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Experimental Study on Effective Parameters for Thermal Cutting of Glass Sheets

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Abstract: The new non-conventional cutting process by the use of thermal shock is a convenient procedure for cutting the brittle materials such as glasses and ceramics. This method is based on the application of localized thermal shock to brittle materials by the use of hot air jet, which induces thermal stresses at the tip of an existed pre-crack. Due to the thermo-elastic behavior of materials, the pre-crack is propagated in the material. By the use of this process, the glass and brittle materials can be cut to any shape without the use of cutting tools. In this paper, based on the presented phenomena and the induced time-dependent thermal shock, the tip of an existed pre-crack in a glass sheet is heated by a moveable point heat source. The effect of parameters such as cutting speed, nozzle orifice diameter, cutting temperature, macroscopic quality of cutting surface on cutting the brittle materials were studied. The results indicated that as far as a pre-defined distance is developed between the moveable heating point and the tip of the existed pre-crack, the crack is propagated in stable manner and under complete control, and hence better cutting surface quality. Based on this distance, the effective cutting parameters are investigated and set to get better cutting process.

Keywords: Glass, Thermal Stress, Cutting, Crack Tip, Surface Quality, Hot Air

بررسی تجربی برش شیشه از طریق شوک حرارتی و عوامل موثر در آن

سید محمدرضا خلیلی

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چکیده: روش جدید غیرسنتی برش با شوک حرارتی یک روش مناسب برای برش مواد ترد و شکننده مانند شیشه به حساب می‌آید. این روش بر پایه اعمال شوک حرارتی موضعی در مواد ترد استوار است که به واسطه ایجاد تنش حرارتی در نوک ترک و استفاده از خواص ترموالاستیک ماده باعث رشد ترک می‌شود. با استفاده از مزیت این پدیده، مواد شیشه‌ای، بدون ابزار قابل ماشین کاری و برش می‌باشند. در این مقاله، براساس روش حاضر و ایجاد شوک حرارتی وابسته به زمان، در نوک پیش ترک ایجاد شده در صفحه شیشه‌ای، وقتی که نوک ترک بوسیله یک منبع موضعی حرارتی، حرارت داده شود، عوامل موثر برش، مانند سرعت برش، قطر سوراخ نازل، درجه حرارت، کیفیت سطح و غیره در آن مورد بررسی قرار می‌گیرند. فاصله نوک ترک تا زیر سوراخ نازل چنانچه برابر با ضخامت شیشه باشد، رشد ترک کاملاً پایدار و در نتیجه عوامل موثر در برش براساس این فاصله بهینه می‌شوند.

واژه‌های کلیدی: شیشه، تنش حرارتی، برش، نوک ترک، کیفیت سطح، هوای داغ

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1. Introduction

Development of glass industries and its wide spread applications in different various fields, indicates the importance of machining and cutting of glass sheets. Several various conventional and non–conventional processes are used to cut the glass sheets in which among them, the most common conventional process is the use of diamond point tool or diamond wheel. In this method, depends on the glass industry's requirements, a particular diamond tip is employed to scribe on the glass sheet and then by application of mechanical loads and induced stress concentration, the glass is cut. This process is used for cutting simple shapes such as straight lines and by some difficulties, the simple curved shapes like circles. The limitations of this process include: practically difficult to cut complex shapes such as concave and convex curves, zig-zag cuts and also the right angle corners in the plate. Induced damage to the plate due to this process produce lot of wastage and needs secondary operations such as grinding, polishing, etc [1]. Sometimes, the damage to the cutting surfaces including micro-cracks and residual stresses causes weakness of the surfaces and then break-off and therefore un-usable of the work piece.

The common non-conventional processes that also used to cut other materials are ultrasonic machining, water jet cutting and laser cutting. There are some advantages using these methods, but the main disadvantage is the high cost of cutting operation. The new non-conventional method of glass cutting by thermal process using impinging hot air jet is a convenient method for cutting the glass and ceramic materials and recognized as a new technology in this industry [2, 3].

