].

Investigation on diamond turning of glass to examine tool wear mechanism recommended that some wear mechanism are predominant to degrade the operation of the tool, in particular these mechanisms are identified to be cleavage and micro chipping. The beneficial application of ultrasonic vibration to the cutting tool suggested the significant improvement in cutting performance. Ultrasonic vibration not only lessened the tool wear rate compared to the one without vibration, but also suppressed brittle fracturing in glass cutting zone [41]. Bakkal et al. [42] also reported severe tool wear condition like chip welding and micro chipping of polycrystalline cubic boron nitride tool while turning of bulk metallic gas.

2.3.1.2 Grinding

Grinding is the most widely used process for machining hard–brittle materials like optical glass. The behaviors of fracture in optical glasses is now a days a subject of intense research. Processes like grinding or indentation and in general, all the processes that involve the use of an abrasive grain to interact on the material surface are far to be completely understood. Malkin and Hwang [43] have reviewed all these contributions and reported two major crack systems that exist in these indentation processes of brittle material. One of them is the formation of lateral cracks which is accountable for material to be removed to generate new surface. The other one instead is produced by the cracks located in radial and median position which work as the origin of strength degradation. However, the improvement of high-precision machine tools ensured the suppression of these cracks using appropriate machining parameters. As explained in [27], material will undergo plastic deformation only when the penetration depth can be kept below the critical, resulting in lower converted energy which is insufficient for cracks to form. This described mechanism is usually referred as ductile regime grinding [27].

Grinding mechanism and all the processes comparable to the material removal by grinding are pushed forward by the growing interest given by industrial sectors. Chen et al. [44] investigated the optimum settings for partial optical glasses and microcrystalline glasses to reach the transition from brittle to ductile using indentation tests and reported that exceptionally smooth surface is possible to generate using diamond wheel with grain size below 10 μm. Brinksmeier et al. [45] found that the modes of material removal for optical glass are not only affected by the cutting depth but also by the fraction of feed rate over cutting depth. Stephenson et al. [46] studied the grinding properties of Bk7 glass using both cross and parallel grinding strategies, and revealed that parameters like roughness of surface and depth of damage under the surface are directly triggered by the setting of grinding modes. Surface grinding on horizontal plane and induced cracks have been analyzed by the use of kinematic strategies. The results suggest dividing grinding mode into four different subfamilies: brittle, semi-brittle, semi-ductile, and eventually ductile mode as shown in Fig. 2.4. These four different grinding modes also influence output parameters like surface roughness as well as the depth of damages under the surface [47].

Zhong and Venkatesh [48] emphasized that the machining of brittle materials in ductile fashion will be constantly growing as rigorous research arena after a through summarization of grinding development. The main reasons behind this involve rapidly increasing industrial demands which requires underpinning knowledge of the ductile mode grinding mechanisms. Engineered wheel for grinding optical glass has also been proposed by Heinzhel et al. [49]. Perveen et al. [50] conducted the effect of various tools geometry such as circular, d-shaped, triangular, and square in the case of Bk7 glass. They found that better performance is obtained by d-shaped micro-grinder, showing a better surface finish, by limiting tool wear and cutting force [51]. In their work, focused on micro grinding of Bk7 glass, Perveen et al. [46] also investigated on PCD micro-grinder wear. According to their research, two

