HEALING OF CRACK IN GLASS BY THERMAL TEMPERING METHOD

A THESIS FOR THE PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF BACHELOR OF TECHNOLOGY

Submitted By

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CERTIFICATE

This is to certify that the thesis entitled, "Healing of crack in glass by thermal tempering method" submitted by Mr. Abhijit Kumar Subudhi, 111CR0540 for the partial fulfilment for the requirements for the award of Bachelor of Technology degree in Ceramic Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date: 11-05-2015

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Date: 11-05-2015

Abhijit Kumar Subudhi

(Abhijit Kumar Subudhi)

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ABSTRACT

The aim of the present work is to find the applicability of thermal tempering method for healing of the glass surface crack. The crack in the glass surface has been generated by Vicker's Hardness Instrument with 1KgF load and dwell time of 10 sec. It is that the healing of the crack may be due to the viscous flow at the glass surface at the temperature greater than glass transition temperature. The driving force for this healing may be the surface roughness around the crack. All the samples were heat treated at 650°C and 700°C with a heat treatment time 2 hours, 4 hours and 6 hours. After the heat treatment for a specific temp and time, all the samples were rapidly quenched so that a surface compressive stress can be as we have experienced in thermal temp process. After rapid quenching, it has been observed that with an increase in dwelling time of the heat treatment the crack length decreases significantly. It has also been found that rapidly quenched glass not only closes the crack but also been observed a significant increase in surface compressive stress and flexural strength.

1.

INTRODUCTION

1.1 GLASS DEFINITION

Glass is as an inorganic product of fusion which has been cooled to a rigid condition without crystallisation [1]. Glasses can also be as solids having the feature of a uniform local geometric arrangement at a short distance (2 – 3 atoms) in the form of structural units. However, these structural units more or less lack a mutual regular and periodic arrangement at greater distances, or, expressed in mineralogical terms, glasses lack the translation of cells identical with the structural units of glass. As regards to chemistry, glasses can be classified as organic glasses and inorganic glasses (oxide glasses, non-oxide glasses). Regardless of its chemical composition, every glass is defined thermodynamically so that its structure is not in a state of equilibrium. Only on heating above the transformation temperature is a glass capable of establishing a metastable equilibrium of an undercooled liquid. Kinetic theory is on the assumption

that every liquid is theoretically capable of producing glass when cooled to the Tg (Glass Transition Temperature) at a rate that prevents crystallisation. Thus, "any material, inorganic, organic, or metallic, formed by any technique, which exhibits glass transformation behaviour and its lattice structure has short range order is a Glass".

Glasses can be in several ways. Most common method is melt quenching. Melt quenching is one of the processes, in which the glass batch melt is from the liquid state above the melting point to low temperature. A melt, when cooled, can form glass as well as crystal depending upon the critical cooling rate. The enthalpy vs. temperature graph is in Fig.1.

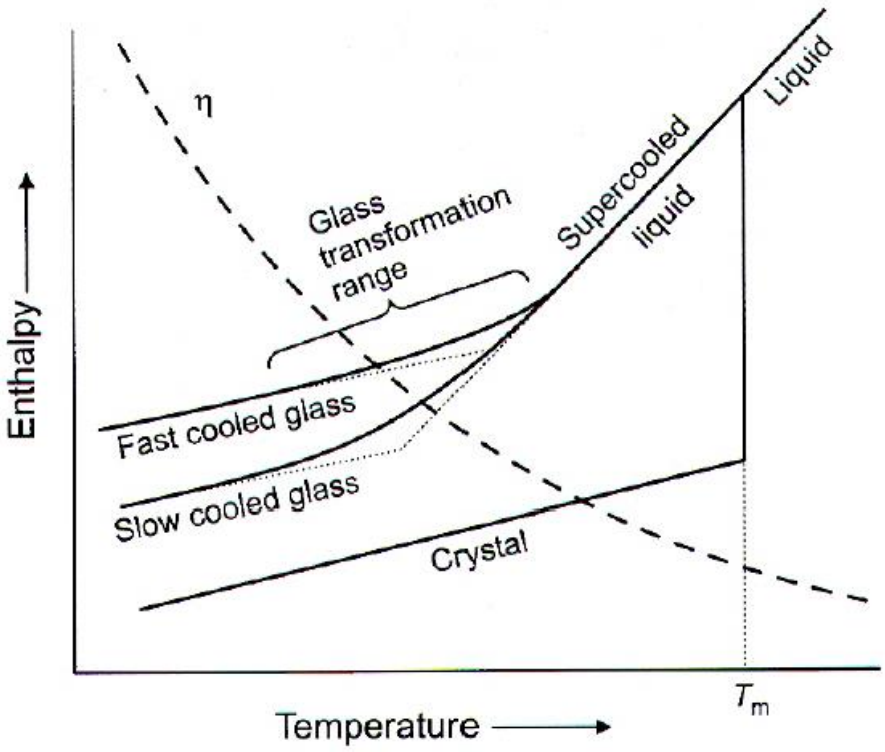


Fig. 1 *- Glass and Crystal formation curve*

Depending upon the rate of cooling, glass transition temperature and specific volume of glass changes that leads to arresting of the structure making it brittle.

1.2 EFFECT OF CRACK ON GLASS SURFACE

Glasses are widely used in daily use like packaging of food items, windows, reinforcement structures in housing and buildings, tableware, interior design, appliances and electronic equipment, automotive and transport, medical technology, radiation protection from gamma rays, fiber optic cables, solar energy glass, wind turbines etc. Glass is brittle in nature, as it is supercooled structure, hence when a tensile load is to it, it breaks and forms sharp corners. If by any means a crack on surface forms, then it can lead to catastrophic failure and it has to be. The stress intensity at the crack tip is very high; thus crack can propagate at a very high rate without plastic deformation. The cost of replacing glass and manufacturing of it from cullet is very high. So an alternative method is being studied where the cracks can be and can be reused without wasting it.

1.3 HEALING OF CRACK VIA HEAT TREATMENT

On reheating the glass, the viscosity decreases and flow of viscous glass takes place. The crack tips are blunt by the fill of viscous glass from the nearby surface. The rearrangement of the structure takes place that leads to decrease stress in the crack center and tip. When it is above glass transition temperature there is a chance of crystallization, but widely used Soda – Lime – Silicate glass does not crystallise due to high viscosity. On cooling it at a low cooling rate, it requires a very high dwelling time so that crack can be. When the glass is from high temperature, there is a generation of very high surface compressive stresses. This is thermal tempering technology, when

this is applied to crack healing then it can reduce the dwelling time and can reduce the cost of crack healing. Our present study is to see if this compressive stress and as well as viscous flow leads to crack clouser.

1.4 OBJECTIVE OF PRESENT WORK

- To study the applicability of thermal tempering method on crack healing on glass surface
- To heal the artificial crack that is made on the surface of the glass
- Thermal treatment of the glass at different temperatures and at different dwelling time
- Study of the behaviour of crack healing
- Study of the variation of Flexural Strength and Residual/ Regenerated Compressive Stress on the surface of the glass after thermal treatment

2

LITERATURE REVIEW

Cracks can be healed using thermal treatments in the glass sample. So Vickers's indentation is required to generate the crack on the samples and are subjected to heat treatment. Healing of cracks can take place by blunting and pinching of crack tips, grooving and rounding and breaking of radial cracks, receding up of lateral and median cracks, and spheroidization and cylinderization of closed cavities [2]. Due to temperature rise, above Tg, the viscosity of the glass decreases around the cracks and flow of viscous glass is done by capillary pressure.

When the temperature is , the strength of cracked glass increases up to its original strength and on further increase in temperature results in also increase in its strength then followed by decreasing the strength. The increase in strength is due to crack grooving and branching at high temperature and longer time. When the flow content reaches or exceeds the pre-existing flaws and dwelling time is less, then the

strength of the glass decreases. This occurs at very high temperature, viscosity decreases and atom diffusion and flaw distribution increases. The strain distribution around the crack is also important.

Humidity, time and temperature variation can change the degree of healing in glass [3]. Increasing the relative humidity decreases the temperature of healing cracks and with an increase in time the crack lengths decrease and thus strength increases. Again at low humidity a higher temperature is required because the crack closing mechanism for this type of crack healing is crack regression and then pinch-off of crack. High humidity above the glass surface causes an increase in driving force for viscous flow, results in crack clouser. ESEM (Environmental Scanning Electron Microscope) helps in the creation of specific humidity on the glass surface as well as analysing the crack healing technique.

In case of float glass, crack healing properties may vary depending upon which side the crack is present, in airside or in the molten Tin side [4]. There is an effect of Tin in glass healing property. In normal scenario if a crack exists on the “air side” then on heat treatment cracks tend to speherodize and at a high dwelling time it closes and pinches off. There is blunting of crack tips and cyllindrization of the large curved cracks. But crack on the “Tin side” does not follow this step. A very high temperature is required to make the nearby viscous glass flow into the crack. This is due to the presence of some concentration of Tin on the surface which oxidizes to Tin oxide and it forms a layer on the surface in oxidizing atmosphere. The presence of this layer hinders the movement of the viscous glass on to the crack depth. The concentration of Tin inside the glass decreases on increasing the depth of the glass.