2. Thermal cutting process

2.1. Idea of the present process

Glass like the other brittle materials has the compressive strength higher than the tensile one. Therefore, due to the presence of micro-cracks in the glass plate, application of tensile stresses would cause the opening and propagating of these cracks. Hence, the resistant of glass subjected to the heating thermal shocks, is higher than cooling thermal shocks, since in the later the tensile stresses is developed on the surface of the glass. For example, consider the case of isotropic and homogeneous glass rod which is fixed at both ends and subjected to the temperature changes. The induced thermal stress can be obtained as follows [4]:

$$\sigma_{\max} = \frac{E\alpha(T_0 - T_f)}{1-\nu} \qquad (1)$$

In equation (1), E is the elastic modulus, α is the linear thermal expansion coefficient, T_0 is the initial temperature, T_f is the final temperature and ν is the poison's ratio for the glass. This equation is for large Biot number. As $T_0<T_f$ (the glass temperature falls), the stress would be positive and indicates tensile stress and on contrary, when $T_0<T$ (the glass temperature rises), the induced stress would be compressive. Thermal shock defined as fracture of material due to the thermal stresses caused by sudden changes of temperature in the material. To express the material behavior subjected to thermal shock, the TSR number or the resistance to thermal shock is used which can be obtained from the following [5]:

$$TSR = \frac{\sigma_f K}{E\alpha} \qquad (2)$$

where σ_f is the fracture stress, K is the thermal conduction coefficient, E and α were defined as above. As it is obvious from equation (2), by reducing the thermal conduction coefficient or by increasing the linear coefficient of thermal expansion, the TSR number decreases. Hence, the glass and other brittle materials which are poor in thermal conduction, have high sensitivity to the thermal shocks and by the use of this characteristic, the present cutting method these materials was developed.

Assuming the presence of an existed pre-defined crack or scratch in the material and the possibility of changing the energy field in the vicinity of the crack by inducing different stress fields around the crack tip, the crack would propagates in the direction of high energy release path and would develop the new surfaces. Instead of providing this energy by application of high mechanical stresses as in the process of diamond cut, it is possible to provide this energy by inducing thermal stresses at the low temperatures.

Using a point heat source and the thermo-elastic behavior of the material and the difference of temperatures at two regions around the crack tip, at the higher temperature region compressive stresses is developed, where as at the lower temperature region the tensile one. These different thermal stresses around the crack tip would create energy unbalances and changes and hence the release of energy, which is required to propagate the crack in the plate. On the other hand, the differences in the temperature magnitudes and signs or the induced thermal stress fields around the crack tip, shows that the energy release rate must be such that to propagates the crack in a control and stable manner and not to behave as an unstable crack which propagates suddenly.

It means that there is a boundary beyond which the material is overheated and is subjected to compressive stress and closure of the crack and before that the material is under tensile stress and hence opening the crack. So, the tensile region wants to open the crack, but the compressive region tries to close it and stop its propagation. Therefore, it is the go-ungo mechanism for the crack. If it is possible to move this boundary, the crack would follow it and propagate in a stable and control manner. Hence, the temperature of two successive points in the plate, at each instant could be changed by an amount, so that a defined magnitude of thermal stress difference induced between these two points, which creates a defined energy release rate to propagate crack between these two points. This means that the temperature, the thermal stresses as well as the energy release rate should be time dependent.

The above situation is achieved by applying movable point heat source to create thermal stresses in the plate containing an existed pre-defined crack. The air was compressed and heated and then jet vertically towards the surface of the plate by a special engineered design nozzle concentrated at a very small region. By moving the nozzle, the air jet would induce a time dependent thermal shock in the plate. This thermal shock is used to propagate an existed pre-defined crack in the plate on a given or arbitrary path and in a stable and control manner.

The new cutting device in which air is the cutting tool and is used for cutting the glass materials named as **AIR GLAZIER**. Not only by the use of this process different complex shapes could be cut on the glass with strong, smooth and finished quality surfaces, but also a waste-less, noise-less and clean processing of the brittle materials with the low cost machining can be achieved [2]. In the present paper, the various effective parameters on the given thermal cutting process have been investigated.