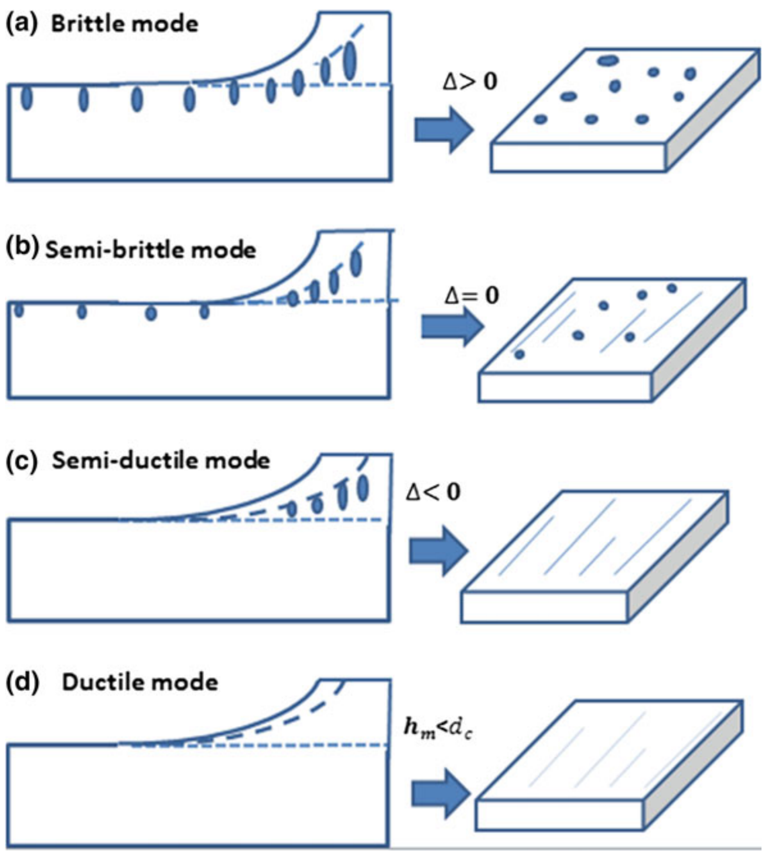

Fig. 2.4 Four different modes of grinding during horizontal surface grinding (maximum penetration depth h_m and critical depth d_c) [45] with kind permission from Elsevier

basic types of tool wear were noticed. First one is edge chipping which appears near to tool rim and contributes on the reduced diameter of tool. Second, abrasive wear occurring by the fast grain boundary breaks down, also initiates some intergranular cracks to propagate. This propagation makes its path either through a group of grains or through the grain boundary causes the grain spalling thus forming wear zone [46]. By applying taper polishing technique, surface cracks formed during grinding processes have been characterized as near-surface lateral and deeper trailing indent type fractures on silica glass. Both the average crack length and surface roughness shows linear relation with the maximum SSD depth. In addition, these relationships can be used to identify and measure the SSD depth without destructing the part [47].

2.3.1.3 Micro-Milling

Recently, increasing advancement in microelectronics has raised the necessity for micro-components using complicated geometries and three dimensional features. In order to fulfill this demand, investigation on the material removal using plastic deformation technique with the use of multi-cutting edge tool has started to get more attention, due to the limitation associated with single point tool. Milling is basically an interrupted cutting operation where teeth of milling tool remove materials in an intermittent manner with tool rotation. Milling process can be either up milling or down milling type. In up milling, direction of cutter rotation opposes feed motion so that maximum chip thickness is at the end of the cut as shown in Fig. 2.5. Contrarily, for down milling, cutter rotation is in the same direction with feed motion and chip thickness remains maximum at the beginning of the cut. Takeuchi et al. [48] used ultraprecision milling machine to conduct ultraprecision 3D micromachining of glass. They demonstrated the possibility of manufacturing 1 mm diameter glass mask with roughness value of 50 nm using pseudo ball-end mills. Matsumura et al. [49, 51, 52] achieved fracture-free machining of glass by exploiting different geometry tool, in particular milling tool with flat end and ball-end. The machining of micro-channels in glass is also possible in ductile manner by multi-edge cutting tool if the cutting edge is sharp enough. It is also suggested that ductile mode machining involves smooth signal of cutting force while brittle mode machining is characterized by sharp fluctuations in the cutting force because of the occurrence of repeated fracture above the critical value of chip thickness. As reported by Foy et al. [2], improvements in surface finish during milling of glass are possible by tilting the ball-end mill along the direction of feed. It is also demonstrated that ductile mode machining of glass is possible with carbide end mill if the edge roundness is at submicron level. It is suggested that cooling time during the cut increases by tilting the end mill which suppresses the tool wear considerably.

End milling process can either be side or slot milling type. For up milling orientation in case of side milling, uncut chip thickness varies from zero to maximum with tool rotation. However, when this chip thickness reaches critical limit imposed by the transition from ductile to brittle mode, fracture begins to appear.

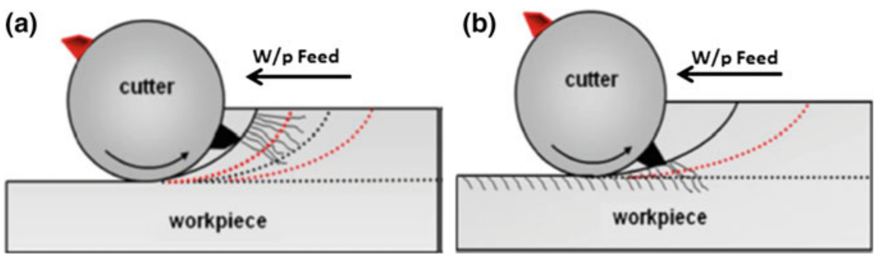

Fig. 2.5 **a** Low feed per edge ductile mode milling process; **b** High feed per edge brittle mode milling process [54]

Again, tool feed per edge will determine whether this brittle fracture point should be far (low feed per edge) or near to the finished surface (high feed per edge) as shown in Fig. 2.5a, b. If the specific brittle fracture limit is distant from the finished surface, the fractured part will be eliminated by the cutter rotation later on as depicted in Fig. 2.5a, contrarily brittle fracture that cannot be eliminated by cutter rotation reaches to the surface as shown in Fig. 2.5b [6, 53]. Cutting force acting tangential to the tool axis is proportional to the undeformed chip area. Therefore, domination of plastic deformation causes the cutting force to be increased linearly within ductile region, whereas fluctuation of cutting forces referring the initiation of fracture when the uncut chip thickness reaches the critical value [54].