The healing of crack also depends on water content [5]. In the presence of water on the glass surface, there is the occurrence of hydration and dehydration. The hydration helps to pinch the crack. Above the boiling point of water there dehydration and this results in increase in humidity above the glass surface. This results to decrease in healing temperature and increase in driving force.

Heating the glass above glass transition temperature and rapidly quenching it to room temperature causes an increase in strength of the glass [6]. This is due to the formation of compressive stresses on the surface of the glass and tensile stresses on the inside of the glass. There is a stress variation along the width of the glass. The higher the compressive stress, the better the glass would be. The heat transfer is an essential factor for getting a high strength glass [7]. A higher amount of air is needed inside the nozzle to create a high heat transfer within few seconds that will result in the freezing of the viscous glass.

3

EXPERIMENTAL PROCEDURE

3.1 SAMPLE DESCRIPTION

The Soda – Lime – Silicate glasses available in the market were used as the specimen. Glasses were cut to the dimension 50 mm * 25 mm * 3.82 mm. The details of glass samples is given in below table.

Company	**Saint-Gobain**
Density	2.5 gm/cm^3
Compression Resistance	800 – 1000 MPa
Modulus of Elasticity	70 GPa
Softening Temperature	600 °C
Specific Heat	0.8 J/g/K
Thermal conductivity	0.8 W/m.K
Thermal expansion coefficient	9×10^{-6} K^{-1}
Refractive Index	1.52
Thickness	3.82 mm

Table 1:- *Properties of glass samples (data from - http://in.saint-gobain-glass.com/)*

3.2 VICKERS'S HARDNESS TEST

Vicker's hardness test provides hardness of the sample by creating an indentation. The resistance to plastic deformation in a material is its hardness. In case of Vicker's hardness test method, a diamond indenter, which is in the form of a right pyramid having a square base measuring an angle 136 degrees between opposite faces, is for indentation. Vicker's hardness instrument is in fig.2.

Fig. 2 – *Vicker's Hardness Test Instrument*

A load of 1 Kg.F is applied onto the glass surface which created a rhombus structure on the glass surface. The hardness is given by the below formula

$$HV = \frac{1.8544 * F}{d^2}$$

Where, HV is hardness value

F is applied load in Kg.F

d is average diagonal length of rhombus in μm

The indentation by this instrument creates crack in the glass near by the rhombus structure. This crack resembles the micro version of the crack in daily use. The healing of this crack is carried out in this project.

3.3 ADVANCED OPTICAL MICROSCOPE

A microscope is used to view the magnified image of samples in high resolution. It consists of the sample holder, eyepiece lens, and objective lens in perfect position so that a clear image can be seen. In the case of Advanced Optical Microscope, an additional light-sensing camera is attached to it so that it can capture optical micrograph of the sample. This microscope consists of an eyepiece, sample holder, objective lenses, light source, and focus nub. The advanced optical microscope image is in Fig. 3.

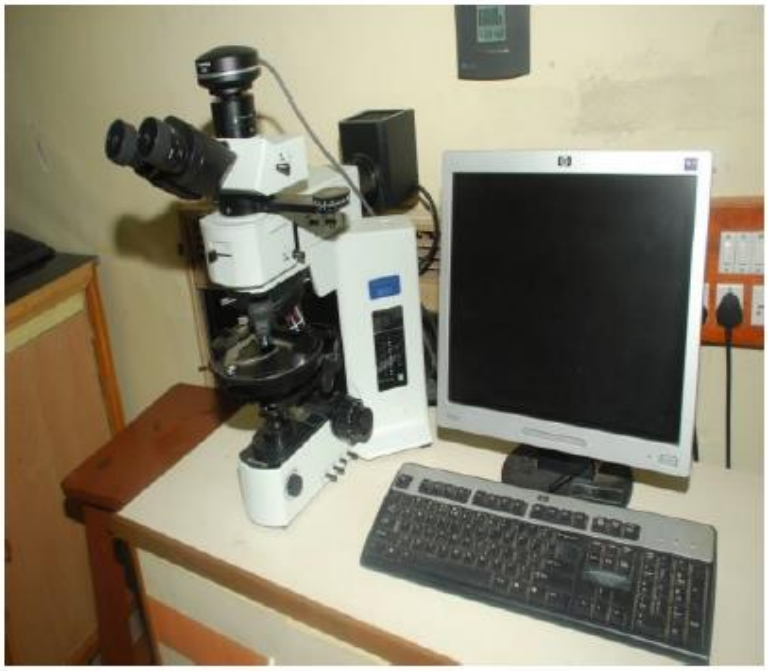


Fig. 3 – *Advanced optical microscope, Olympus Corporation, Japan/ BX-5175E21P*

The indented samples were observed under advanced optical microscope at a magnification of 10x, 20x, and 50x and the micrographs were captured. Then after the thermal treatment again the samples were observed under this microscope and the crack healing analysis was carried out.

3.4 HEAT TREATMENT

As the softening temperature of the glass is 600°C, thermal treatment or tempering was carried out at 650°C and 700°C. The sample was cleaned properly after the indentation and was put in the muffle furnace on an alumina plate. Heating above 700°C caused sticking of glass samples on the plate, fine alumina powder was spread over the alumina plate to avoid sticking of the glass sample over alumina plate. A heating rate of about 3°C per minute was provided. The holding time at 700°C or at

650°C was 2 hours, 4 hours and 6 hours. Sudden quenching was done after holding on a graphite plate. Air is blown on the top surface of the heated glass to dissipate heat more quickly. The rapidly cooled samples was then observed under advanced optical microscope.

3.5 SAMPLE IDENTIFICATION

The heat treated sample are marked as shown in Table 2.

Sample Name	Temperature (°C)	Dwelling Time (hours)
S12	650	2
S13	650	4
S3	700	2
S5	700	4
S6	700	4
S8	700	6
S9	700	6
S10	700	2
S15	700	4

***Table 2** – Sample identification with heat treatment schedule*

3.6 SURFACE STRESS DISTRIBUTION

The compressive stress on the surface of the glass can be measured using PS-100-SF polarimeter. This is a precision device used for the measurement of retardation/bifringence. It consists of a strainoptics SA-100 Analyser, Analyser scale and Quarter Wave Plate. The strainoptics PQI Illuminator consists of three main parts i.e. a light source mounted on a base plate, a polarizing screen, and a mounting post for the analyser and accessories. The light source is designed to provide uniform illumination over the viewing field. If stresses are present in the glass sample, a pattern of colour and black fringes appears. Mono-chromater blocks other colour light rather passes only a single wavelength and fringes can be observed due to variation in intensities. The polarimeter is shown in Fig. 4.

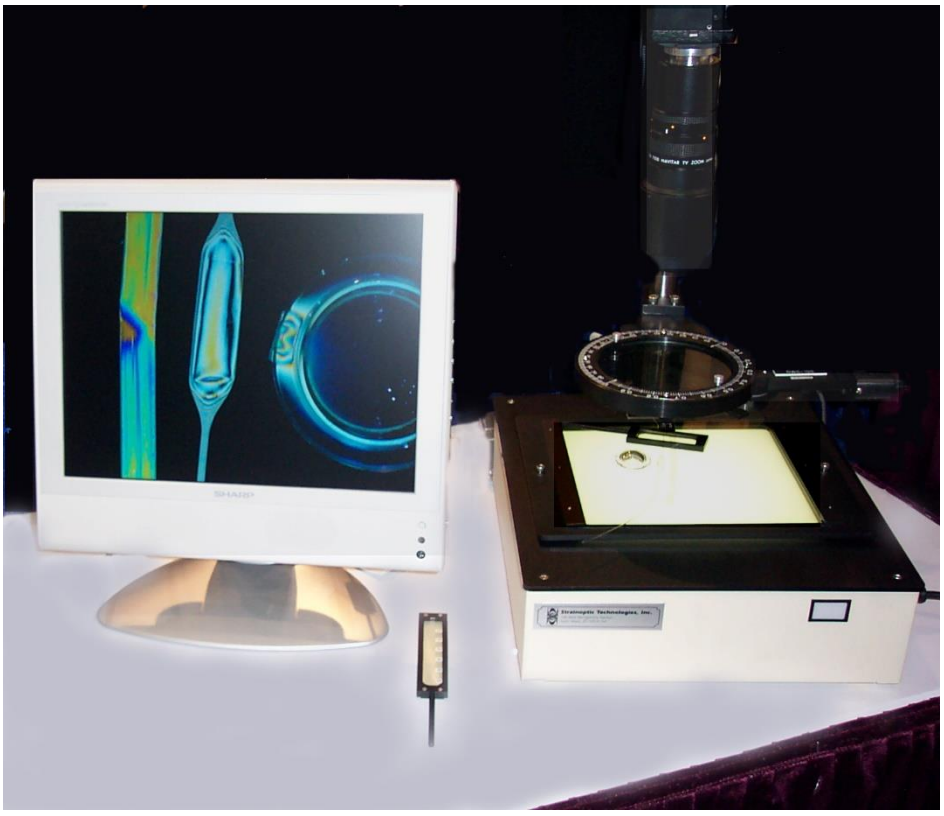


Fig. 4 *– PS-100-SF Polarimeter, Strainoptics, INC. North Wales, PA 19454 USA*

The sample was placed on the illuminator screen and it was adjusted in such a manner that maximum fringes could be observed. Analyser scale was pointed to zero. The nearest lower order fringe is determined. The sample was covered using a mono-chromater. A Point of Interest (POI) is determined on the surface of the glass where there maximum stress. On rotating the analyser the bright fringes turns dark and the vice versa. When the POI turns to exact opposite intensity the reading on the analyser is observed and the compressive stress on the surface is calculated from the below formula 1 (manual provided by Strainoptics, INC. North Wales, PA 19454 USA) and were analysed.