2.2. Fabrication of a laboratory Air Glazier

On the basis of the idea described above for the present work, a laboratory Air Glazier device was designed and fabricated for cutting the glass material and different experiments were conducted to investigate various effective cutting parameters. This device has the following features [6]:

1-cutting the work pieces with different thicknesses
2-cutting the complex shapes
3-cutting with adequate accuracy
4-cutting with repeatability
5-cutting automatically and non-automatically
6-cutting with various speeds
7-cutting with no expert operators
8-low cost and simple design device
9-cutting with safety

On the basis of the above features, various cutting tables and systems had been studied. Among them the rail movement system with the cartesian co-ordinates was selected. This design was considered, because of its low cost, easy fabrication and no requirement to sophisticated technology. Fig. 1 shows the complete view of the device. The main body of the device was made from two parallel rectangle bars. The longitudinal movement of the Air Glazier was possible by a trolley mounted on these two parallel rails, moving by the slotted wheels. The drive for moving the wheels were square threaded screw mounted on one side of the device frame. The transverse movement trolley was mounted on the longitudinal trolley and could also move by the use of a square threaded screw. The Glazier contained a heating chamber on the top of an engineered designed vertical cylinder and a special nozzle was attached to the bottom end of the cylinder which contained a designed interchangeable orifice diameter. The air from a compressor under a given pressure and velocity was passed through the chamber and the cylinder to get hot, and then was jet vertically at high velocity to the surface of the work piece. The height of the nozzle of the Glazier can be adjusted for various thicknesses of the work pieces [6].

The electrical control board for the device, electrical dimmer and the computer was placed on the operator table at the end of the device. At the end of each threaded screw, a stepped-motor with the accuracy of 1/8° was fixed and controlled by a computer program which guided the Glazier nozzle to move on the x-y plane followed the pre-defined path. The code for this purpose is able to store the output files for various given shapes and also read them and use as input files for the cutting purposes. By use of the same computer code, the accuracy required and the cutting speed could be set for the process. Using the screws and the motors, the rate of linear movement of the Glazier on account of each electrical pulse given to the motors was about 25 micron, where provided high precision and repeatability cutting process to the device. Fig. 2 shows the Glazier on the instant of cutting a circle on a glass plate.