For slot milling, undeformed chip thickness remains very small both at the starting point and the final point of cut, and the maximum value can be found at the cut center. If the fracture occurs due to larger contact angle between cutter and work piece, it can be eradicated by succeeding cutter flute (Fig. 2.6a) so long the depth of fracture remains lower than the depth of axial cut. However, the damage will sustain on the final surface if the axial cutting depth is overtaken by the depth of fracture. Damage will also retain for larger axial depth of cut (Fig. 2.6b).

Fracture will occur at smaller contact angle for higher feed compared to that of lower feed. Therefore, smaller feed rate and low axial cutting depth are considered for fracture-free slots. In addition, up milling occurs at one side of the cut and down milling occurs at the other side of the cut as shown in Fig. 2.7. Due to this typical cutting mechanism, the two ends of the slot may experience different surface quality [6].

While investigating the capability of the end milling of glass, Arif et al. [53] also identified two different types of tool wear. The first type of wear is abrasion wear which has been found on the flank face created under the condition of smaller uncut chip thickness. A second type of wear is basically constituted by the formation of grooves on tool cutting edge which in turn causes continuous deformation of cutting edge after longer machining time. Shifting of cutting mode from ductile to brittle can be heavily influenced by this tool wear.

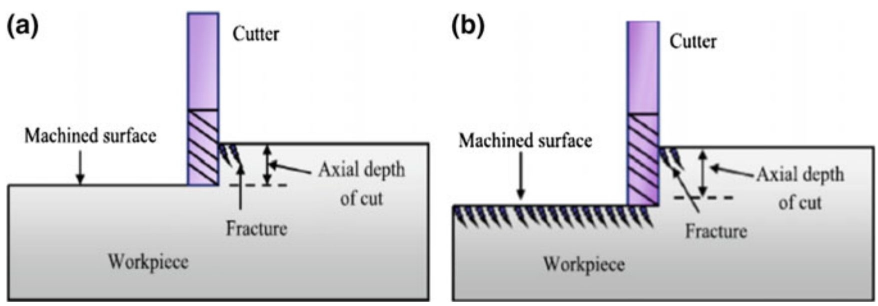

Fig. 2.6 **a** Slot milling using small axial depth of cut **b** Slot milling using larger axial cutting depth [6] with kind permission from Elsevier

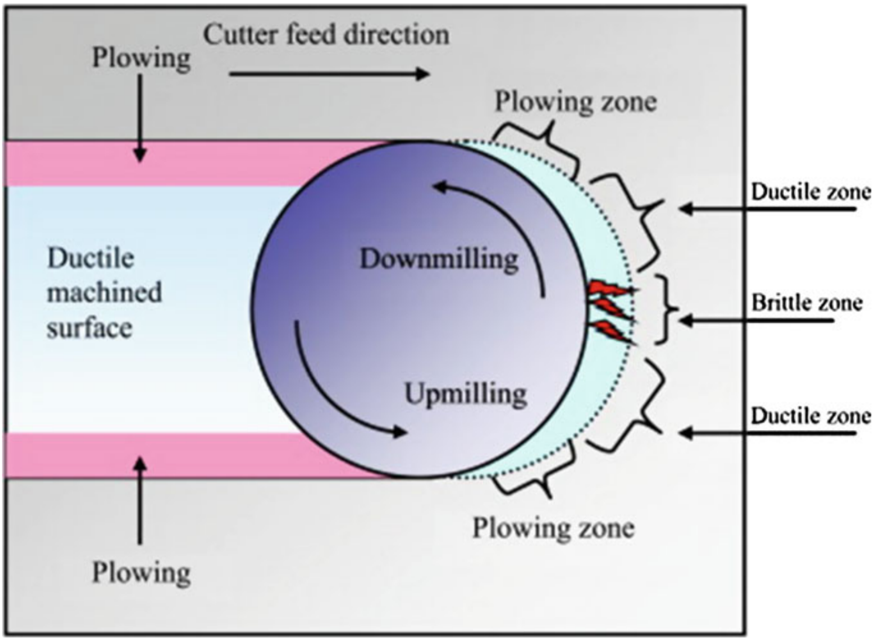

Fig. 2.7 Different regimes machining in slot machining of glass [6] with kind permission from Elsevier

2.3.2 *Nonconventional Machining*

2.3.2.1 Ultrasonic Machining (USM)

Ultrasonic machining is a popular machining technique for the materials with low ductility and high hardness (above 40 HRC), irrespective of their conductivity. In USM, mechanical vibrations of greater than 20 kHz with 5–50 μm amplitude are obtained by converting high frequency electrical energy using transducer, booster, and horn. To avoid the resistance of cutting action, controlled static load is maintained on the tool. A mixture of SiC/B_4C with water is hammered on the workpiece surface by the tool vibration and thus removes the material by microchipping [55].