$$\sigma = \frac{((n+1)-f)*\lambda}{t*C} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \{1\}$$

Where,

σ = Compressive Stress on the surface (in MPa)

n = Lower full order fringe number

f = Scale reading from the analyser

λ = Wavelength of light (565 nm in glass)

t = Thickness of the specimen

C = Stress constant of the material in Brewster (2.6 Brewster in glass)

3.7 UNIVERSAL TESTING MACHINE

Three point bending test or flexural strength is carried out in Universal Testing Machine. It consists of screw press, pin holder, sample holder. Flexural strength is calculated by 3 point bending test. There is compressive stress on the top side of the sample and tensile stresses on the bottom side of the sample. Flexural strength provides the stress that is applied in a specific area that can break the material. Flexural strength is given by formula 2.

$$\sigma = \frac{3PL}{2bd^2} \quad \text{..... \{2\}}$$

Where,

σ = Flexural Strength in MPa

P = Load at which the sample breaks (in Newton)

L = Span Length (in mm)

b = Width of the sample (in mm)

d = Thickness of the sample (in mm)

Fig 5 – Universal Testing Machine,

The Fig. 5 shows a universal testing machine. The span length is adjusted to 35 mm and the sample is placed onto sample holder positioning in the centre. The indented portion is faced downwards so that actual flexural strength can be observed. Then there is application of the load at a constant rate. When the sample breaks, the load is observed and the flexural strength is calculated.

4

RESULTS AND DISCUSSION

4.1 VICKER'S HARDNESS TEST

Glass samples were indented using Vicker's Hardness instrument and the hardness value is given in Table 3.

Sample	Load (Kg.F)	Dwelling Time (sec)	d_1 (µm)	d_2 (µm)	Hardness (HV)
S3	1	10	57.8	58.8	546.6
S5	1	10	61.3	59.6	507.5
S6	1	10	57.3	59.8	540.6
S8	1	10	60.3	60.9	505
S9	1	10	60.2	60.2	539.1
S10	1	10	61.3	62.2	486.3
S12	1	10	61.5	61.8	487.9

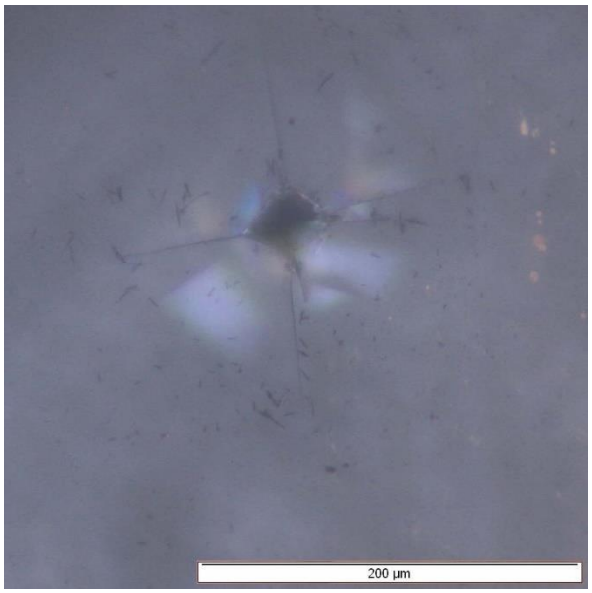
S13	1	10	60	58.1	520.3
S15	1	10	61.2	61.1	495.9

Table 3 – *Hardness value for indented cracked glass*

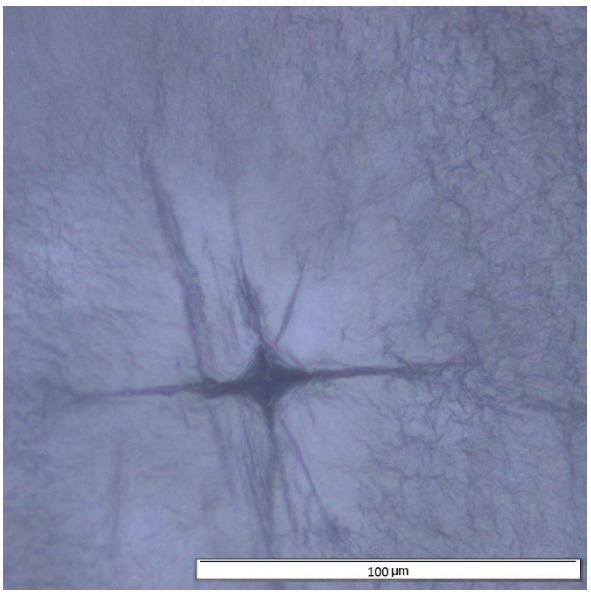
Average hardness is found to be **514.36 HV**. As the load is very high for a glass sample, a good length of crack is obtained. The crack is observed under optical microscope.

4.2 CRACK ANALYSIS WITH CRACK LENGTH AND COMPRESSIVE STRESS

4.2.1 HEAT TREATMENT AT 650°C



(a)



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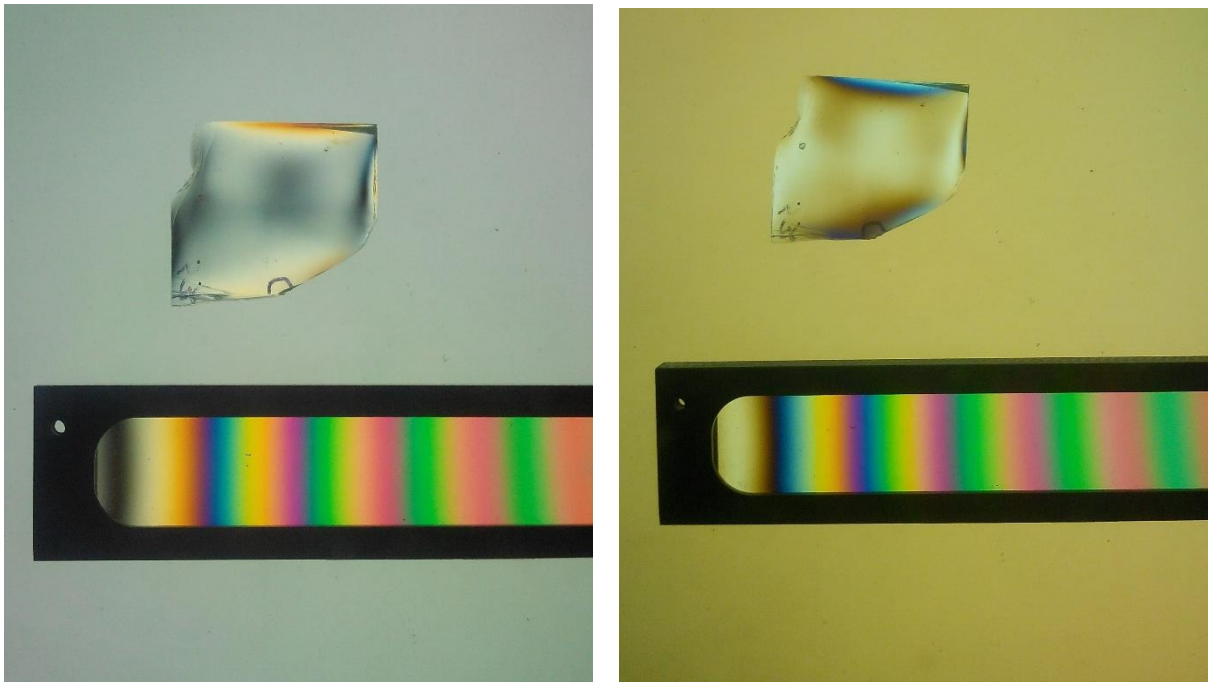
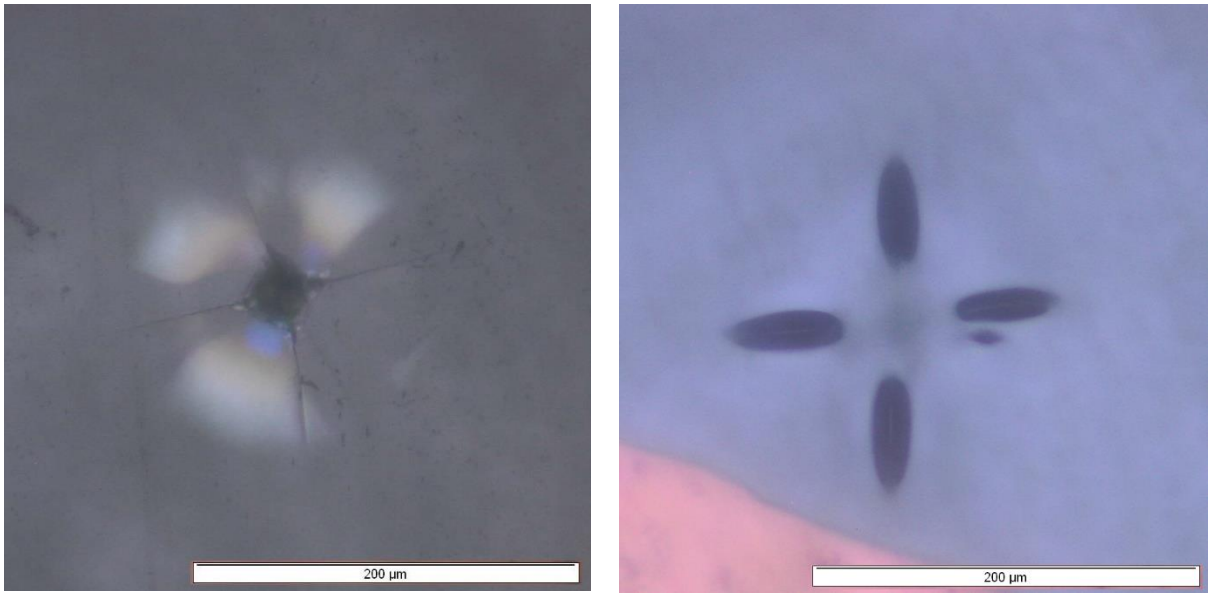