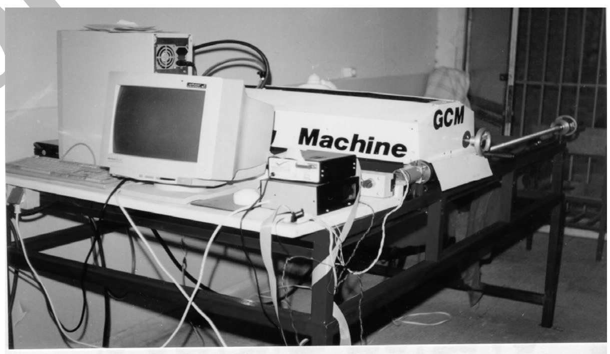

Fig. 1. Complete view of the laboratory Air Glazier device

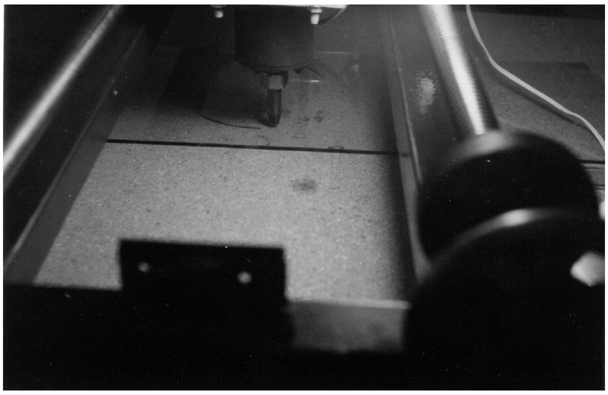

Fig. 2. Glazier on the instant of cutting a curve on a glass plate

3. Experimental results and discussion

Since cutting the glass by thermal process of hot air jet is a new phenomena and the Air Glazier is a new device for cutting the glass plates, several various unknown parameters must be studied to understand and hence to improve the cutting process. Therefore, the aim of the present work was to study and understand the effective parameters in thermal cutting of the glass plates by Air Glazier. In this work, the cutting of glass plate in the form of straight and curved lines with respect to the parameters such as cutting speed (CS), nozzle diameter (ND), plate thickness (PT), height of the nozzle from plate surface (HNPS) and the exit air temperature (EAT) was studied. Two hundred and fifty specimens made of commercial flat glass plates (soda lime glass) with the dimension of 6x15 cm and the various thicknesses of 3, 4, 6 and 10 mm were tested and the results obtained in the form of graphs.

As indicated earlier, to conduct cutting process, an existed pre-defined crack was needed in the plate which could be produced on the surface of the glass plate by the use of a diamond tool and then the movement of the nozzle could propagated this crack in a stable and control manner on a pre-defined path. As the experiments were repeated, a conclusion was made that as the cutting process and the crack propagation become more stable, the cutting surface quality as well as the situations during the cutting process would improve.

As it was observed during the experiments, the crack was always behind the heating point. Therefore, attention was made to the crack propagation and the movement of the nozzle. By conducting several experiments, it was concluded that the nozzle point to crack tip distance (NPCTD) is a crucial parameter and the improvement of the process is related to this distance. At the beginning of the cutting process, as the nozzle moves exactly equal to the thickness of the glass sheet from the edges, the through thickness crack is occured. At the end of cutting process also, the crack would stop exactly equal to the thickness of glass sheet from the edges and no further propagation occured. If this distance doesn't change and remains same during the cutting process, the condition of cutting as well as the surface quality would be the best. The same situation was observed, while cutting the curved path. Therefore, all the experiments were conducted to maintain this distance equal to the plate thickness. Fig. 3 shows the graphs of variation of NPCTD with EAT for various PT, when CS, ND and HNPS were given constant values. At the particular value of 220˚C for EAT, the NPCTD would be equal to the PT and is remained constant. Fig. 4 shows the graphs of variation of NPCTD with CS, but at the given EAT. It can be seen from the graphs that the CS of 1 mm/s under the given condition is convenient speed in which the NPCTD becomes equal to the PT, beyond which the distance is increased. Figs. 5, 6 and 7 show the variation of NPCTD with HNPS for various ND and different particular CS, but constant EAT and PT. As it is obvious from the graphs, with the increase in CS and HNPS, the NPCTD is increased. The best HNPS is 2 mm and among the various ND, 2 mm and 3 mm diameters are the best for the Glazier nozzle. It could also be concluded from Fig. 6 that by decreasing HNPS, NPCTD is decreased. The best is Fig. 6 in which at 1mm/s CS and HNPS of 2 mm, the NPCTD is equal to PT. Fig. 8 shows the variation of NPCTD with HNPS for various PT and particular CS, ND and EAT. Fig. 9 shows the graphs of macroscopic cutting surface quality of glass sheets obtained by Air Glazier at various CS as well as the diamond cut. The macroscopic investigation of the quality of diamond cut is shown to be worse, contained lot of micro cracks and uneven fractured surfaces. This surface quality was taken as the basis for the classification of the quality of the glass cut surfaces. The best surface quality was achieved at the CS of 1 mm/s. By increasing or decreasing the CS at a particular EAT, the cutting surface quality decreases. Figs. 10 and 11 show the cutting surfaces of the work pieces with the CS of 1 mm/s and diamond tool respectively which obtained by optical microscope under high magnification.

