# Overview of the Modeling and Simulation of Laser Machining of Glass

Charles M. Kagiri, Bernard W. Ikua, James N. Keraita and Esther W. Gituku

*Abstract*—Glass is an important engineering material used in the manufacture of different components of engineering systems. Sodalime glass is the most common form of glass whose application includes manufacture of glass plates which are used in modern devices including TFT-LCDs, touch panels, thin-film solar cells, and color filters.

For any application, the cutting of glass is the initial step in fabrication. The conventional method of glass cutting involves using a diamond point tool or wheel to mechanically score a line along the desired path. This is followed by application of bending force to break the glass along the scored line. This method has disadvantages that include: microcracks that serve as stress risers of tension and cause the fracture of the glass if loaded, rough edges requiring further machining and material wastage among others.

Laser cutting has numerous advantages over the conventional methods regarding quality and is attaining wide acceptance in machining of glass. Laser machining can be achieved through melting and vaporization or thermal stress fracture. The performance and thermal effects of a process must be well understood in order for process control to succeed. This paper gives an overview of current status of research in modeling of laser machining of glass.

*Keywords*— Glass, Laser machining, Sodalime glass, Modeling

## I. INTRODUCTION

TRADITIONALLY, glass and other brittle materials are conventionally cut mechanically by scoring process. This produces a line of weakness along which the material is then broken mechanically or thermally. This method causes an increase in the appearance of undesired scratches, chipping and leaves residual stresses on the cut edge [1]. The cut edge requires further machining and cleaning to improve the quality of the finish.

There are several non-traditional machining methods used in the machining of glass to overcome the limitations of the traditional method. Ultrasonic machining is one of the non traditional machining methods. It causes material removal by erosion through utilizing mechanical energy and has been used in machining of glass and research is ongoing [2], [3]. It has a low material removal rate and there is high wear of the tool making it expensive. Abrasive jet machining (AJM) has also been used in the machining of glass. It uses small high speed abrasive particles for material removal from the work piece [4]. It is however very slow for cutting and produces a cut that has a taper.

Laser beam machining method has become a major tool in machining of materials. It is not a mass material removal process. It is a fast, easily controlled process with a non-contact, non-wearing tool [5].

The laser machining process can be divided into one, two and three dimensional process as illustrated by Fig. 1. The laser beam being a directional heat source, can be viewed as a one dimensional line source with a line thickness equal to the beam diameter [6]. For a one dimensional process such as drilling, the laser beam is stationary relative to the workpiece. The erosion front,which is located at the bottom of the drilled hole, propagates in the direction of the line source in order to remove the material. In case of two-dimensional process such as cutting, the laser beam is in motion relative to the workpiece. Material removal occurs by moving the line source in a direction perpendicular to the line direction forming a two-dimensional surface. The erosion front is located at the leading edge of the line source. For three-dimensional machining such as milling, two or more laser beams are used and each beam forms a surface through motion relative to the workpiece. The erosion front for each surface is found at the leading edge of each laser beam. When the surfaces intersect, the three-dimensional volume bounded by the surfaces is removed [5].

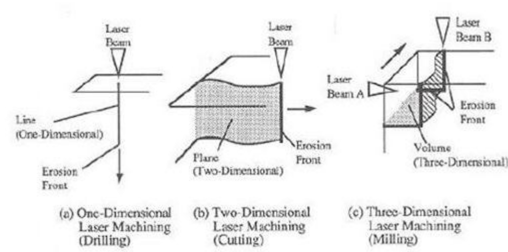


Fig. 1. Schematic showing one, two and three dimensional laser machining [6]

The laser beam used for machining may be operated in continuous wave(CW) mode or pulsed beam mode as shown on Fig. 2 [6]. CW operation has the advantage of smooth surface after machining. Pulsed beam operation allows for deeper drilling or cutting depth to be achieved compared to a continuous beam operating at the same beam power. However, pulsed operation may result in more surface irregularities in the machined parts due to a periodic beam output [6].

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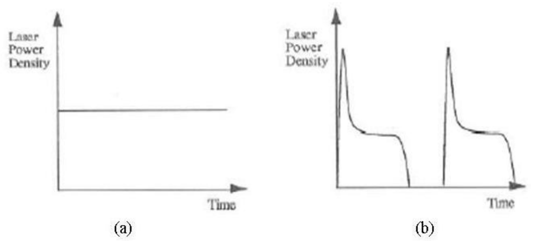


Fig. 2. Laser beam temporal modes(a) continuous wave (b) pulsed mode [6]

Laser beam machining been applied in the fabrication processes of complex and fragile glass products with fine edges [1].

## II. PROPERTIES OF GLASS

The mechanical and thermal properties of a material greatly affect the choice of machining method and the specific parameters that produce desired quality.