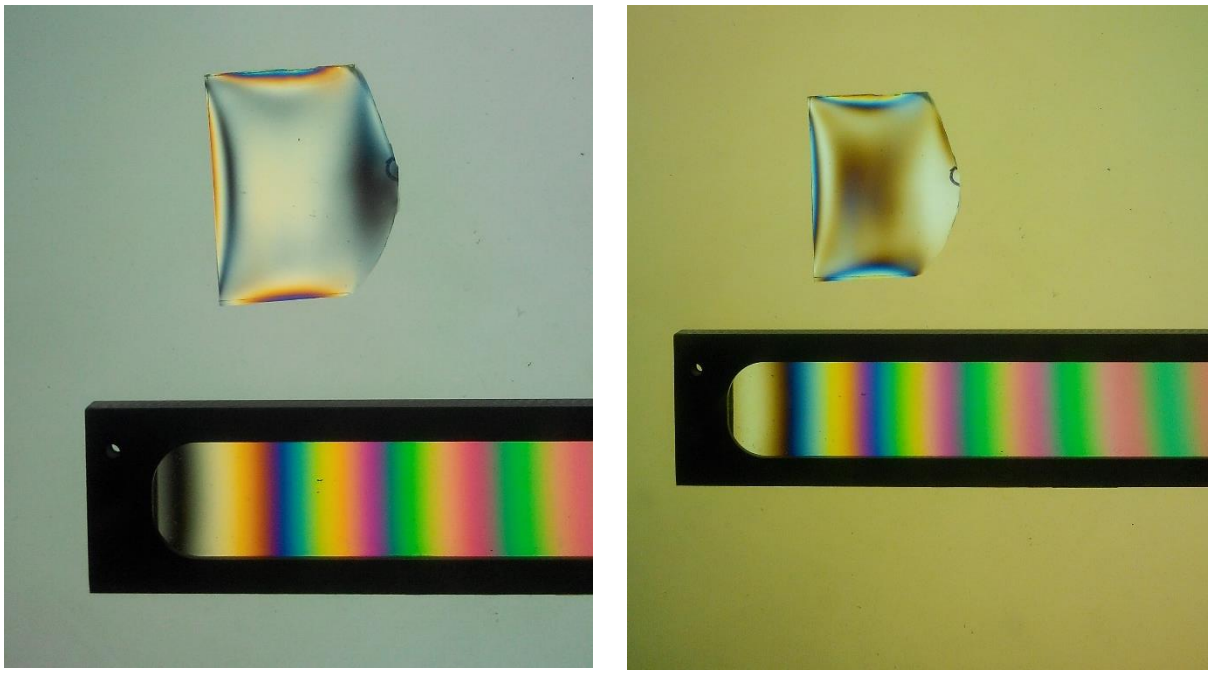
(c) (d)

Fig. 6 – (a) Glass sample S12 before heat treatment, (b) Glass sample S12 heat treated at 650°C for 2 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

Average crack length before heat treatment is 85.499 µm and average crack length after heat treatment is 57.142 µm. There is a decrease in **33.166 %** of crack length. The regenerative compressive stress on the glass surface is **87.039 MPa.** It can be seen from Fig. 6 (a), and (b) that there is very less decrease in the crack length, also there is no sign of blunting of crack tips. Only there is a viscous flow of glass into the indentation and there is formation of surface crazing. The sharpness of crack tip suggests that the overall flexural strength of the sample will be low, but due to the presence of high compressive surface stress, strength value will not vary at a large scale.



(a) (b)



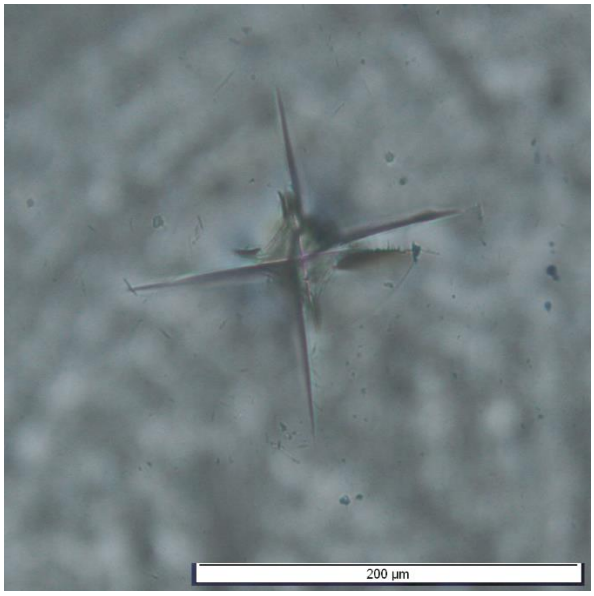
(c) (d)

Fig. 7 – (a) Glass sample S13 before heat treatment, (b) Glass sample S13 heat treated at 650°C for 4 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

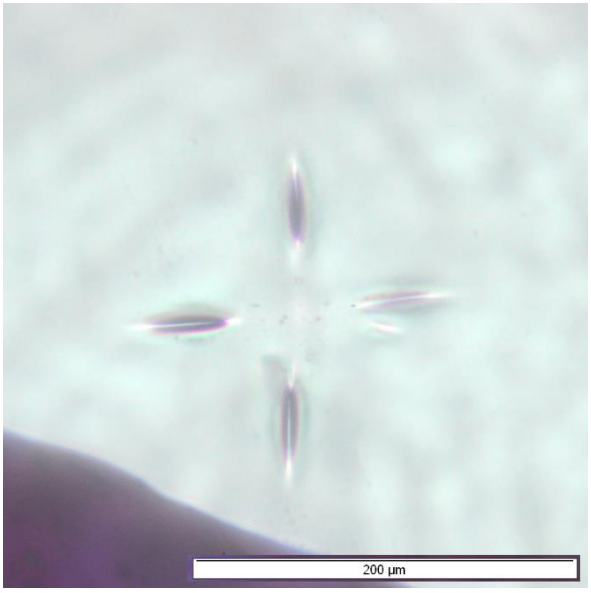
Average crack length before heat treatment is 77.755 µm and average crack length after heat treatment is 46.428 µm. There is a decrease in **40.29 %** of crack length. The regenerative compressive stress on the glass surface is **91.71 MPa**. In this glass

sample on thermal tempering of crack shows a blunting of crack tip, fill up of indented cavity, decrease in crack depth as well as spheroidization of lateral crack. This may be a result of high compressive stress and high dwelling time.