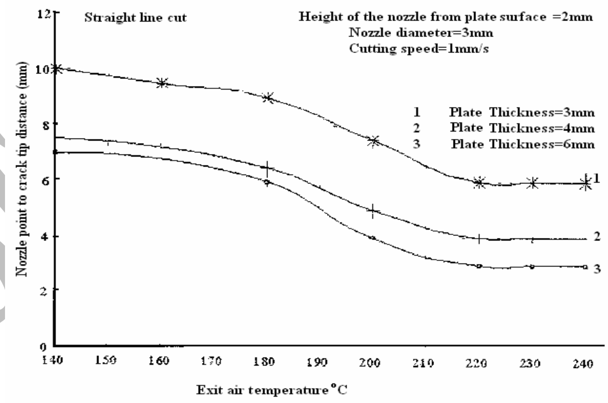

Fig. 3. Variation of NPCTD with EAT

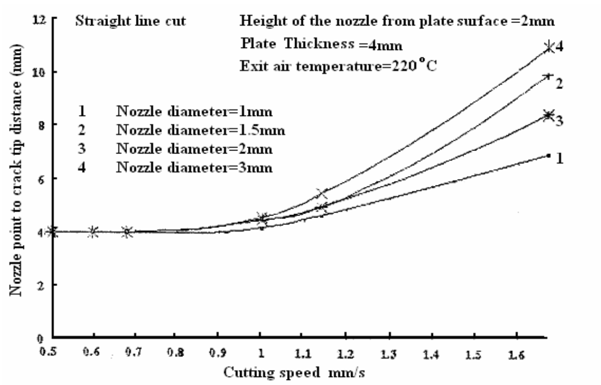

Fig. 4. Variation of NPCTD with CS

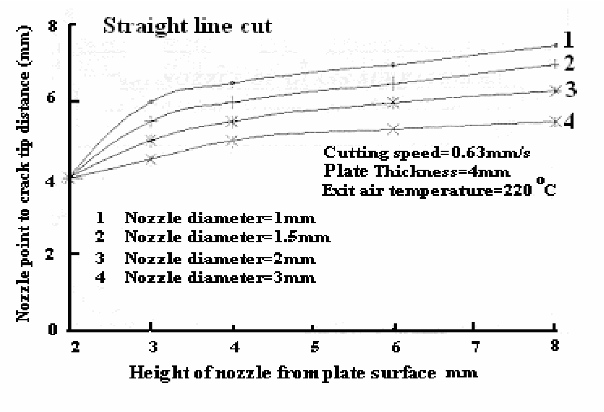

Fig. 5. Variation of NPCTD with HNPS for CS=0.63 mm/s

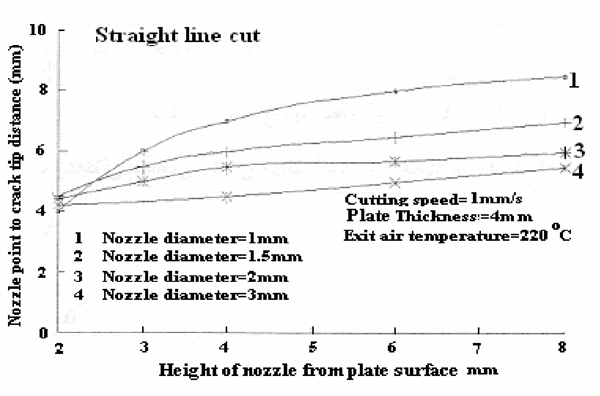

Fig. 6. Variation of NPCTD with HNPS for CS=1mm/s

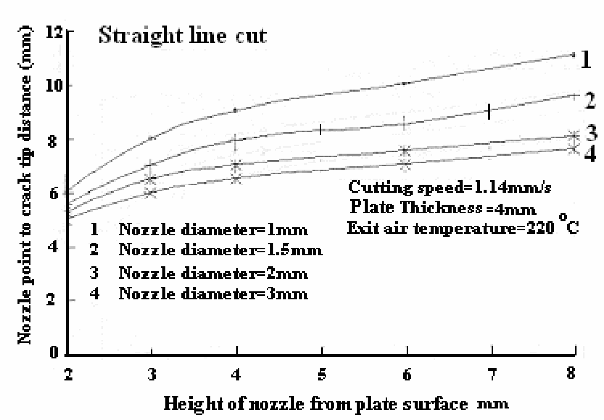

Fig. 7. Variation of NPCTD with HNPS for CS=1.14 mm/s

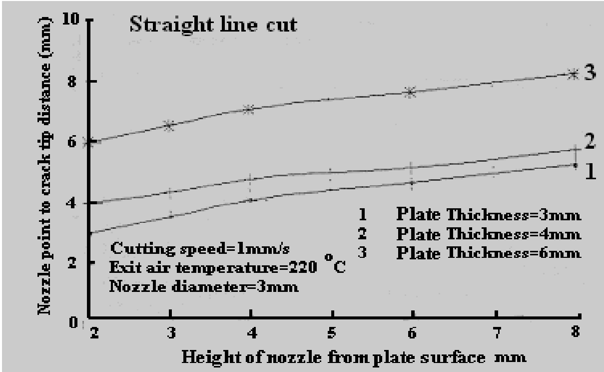

Fig. 8. Variation of NPCTD with HNPS for various thicknesses

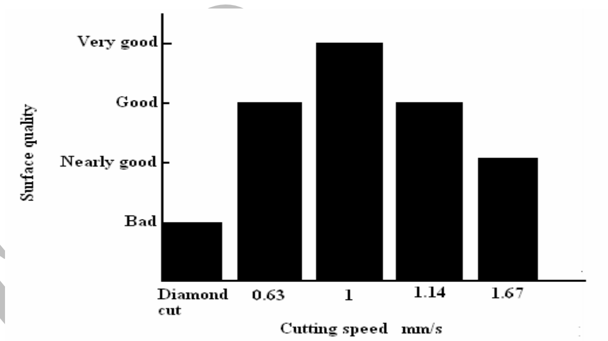

Fig. 9. Macroscopic comparison of surface quality at different cutting speeds and diamond cut