Very poor thermal conductivity of glass and the friction generated between glass and tool during conventional cutting are great causes of temperature accumulation around the cutting edge of the tool. By applying an ultrasonic assisted cutting technique, a vacuum region may be constituted around the primary cutting zone and the pumping effect is formed in this area, which may enhance the cutting fluid penetration into the cutting zone accelerating cooling at the tool-tip. On top of that, ultrasonic assisted cutting technique also converts the engagement type of cutting tool-chip into an interaction manner of a small amount of vibration. Thus, appropriate application of ultrasonic assisted technique process can actually improve the cutting performance [56]. Applying workpiece vibration as illustrated in Fig. 2.8a, a new method of micro-ultrasonic machining (MUSM) has been developed which is considered one of the important achievement of USM so far. With the help of this method, microholes with diameter smaller than 5 μm has been obtained in fused quartz as seen in Fig. 2.8b. The high tool wear associated with MUSM is addressed using a sintered diamond tool [57]. A combination of MUSM and Micro-EDM represents an interesting hybrid process for manufacturing extremely precise holes with the advantage of higher aspect ratio.

Another improvement of USM, process can be achieved by addition of chemical assistance with the use of HF particularly in low concentration. With this technique, typical drawbacks like deteriorated roughness and small-scale removal can be overcome. The mechanism of this action is given by the interaction between HF solution and glass. The superficial silicon molecules experience reduced bond strength due to the acidic action, thus improving the effectiveness of USM method. Significant enhancement in surface quality (40%) and improvement in MRR (200%) were reported by Choi et al. [58] while micro- and macro-drilling of glass by ultrasonic machining technique (Fig. 2.9). However, due to the hole enlargement occurred in chemically assisted USM; below 5% HF solution is suggested.

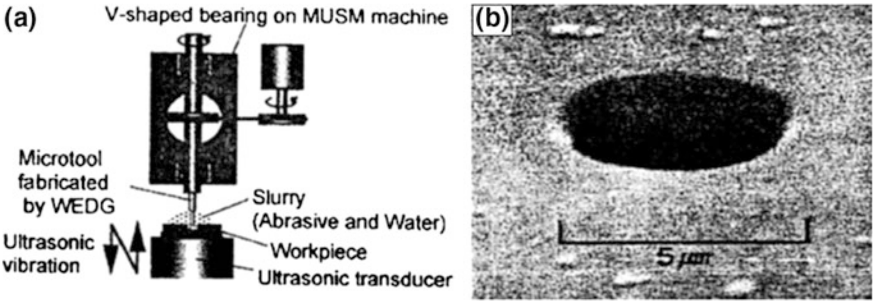

Fig. 2.8 **a** MUSM process **b** Micro hole of 5 μm diameter (quartz glass, depth: 10 μm, amplitude: 0.4 μm, tool diameter: 4 μm, machining load: 29–59 μN) [57] with kind permission from Elsevier

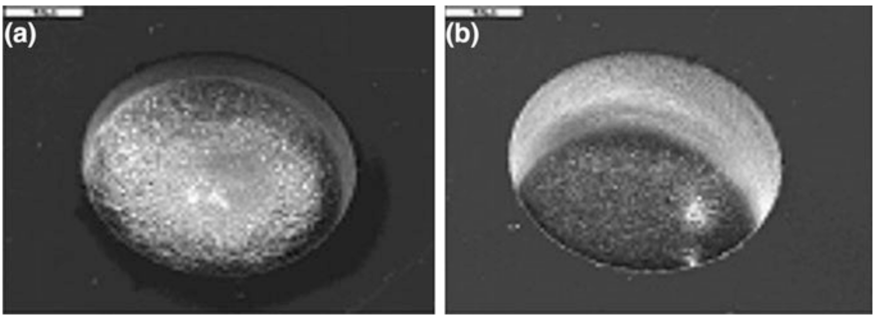

Fig. 2.9 Comparison of material removal by 1.5 mm diameter tool using **a** USM (550 μm depth) and **b** CUSM (950 μm depth) [58] with kind permission from Elsevier

2.3.2.2 Abrasive Jet Machining (AJM)

Abrasive jet machining (AJM) operates on materials without producing shock and heat. In this method, the surface to machine is bombarded with an intense jet composed of a mixture of gas/air and abrasive particles (Fig. 2.10). At the nozzle exit, the pressure of the carrier fluid induces a jet of particles with high kinetic energy, which impacts on the surface to remove materials using micro cutting action along with brittle fracture. AJM has the capability to perform primary operations like machining, drilling, and surface finishing efficiently [59].