4.2.2 HEAT TREATMENT AT 700°C FOR 2 HOURS



(a)



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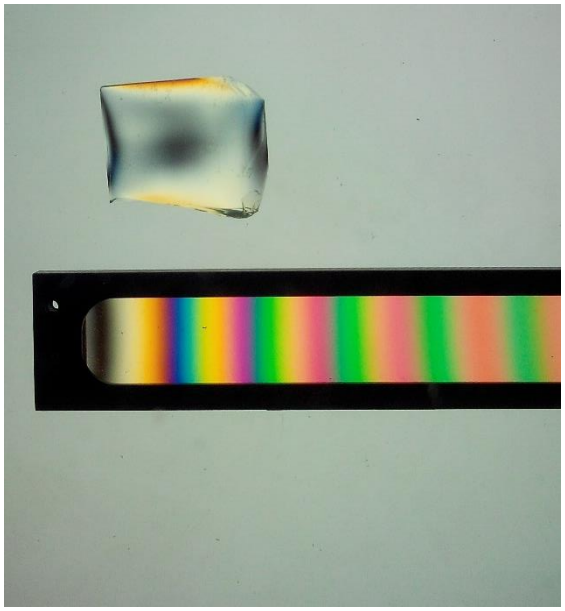

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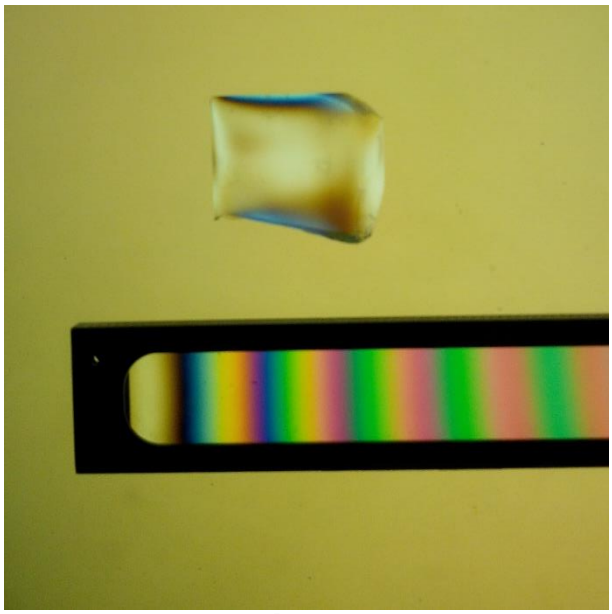
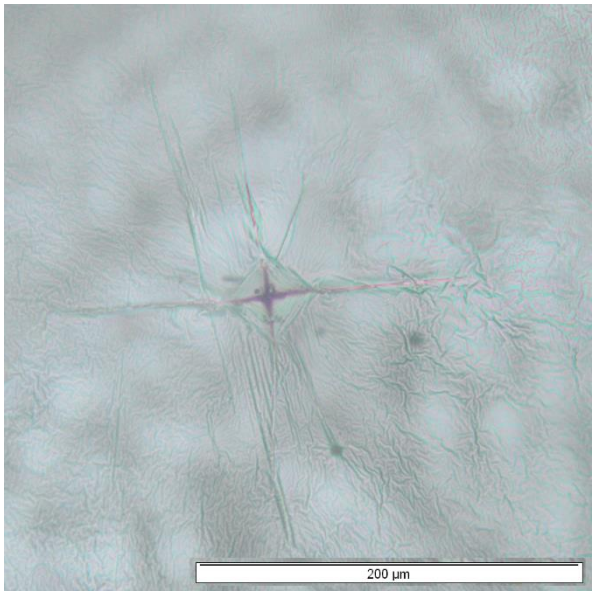


(d)

Fig. 8 – (a) Glass sample S3 before heat treatment, (b) Glass sample S3 heat treated at 700°C for 2 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

Average crack length before heat treatment is 75.829 µm and average crack length after heat treatment is 42.857 µm. There is a decrease in **43.52 %** of crack length. The regenerative compressive stress on the glass surface is **90.544 MPa.**

(a)



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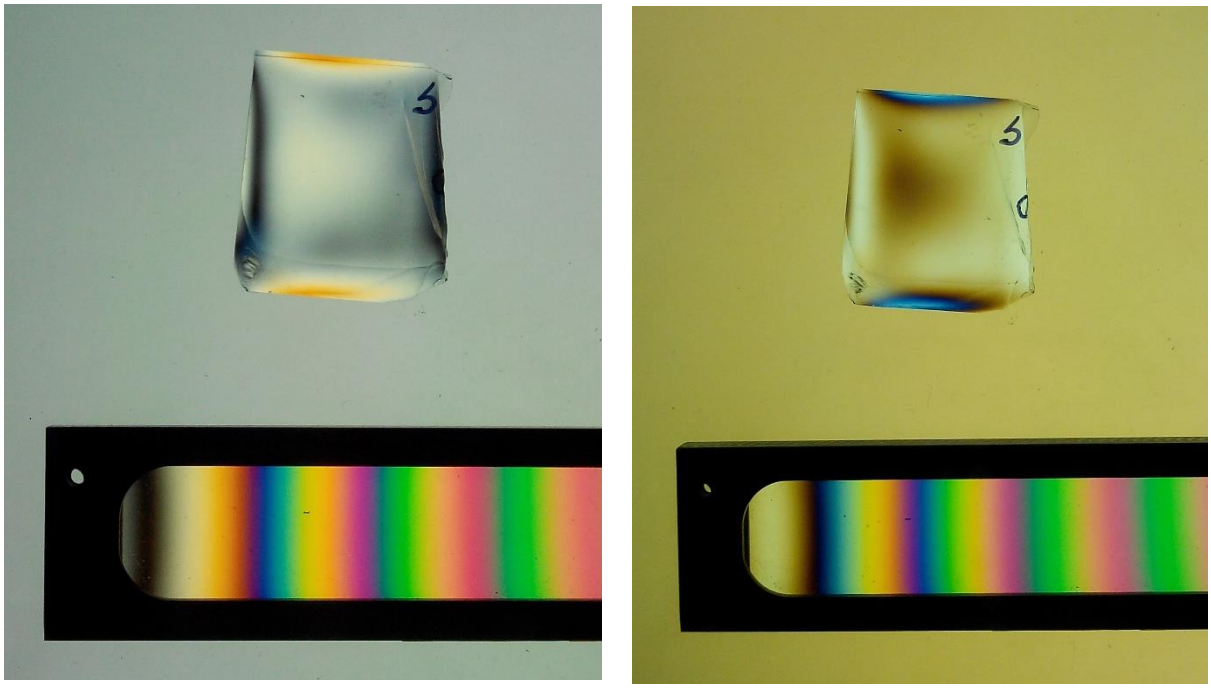


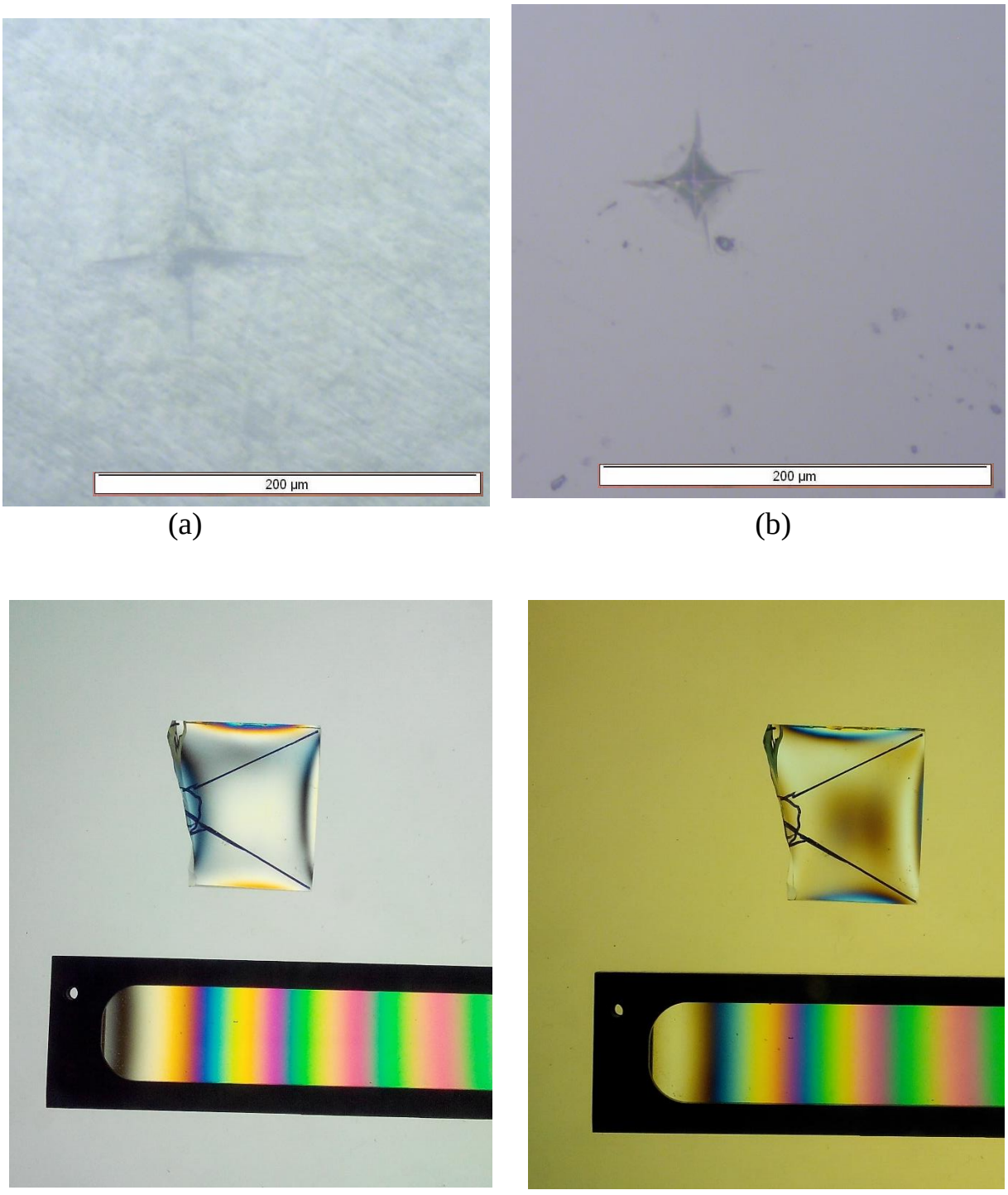
(c) (d)