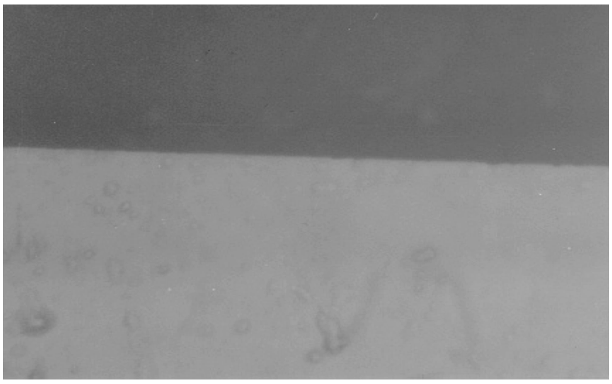

Fig. 10. Cutting surface quality by Air Glazier at CS=1 mm/s

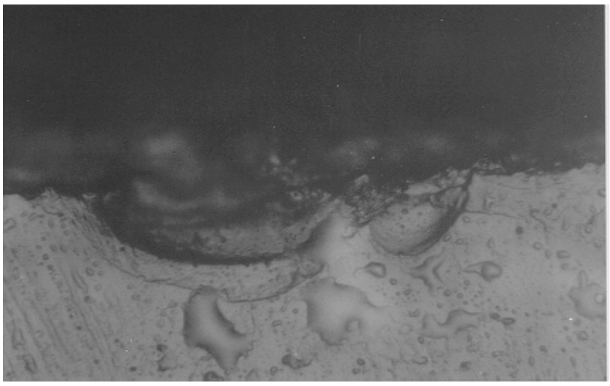

Fig. 11. Cutting surface quality by diamond tool

In order to study the possibility of the incline cut as well as the angle cut, several experiments were conducted according to the entrance inclined cutting angle α shown in Fig. 12 and the acute cutting angle β shown in Fig. 13. The experimental results are indicated that if the inclined cutting angle $\alpha \geq 45^{\circ}$, and if the acute cutting angle $\beta \geq 30^{\circ}$, the cutting process for glass is possible.