Glass is a non-crystalline and brittle material. It has a linear stress-strain relationship up to fracture. The strength of glass is highly dependent on the type and presence of defects [7]. The nature of the glass surface has a significant effect on its tensile strength. The stresses are magnified at points of imperfection on the surface and the non-ductile nature of glass means stress concentration cannot be relieved [7]. These mechanical properties are highly temperature dependent. Ductility increases with increase in temperature while the strength decreases with increase in temperature.

Thermally, glass is described as a supercooled liquid without a critical temperature [8]. Its viscosity will change continually with change in temperature [7].

Table I summarizes the mechanical and thermal properties of sodalime glass [7] [9].

TABLE I
PHYSICAL PROPERTIES OF SODALIME GLASS [9] [7]

| GLASS TYPE | SODALIME |
|---|---|
| Density, kg/m$^3$ | 2400 |
| Tensile Strength, MPa | 27.58 68.95 |
| Modulus of Elasticity,GPa | 67.57 |
| Thermal Expansion Coefficient, $10^{-5}$ m/m/C | 0.92 |
| Vaporization Point [43], C (F) | 1500 (2732) |
| Melting Point [43], C (F) | 1200 (2192) |
| Softening Point, C (F) | 693 (1280) |
| Annealing Point, C (F) | 510 (950) |
| Strain Point,C(F) | 477(890) |
| Thermal Capacity at 300 K, J/kg.K | 840 |
| Thermal Conductivity at 300 K, W/m.K | 0.88 |

## III. MODELING AND SIMULATION OF LASER GLASS CUTTING

Most mathematical models of the heat flow phenomena in laser cutting were based on the application of the classical heat conduction equation for stationary solid, using the concept of an instantaneous heat source for an infinite volume. Cases with and without phase change and a variety of radiation or source conditions have been studied. The problem of melting with complete removal of melt subjected to different types of boundary conditions has been studied by Soodak [10]. He considered constant heating of the surface and numerically evaluated the steady state melting rate. Landau [11] considered melting with complete removal of the melt from a one-dimensional slab with one end insulated. He obtained the time-dependent temperature distribution and the position of the melting front.

Minardi and Bishop [12] developed a two-dimensional transient computer model to determine the temperature distribution within a material subjected to radiation, the intensities required for laser drilling, and the effect of spatially varying laser intensities on the temperature distribution. The model accounts for both sensible heating and phase change (solid-to-liquid and liquid-to-vapor). Glass, et. al. [13] investigated the effect of various parameters in laser cutting of metallic glass ribbon that undergoes ductile-to-brittle phase transitions when heated above crystallization temperatures. They modeled the laser/material interaction using a quasi-steady, three-dimensional finite difference technique to predict the temperatures and cooling rates in the heat-affected zone and compared these with experiment results.

There was an attempt by Yilbas, et. al. [14] to perform steady-state analysis of the heat transfer mechanism during laser drilling. The one-dimensional model was able to predict the maximum temperature in the material, the explosion process and the drilling efficiency. The numerical results correlated well with experimental findings.

Tsai and Chang [15]used the software ANSYS to explain the mechanism of the breaking process in the use of pulsed CO2 laser breaking technique in cutting glass substrates. The technique which was built on the unstable fracture technique used a diamond-point scoring tool was used to scribe a groove and create a median crack (grooved-crack) along the cutting path in a glass substrate. A pulsed CO2 laser was then applied at the cutting path to cut the glass substrate as shown in Fig. 3. A ration of energy used to generate thermal stress was 85 percent of total laser energy. The temperature field was calculated using the transient solution procedure. The results showed the stress distribution along the grooved crack tip shown on Fig. 5 based on the coordinate system on Fig. 4.

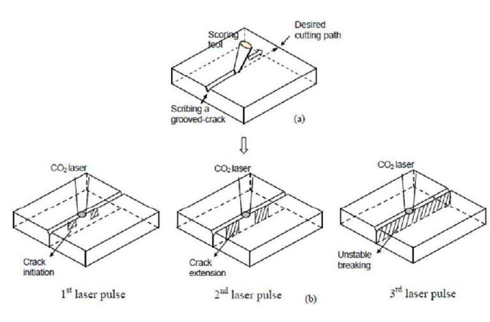


Fig. 3. pulsed laser breaking process of (a) diamond scribing and (b) laser breaking [15]

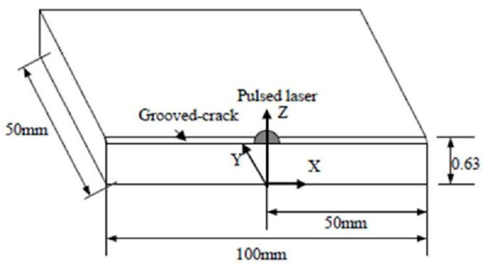


Fig. 4. Half of the glass substrate and the coordinate system [15]