Fig. 9 – (a) Glass sample S10 before heat treatment, (b) Glass sample S10 heat treated at 700°C for 2 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

Average crack length before heat treatment is 81.249 µm and average crack length after heat treatment is 35.714 µm. There is a decrease in **56.04 %** of crack length. The regenerative compressive stress on the glass surface is **91.13 MPa.**

Heat treatment at 700°C for 2 hours showed an increase in change in crack length. This change in crack length is due to the high temperature results to a lower viscosity. The sudden quenching after 2 hours creates stress that overcome the uneven nature of the crack.

4.2.3 HEAT TREATMENT AT 700°C FOR 4 HOURS

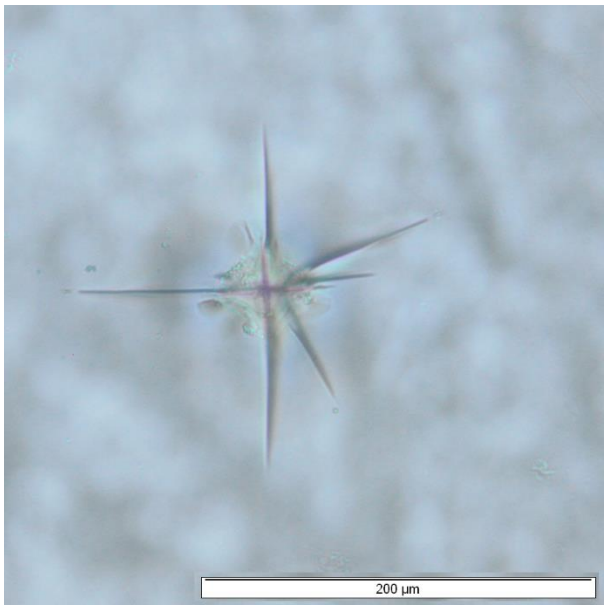


(a) (b)

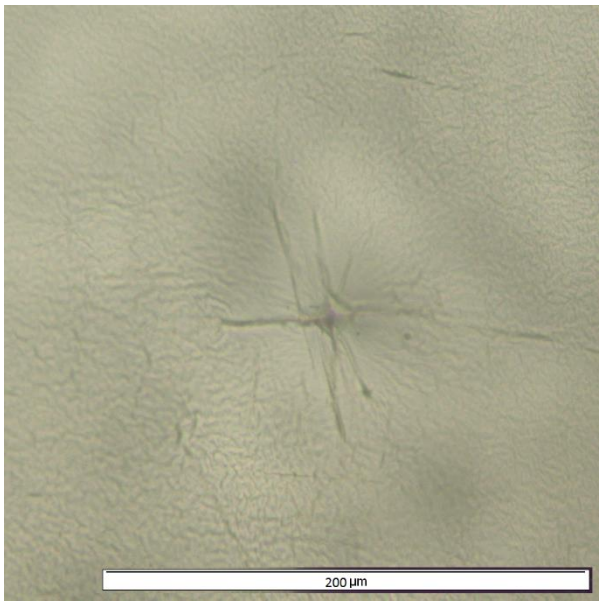
(c) (d)

Fig. 10 – (a) Glass sample S5 before heat treatment, (b) Glass sample S5 heat treated at 700°C for 4 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

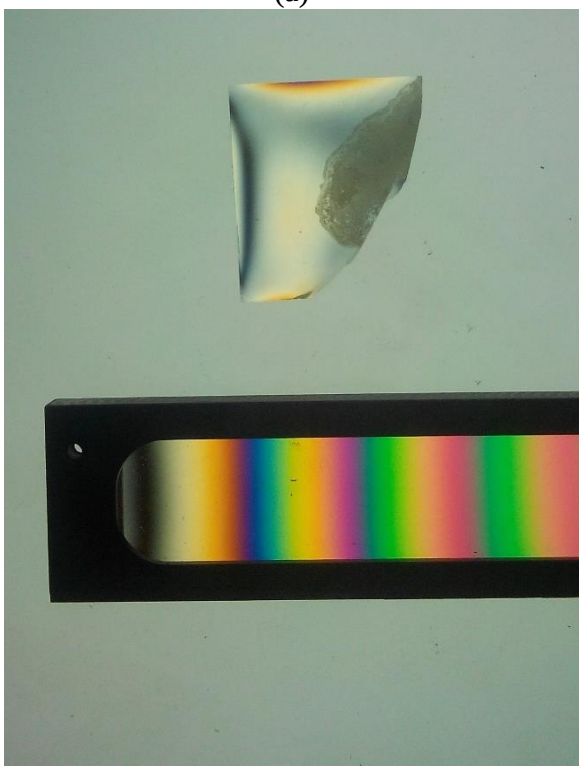
Average crack length before heat treatment is 61.116 µm and average crack length after heat treatment is 18.057 µm. There is a decrease in **70.45 %** of crack length. The regenerative compressive stress on the glass surface is **93.46 MPa.**



(a)



(b)



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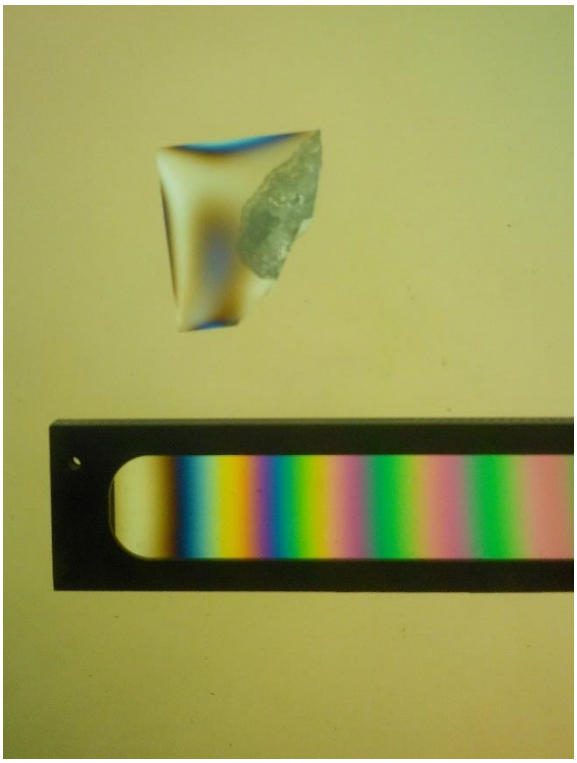
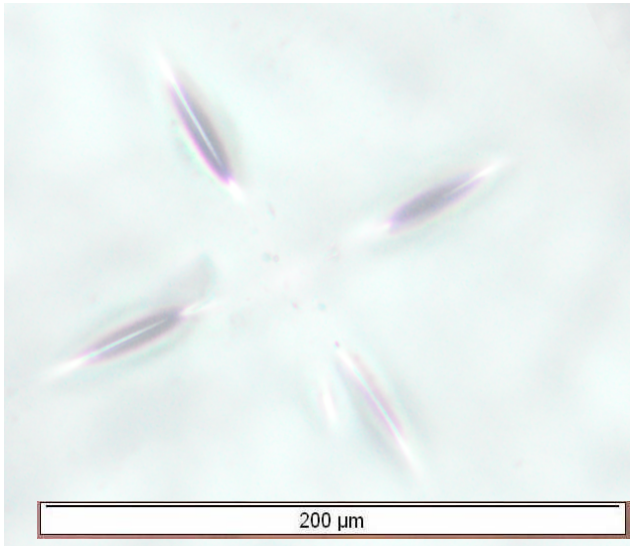


(d)