Another type of AJM, namely abrasive water jet machining (AWJM), makes use of a water jet mixed with abrasive particles instead of gas. Cutting mechanism involves the solid particles to impact and erode on the surface for material removal either by cutting wear or by deformation wear. Erosion taking place at smaller impact angle is known as cutting wear whereas erosion at higher impact angle with repeated bombardment is known as deformation wear [60]. While investigating erosion behavior of borosilicate glass, Aich et al. [61] observed brittle fracture on the top surface of glass due to the high velocity of abrasives particles that impinge on the workpiece. Significant turbulence is created at the lower zone of cutting due to the damping of axial velocity of water which causes changes in radial energy distribution. Therefore, material removal is dominated by plastic deformation.

One of the major advantage offered by AWJM is the possibility of suppressing heating during the material removal, in particular the area of machined surface remains unaffected by heat. Azmir et al. [62] established that it is possible to produce better surface by playing with kinetic energy of AWJM process, in particular they found that an increase of energy is beneficial for machining glass composites reinforced with plastic fibers. According to their research, machining performances like

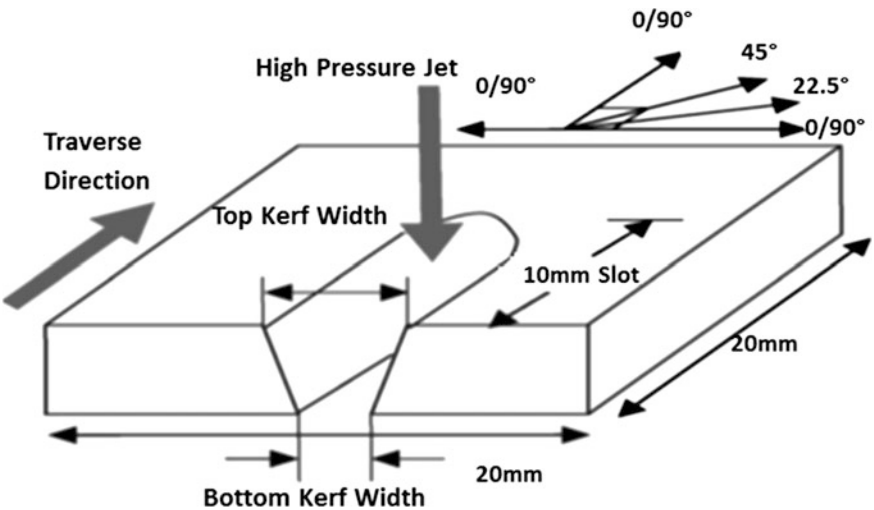

Fig. 2.10 Schematic of AWJ machining on glass/epoxy laminate [62] with kind permission from Elsevier

roughness and kerf taper ratio can be enhanced by increased hydraulic pressure and abrasive mass flow rate. However, increasing the standoff distance and traverse rate affects the performance in opposite manner. Khan et al. [63] observed several important facts while analyzing the cutting performance of three different types of abrasives such as garnet, SiO_2 and, Al_2O_3 particles on glass. According to their study, the taper of cut slot increases if the standoff distance and work feed rate are increased, however, it decreases with higher nozzle pressure. Garnet causes the taper of cut to be bigger followed by Al_2O_3 and SiC. In addition, SiC offers higher average width of cut followed by Al_2O_3 and garnet due to its higher hardness. Width of cut is also influenced positively by the increased stand off distance of the nozzle from the work due to divergence shape of the abrasive water jet.

2.3.2.3 Electrochemical Discharge Machining (ECDM)

The needs for nonconducting materials machining process have led to the development of another module of high-energy density machining process such as ECDM, which aims to remove material by using the combined effect of anodic dissolution and electrical sparks [64]. In ECDM (Fig. 2.11), difference of potential as low as 20 V is applied between tool electrode and counter electrode, while workpiece is dipped inside the electrolytic solution (NaOH, KOH) [65]. A chain of micro-explosions occurs on the workpiece surface layer due to electrical sparks following electrochemical reaction once the applied voltage reaches above the critical value; thus, removing material in small quantity with the occurrence of melting, or vaporization or both of these phases [66].

Along with this removal, chemical etching also adds on to the machining process. Figure 2.12a, b show images of holes entrance curved in Pyrex glass [68].