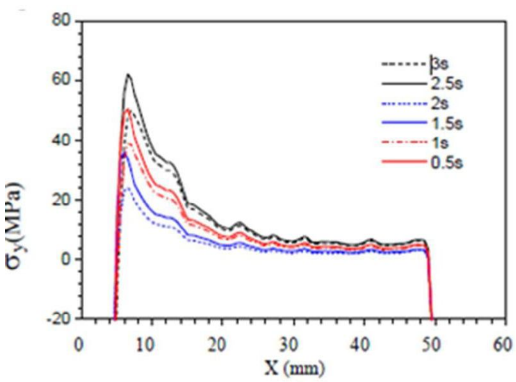


Fig. 5. Stresses distribution simulation results along the grooved crack tip (y=0, z=0.548 mm). [15]

Nisar et al. [16] proposed a finite element method using ABAQUS to analyze stress and temperature fields during diode-laser cutting on soda-lime glass sheets. A sequentially coupled thermal-stress analysis was used in which the heat generated due to deformation response that is crack propagation in the cleaving process,was neglected. The initial temperature $T_0$ was set to be $25^0C$, 3D brick elements with 8 nodes was used with a finer mesh around the laser beam because of steep temperature gradient around the heating zone. In the thermal model, a volumetric heat source was used. This was because the absorbtion length was greater than the diffusion length for the given parameters. A transient solution procedure was used to obtain the temperature field $T(x, y, z, t)$ by the heat diffusion equation, Eqn. 1.

$$k(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + Q = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

Where $k$ is the thermal conductivity, $\rho$ is the density, $C_p$ is the specific heat capacity and $Q$ is the amount of heat generated per unit volume due to irradiation by the laser.

The simulation results showed that different beam geometries may generate precise, accurate stress fields at leading and trailing glass-sheet edges.

Jiao et al [17] proposed a dual laser beam method to minimize unwanted fracture in laser cutting. An off-focused $CO_2$ laser beam was repeatedly scanned on the surface of the glass creating a preheated band. The preheated band served

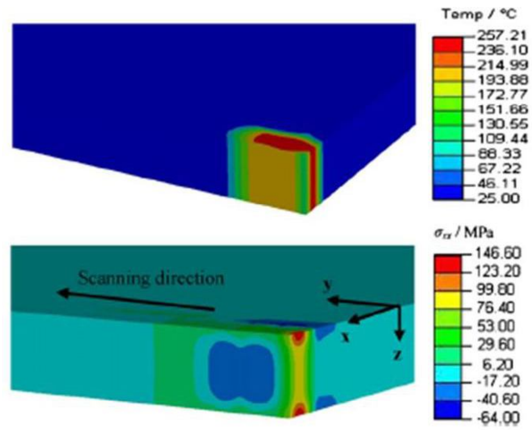


Fig. 6. Simulation results showing temperature and stress distribution across the thickness at the leading edge of glass at 0.2s along the scanning direction. [16]

to reduce the temperature gradient when the glass was cut by a focused $CO_2$ laser beam. A finite element analysis method was used to numerically simulate the process of cutting glass by dual $CO_2$ laser beam. A distribution of the temperature and thermal stress was investigated. The result of the simulation agreed with results obtained by Chui [18] and Akarapu and Segull [19]. The study concluded that preheating glass before laser cutting is a practical means of reducing microfractures. The thermal stress also decreased with the increasing of diameter of preheating beam as shown in Fig. 7. The reason is that the larger of the preheated laser diameter, the smaller gradient is induced from the cutting zone to the surrounding material, the less thermal stress is produced in the glass laser cutting.

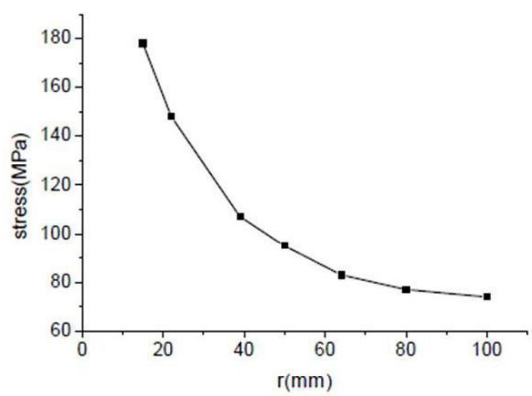


Fig. 7. Plot of maximum stress for different preheating laser diameters. [18]

## IV. Conclusion

The modeling of laser machining is an important step in determining the right machining parameters to be used with various materials. Although it is clear from the information on this paper that considerable work has been done, there is still more investigations that need to be carried out in predicting and controlling outcomes in the laser machining of glass. Most simulation models only take heat conduction into consideration, and the kinematics of melting and vaporizing are not a consideration in any due to the limitation in finite difference method and due to the lack of knowledge about the melting and vaporization mechanism during laser cutting of glass. These aspects require to be investigated to enhance predictability of laser machining of glass. This may be done by use of a different model like the composite model to incorporate these aspects.

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