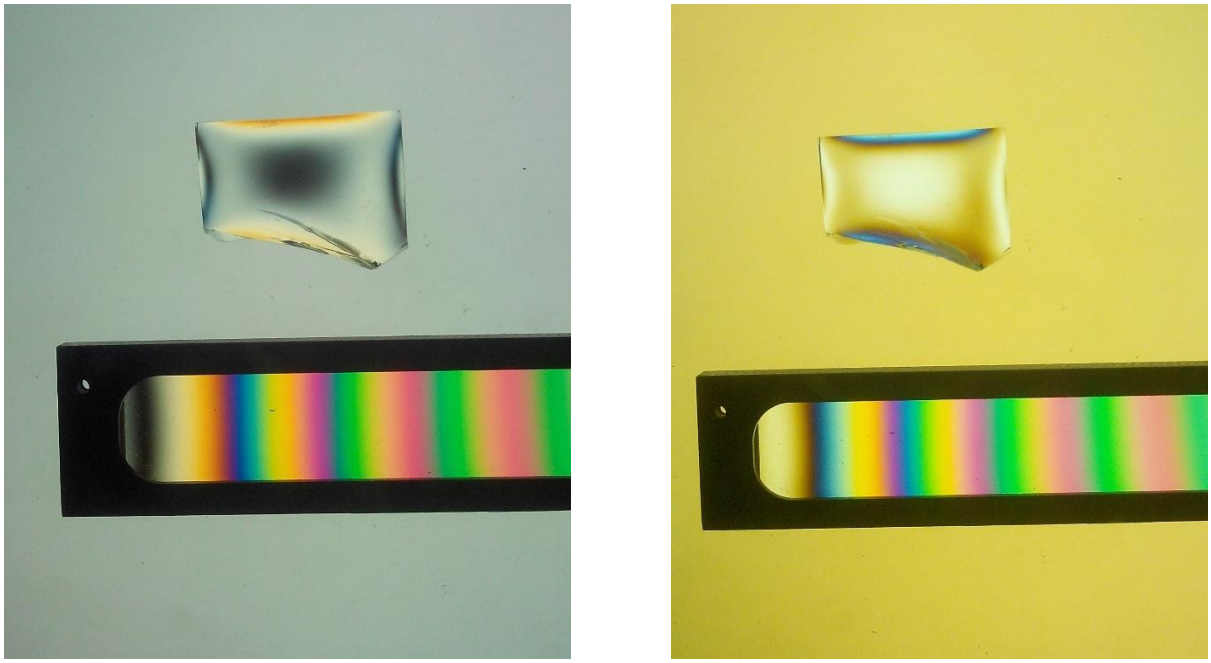
Fig. 11 – (a) Glass sample S6 before heat treatment, (b) Glass sample S6 heat treated at 700°C for 4 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

Average crack length before heat treatment is 67.856 µm and average crack length after heat treatment is 20.535 µm. There is a decrease in **69.736 %** of crack length. The regenerative compressive stress on the glass surface is **92.88 MPa.**

(a)



(b)



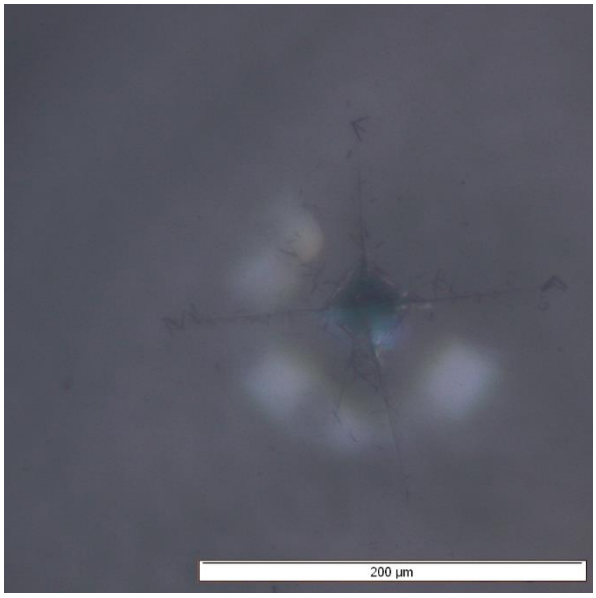
(c) (d)

Fig. 12 – (a) Glass sample S15 before heat treatment, (b) Glass sample S15 heat treated at 700°C for 4 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

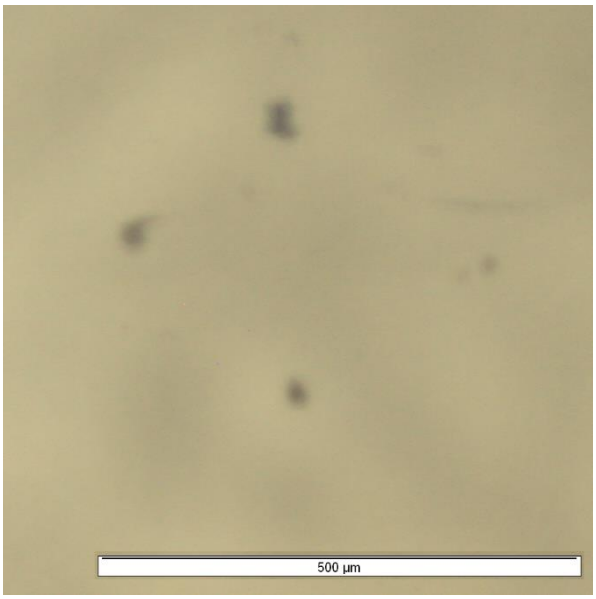
Average crack length before heat treatment is 78.571 µm and average crack length after heat treatment is 21.428 µm. There is a decrease in **72.727 %** of crack length. The regenerative compressive stress on the glass surface is **94.04 MPa.**

Heat treating at 700°C for 4 hours results a great decrease in crack length by nearly 70 %. Fig. 10, 11, 12 shows pinching of crack and a high stress distribution on the surface. A tensile load first has to overcome the compressive stresses and then damage the sample. But this does not take place due to there is a slight presence of crack.

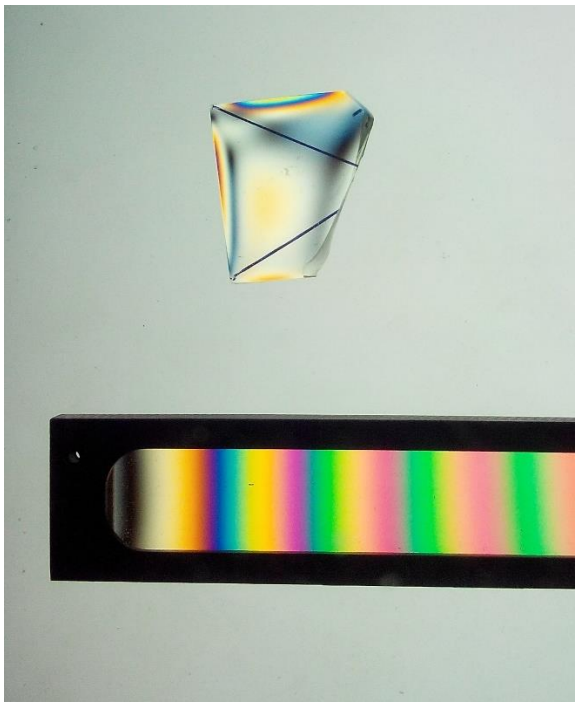
4.2.4 HEAT TREATMENT AT 700°C FOR 6 HOURS



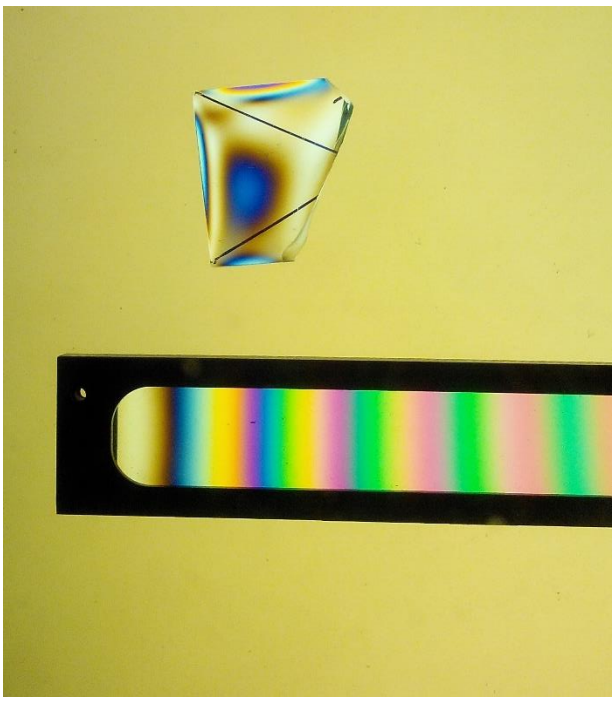
(a)



(b)