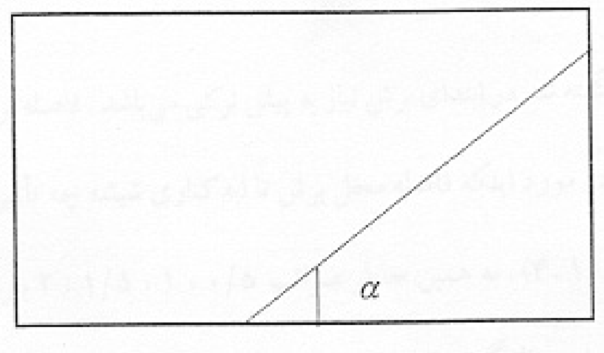

Fig. 12. Schematic diagram showing inclined cutting angle α

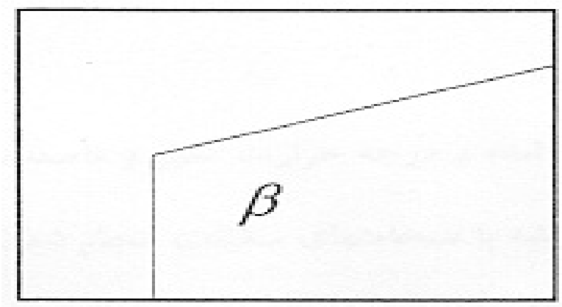

Fig. 13. Schematic diagram showing acute cutting angle β

Both the above results obtained at the improved values for CS, EAT, HNPS and ND. Figs. 14 to 16 show the various angles β which have been easily cut on the glass plate. Also Fig. 17 shows a curved cut (quarter of a circle) which had been done easily on the glass plate. These experiments were conducted on the glass plates with various thicknesses of 3, 4, 6 and 10 mm and the results were satisfactory. In Fig. 18, various shapes cut on the glass plates by Air Glazier on the basis of the process of thermal cutting were shown.

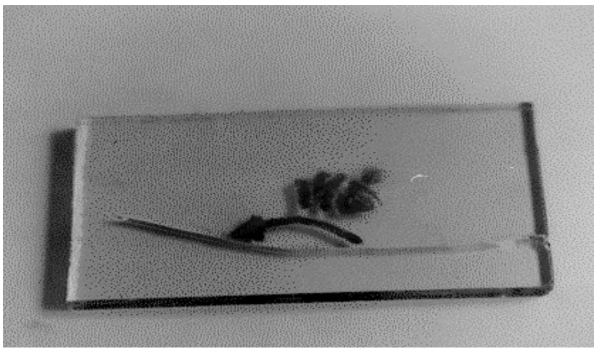

Fig. 14. Cutting glass plate at an angle β=160

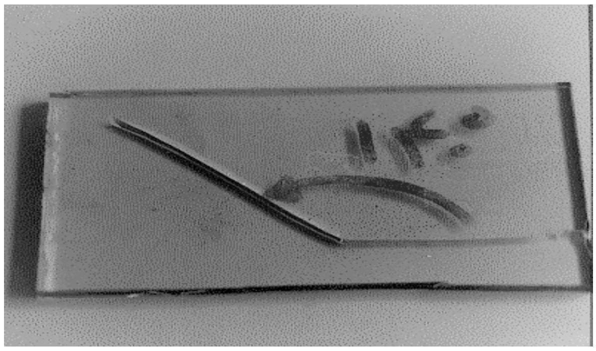

Fig. 15. Cutting glass plate at an angle β=140

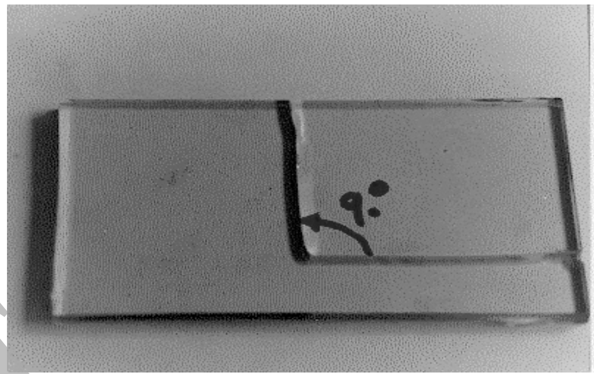

Fig. 16. Cutting glass plate at an angle β=90

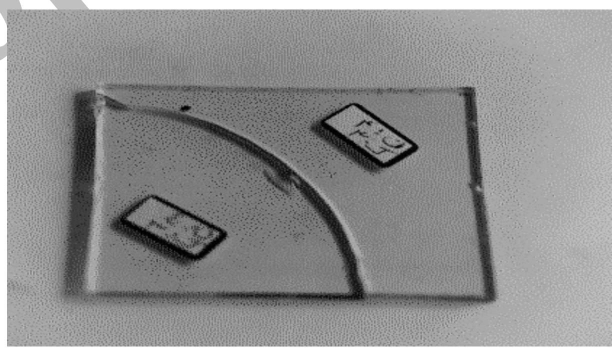

Fig. 17. Cutting a curve path (quarter circle)