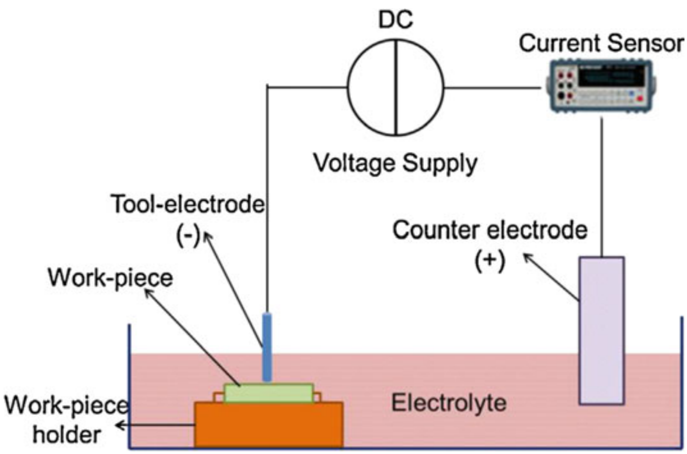

Fig. 2.11 Schematic diagram of ECDM setup [67] with kind permission from Elsevier

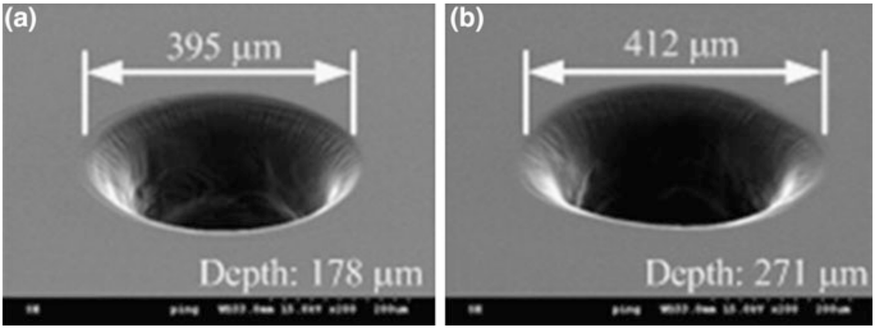

Fig. 2.12 Entrance of holes machined on Pyrex glass **a** 40 V and **b** 45 V (tool diameter 200 µm) [68] with kind permission from Elsevier

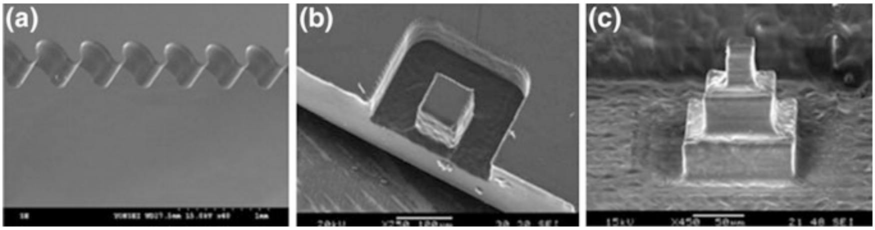

Fig. 2.13 **a** Contour machining using a textured tool (R_a = 1.5 µm, V = 28 V, DC) [70] with kind permission from Elsevier; **b** micro-pillar on soda lime; **c** micro-pyramid on Pyrex glass [71] with kind permission from Elsevier

Similarly, Fig. 2.13a shows a contour scribed in soda lime glass obtained with the help of textured tool [69]. An interesting feature shaped as pillar with height of 55 µm has also been manufactured by the same process (Fig. 2.13b). Furthermore, this process was successfully applied to machine pyramid on Pyrex glass in Fig. 2.13c [68].

While features less than 100 µm have been successfully machined on glass, machining high aspect ratio features becomes a challenge due to overcut and tool wear. Holes with the aspect ratio about 11 or more can be achieved by ECDM using micro-tools and low concentration electrolyte. Moreover, significant reduction in overcut (by 22%), hole taper (by 18%), and tool wear (by 39%) were observed during ECDM, thus increasing the aspect ratio of the microholes [67].

2.3.2.4 Electrolytic in Process Dressing (ELID)

Electrolytic in process dressing (ELID) is a viable substitute of conventional grinding which offers an efficient grinding of mechanical components and parts made of different materials including glass [72]. This technique offers extreme of finish at nano-level finishing on difficult to cut and brittle materials. In ELID, the surface of wheel is electrolyzed with a new oxide layer, following the grain worn out, which removes bonding material from the wheel surface, to protrude new grit. This dressing action becomes active due to the reduction of oxide layer and remains inactive when there is sufficient oxide layer on wheel surface. This way it can always maintain the fresh grain protrusion on the wheel surface. ELID process can overcome the limitation of conventional grinding by lessening the grinding force using in process dressing, however, due to electrolytic action, grinding wheel experiences rust deposition.