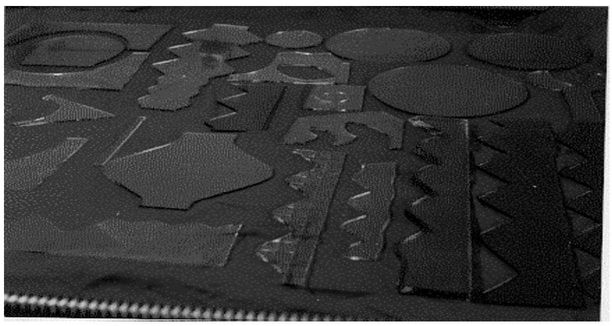

Fig. 18. Various shapes cut on the glass

4. Fabrication of Portable Air Glazier

On the basis of the results obtained above and an easy way of cutting glass sheets by hot air jet, various types of portable Air Glazier for the use in small industries as well as glass cutting shops were developed. The aim was cutting various shapes, low cost device, low cost cutting process and portable device. Based on suggestions taken from different glass industries and depends on the analysis, two kinds of portable and hand Air Glazier were designed and fabricated, the photos of which are shown in the Figs. 19 and 20. They consist of three main parts [7]: 1- hot air nozzle 2- system of producing and compressing the air and 3- engineered handle.

Fig. 19. Portable Air Glazier

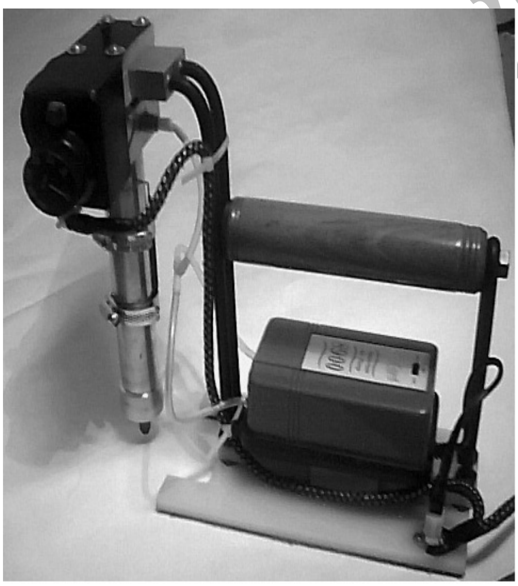

Fig. 20. Hand Air Glazier

5. Conclusions

1- For the best cutting surface quality and smoothness, the nozzle is moved ahead of the crack front by a defined distance. The desired NPCTD is found to be equal to the PT.
2- According to the desired NPCTD, the desired CS, ND, EAT, and HNPS were set on the device.
3- By increasing EAT or by decreasing CS, the experimental graphs showed that the curves for NPCTD reaches a threshold value and then become constant, in which this limited value is equal to the PT.
4- ND within the range taken in the research work, does not affect the cutting condition significantly, but HNPS is a significant parameter effect on NPCTD and hence the cutting condition.
5- For the inclined angle cut, if the entrance angle is greater than 45˚, the cutting process is achieved easily.
6- For the angle cut, if the angle within the cutting edges is greater than 30˚, the cutting process is achieved easily.
7- Cutting the curve paths under the best condition prescribed for the straight lines is achieved easily.
8- The cutting surface quality by the new process is smooth and un-scratch able in nature. The secondary operations are not necessary and the cutting edges are not sharp. Due to use of heat in cutting process, the cut surfaces are also strong enough.

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