Ohmori [68] worked on ELID of silicon wafers, silicon nitride, and BK7 glass. His observations recommend the use of this process to obtain mirror finishing for difficult to cut materials [73]. Figure 2.14 depicts the mechanism of ELID process. Electrolytic action takes place in the separation gap created between wheel surface and cathode which is maintained from 100 to 500 μm based on the process conditions. The electrolyte, flushed into the electrode gap also serves the purpose of coolant. With the correct DC high voltage (preferably 60–120 V), electrolysis initiates and causes the formation of insulating layer of anodic oxide using removed metal bond from the wheel. Softness and brittleness of the layer result in the easy wear off of the anodic oxide during interaction which exposes sharp abrasives of the wheel. In addition, chips and blunt abrasives are removed along with oxide layer removal. Since the oxide layer acts as insulation, the reduction of layer thickness causes the resistance to drop off and dressing current to go high to form more oxide layer. Successive grinding again removes the oxide layer, and the cycle keeps going on as shown in Fig. 2.14. Therefore, oxide layer formation before the initiation of grinding serves as precondition for ELID grinding to take place efficiently. This operation is known as predressing only if it continues for 10–90 min [68, 73].

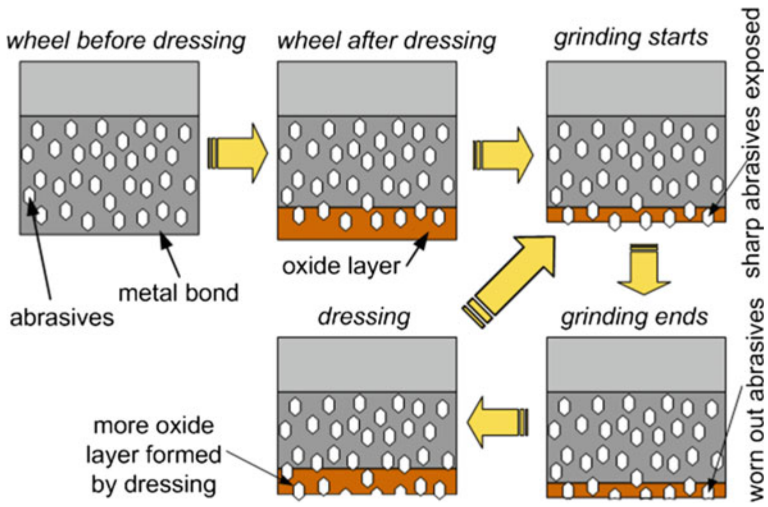

Fig. 2.14 Mechanism of electrolytic in process dressing grinding [68] with kind permission from Elsevier

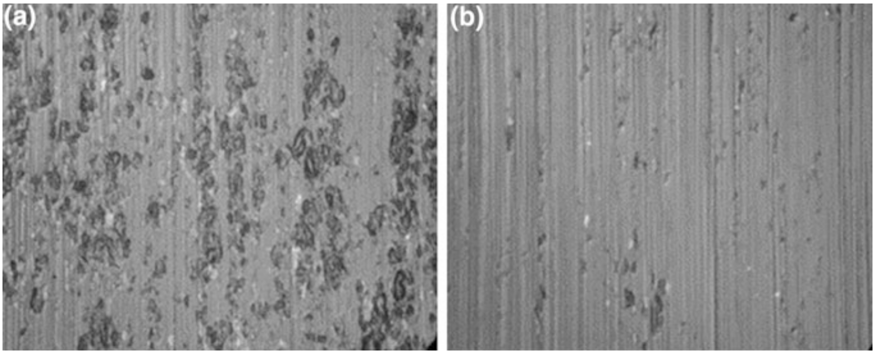

Fig. 2.15 SEM image of ground surface after **a** grinding; **b** ELID [69] with kind permission from Elsevier

The SEM images, as shown in Fig. 2.15, state that significant improvement in terms of surface roughness of BK7 glass is obtained by the use of ELID grinding over traditional grinding. The reason behind this worse result generated by traditional grinding process is the continuous reduction of the active grain per area. On the other hand, ELID offers an enhanced surface integrity and surface roughness by keeping the active grain same per unit area using continuous dressing. The ELID technique also improves the grindability by contributing on the reduction of the bonding strength of contact surface. Although, higher current duty ratio results in better roughness, black strip formed on the surface limits its increment up to certain value. The ELID grinding system developed has provided practical applications of the process such as macro lens fabricated on glass rod etc. [69].

While investigating surface and subsurface integrity of fused silica and fused quartz using ELID grinding, Zhao et al. [74] reported the existence of median and cone cracks that propagate underneath the ground surface with a depth ≤ 0.5 μm. The normal crack length underneath the ground silica surface can have the size of 0.3–0.8 μm depending on different crack system.

2.3.2.5 Laser Machining

MEMS components, integrated vision systems, as well as the family of photonic devices require high standards in terms of edge control, surface quality, and drilling precision, while maintaining the absence of micro-cracks in the glass material. An interesting solution to improve the glass processing could be the use of laser technology [75]. Different laser types can be considered for glass micromachining, depending on the kind of process and physical mechanism which leads the laser light to interact with the material. In this context, pulsed lasers, such as GaN diode lasers or excimer lasers, emitting in near-UV region, can be effective. With different approach, near-IR emitting lasers can also be considered. This list includes crystal based bulk lasers, such as Yb:YAG and Ti:sapphire lasers, as well as Yb-doped fiber lasers [76].

The interaction with transparent materials can be carried out with two different strategies, related to the electron–phonon coupling time τ_c, whose value is around 1 ps in most of the silica-based glasses. This value represents the necessary time to release excited electrons energy to the surrounded lattice, through the onset of a vibrational quantum, usually called phonon. By the use of pulsed lasers, with different pulse duration, the light-material interaction can be longer or shorter with respect to τ_c [77]. In case of longer pulses, in the order of magnitude of ns and more, electrons and lattice reach thermodynamic equilibrium. Therefore, the material removal, which is primarily caused by thermal effects, is obtained by melting and evaporation [78]. With the large spectrum of possibilities given by laser technologies in glass machining, several type of machining with different level of precision can be obtained, ranging from fast cutting and deep drilling to finer and accurate 3D-machining of micro-channels in integrated optical devices or shaping of micro-lenses for vision systems [79].

Nikumb et al. [5] investigated on nanosecond, femtosecond and laser induced plasma to obtain high quality surface on the micro-features on glass. Nanosecond and femtosecond laser can be exploited with the proper control of thermal process to produce crack free, clean surface. Fabrication of microscale shallow features with greater surface quality can be obtained with the use of laser induced plasma (Fig. 2.16a) [5]. Wlodarczyk et al. [80] investigated on the feasibility test of cutting and drilling of thin flex glass substrates of thicknesses 50 and 100 μm by using picosecond laser operating at wavelengths of 1030, 515, and 343 nm (Fig. 2.16b). Experimental results suggested that the highest effective cutting speed can be attained with the wavelength of 1030 nm; however, the quality of the cuts at this wavelength deteriorates. The best cutting outcome is achieved with the wavelength of 343 nm using the lowest cutting speed. The maximum drilling speeds were

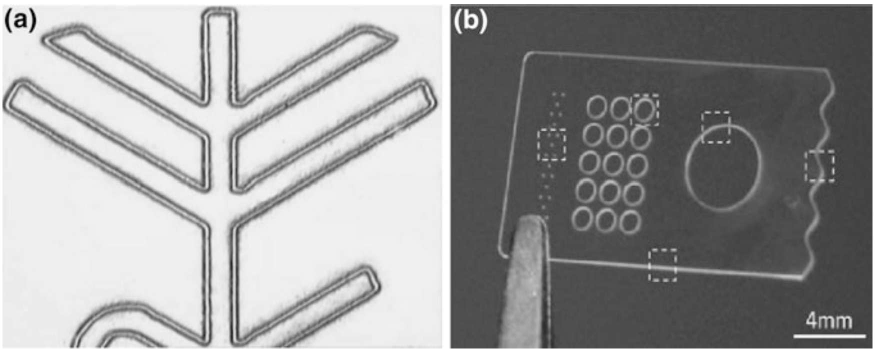

Fig. 2.16 **a** Laser induced plasma machining was used to fabricate micro-channels on glass surface with a width of 8 μm. Laser pulse repetition rate was 1 kHz and scanning speed was 400 μm/s [5]. **b** An example of the laser-cut structure in a 100 μm thick AF32® Eco thin Glass substrate [80] with kind permission from Elsevier

found to be approximately 2 microholes per second for 343 nm and 8 microholes per second for 515 nm, nevertheless presence of debris and heat affected zone were also observed [80].

In this section, conventional and nonconventional machining processess involving glass machining are discussed primarily. Associated process mechanisms and relevant research contributions are illustrated prudently. On top of that tool wear aspect and surface/subsurface integrity aspects are considered as well to provide a deep understanding.

2.4 Summary

This chapter attempts to provide an overview on various conventional and nonconventional techniques used to machine glass materials. Being fragile, manufacturing processes dedicating for glass must consider the probability of cracks generation and breakage. Although most of the conventional mechanical machining seems to be working for thick glass parts, thin glass machining can be conducted using noncontact processes such as nonconventional processes. Substantial research efforts have been dedicated in the past years, in order to reveal the underpinning knowledge related to glass cutting mechanism and development of various machining technologies. An important criterion to take consideration for conventional glass machining is brittle to ductile transition phenomenon. Although, nanofinish in glass surface can be achieved using this phenomenon with proper control of process parameters, tool wear suffers greatly due to abrasive nature of glass and downscaling of chip thickness. Thus research direction of conventional glass machining should direct toward tool wear in order to achieve more economical production process. Another important fact to consider in ductile mode machining process is the influence of temperature. The future work may also pay attention on development of numerical methodology in order to assess the total temperature in the cutting zone and its effect especially on machined surface of glass.

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