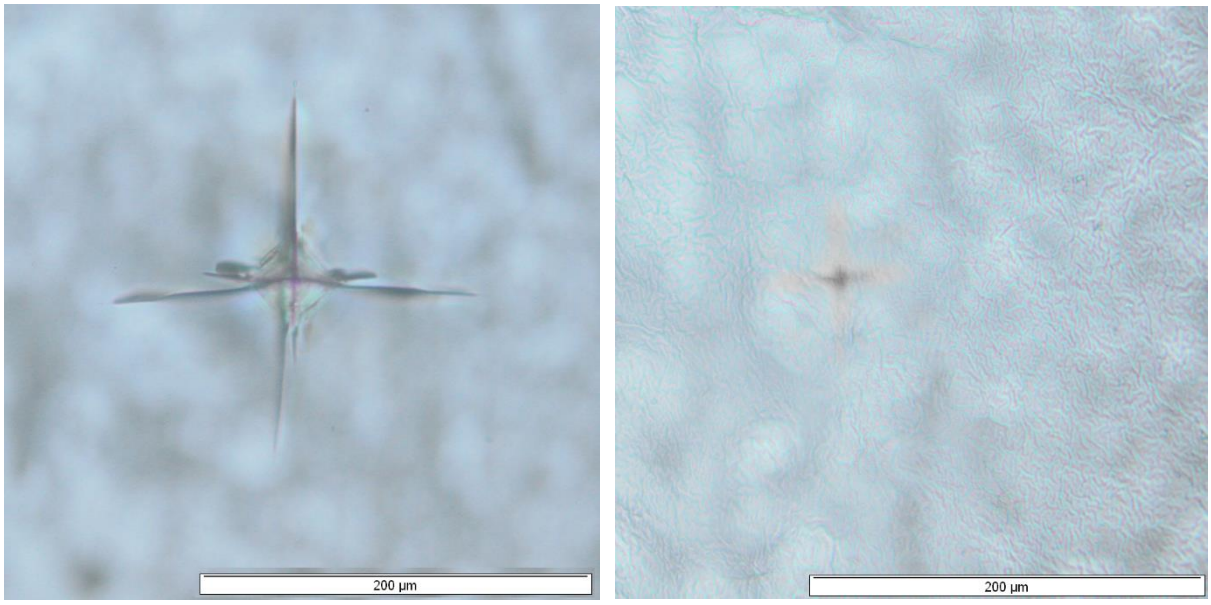
(c)



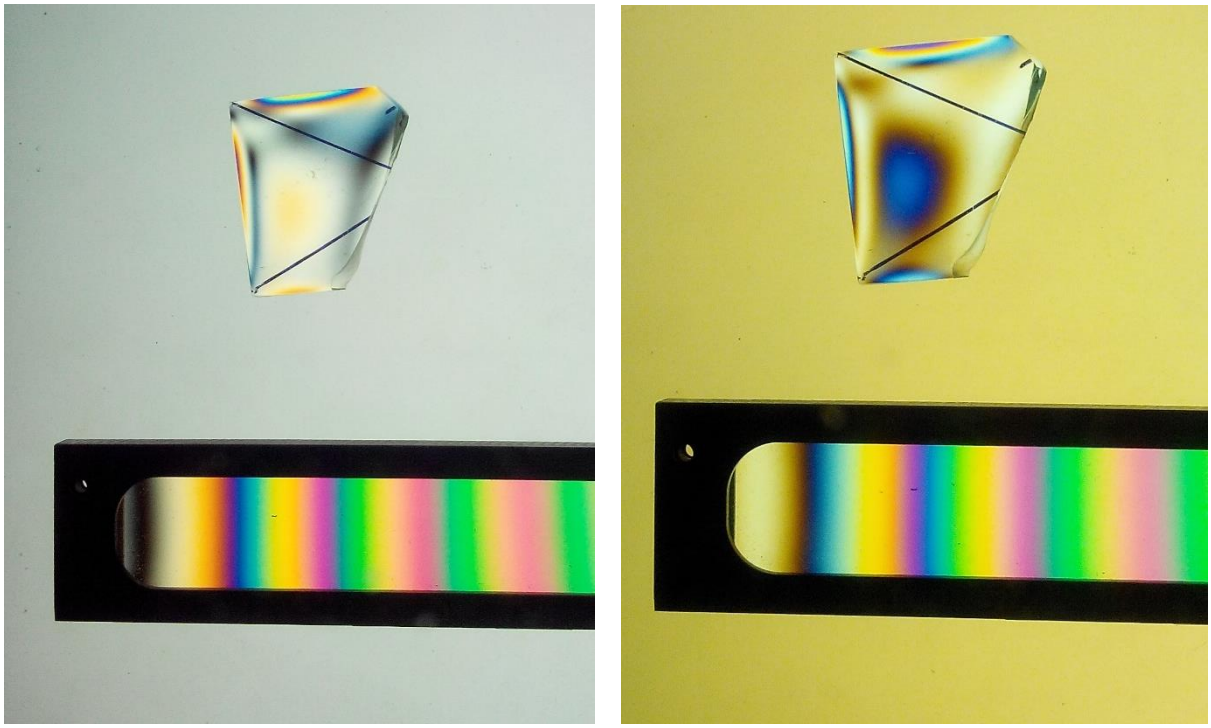
(d)

Fig. 13 – (a) Glass sample S9 before heat treatment, (b) Glass sample S9 heat treated at 700°C for 6 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

Average crack length before heat treatment is 75.892 µm and average crack length after heat treatment is 10.714 µm. There is a decrease in **85.88 %** of crack length. The regenerative compressive stress on the glass surface is **95.80 MPa.** The indentation mark vanishes in this sample and there is cylinderization of crack which can be seen from Fig. 13 (b), shows a hole structure. In this extension of blunting may surely increase the strength of the glass.



(a) (b)



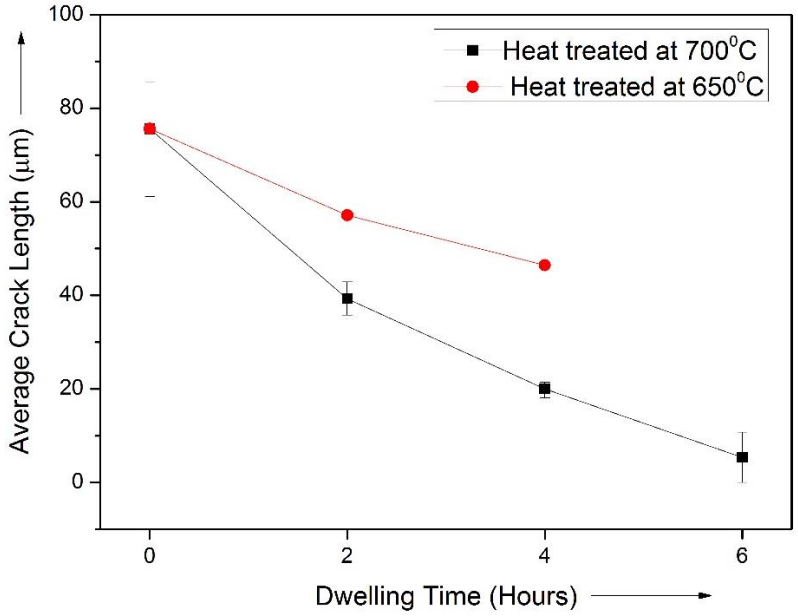
(c) (d)

Fig. 14 – (a) Glass sample S8 before heat treatment, (b) Glass sample S8 heat treated at 700°C for 6 hours, (c) Compressive stress distribution on glass sample after heat treatment when analyser reading is 0, (d) when stress covers Point of Interest (POI)

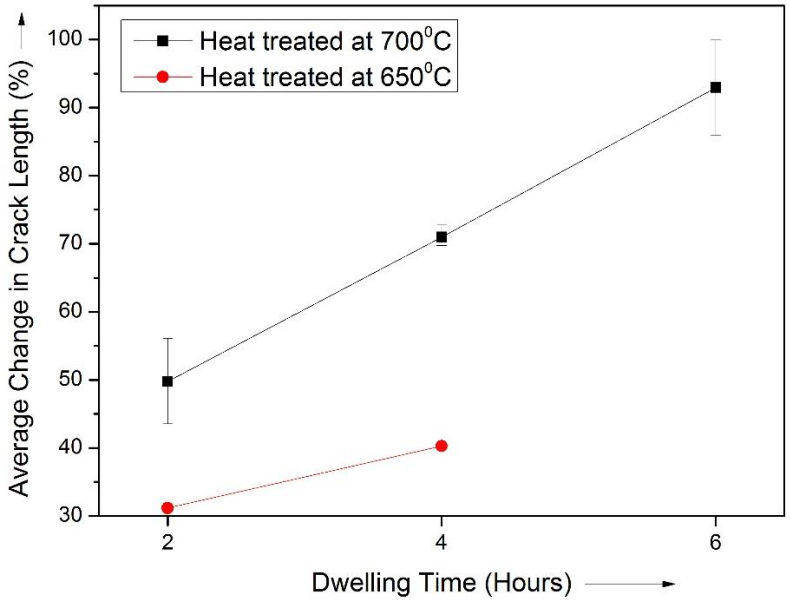
Average crack length before heat treatment is 76.785 µm and average crack length after heat treatment is 0 µm. There is a decrease in **100 %** of crack length. The regenerative compressive stress on the glass surface is **96.07 MPa.** The crack and indentation disappears when the glass is treated for 6 hours.

Dwelling for 6 hours gives a very high regenerated compressive stress of around 96 MPa which is compressive stress for a toughened glass. Thus the glass is healed and the corresponding strength also increases.

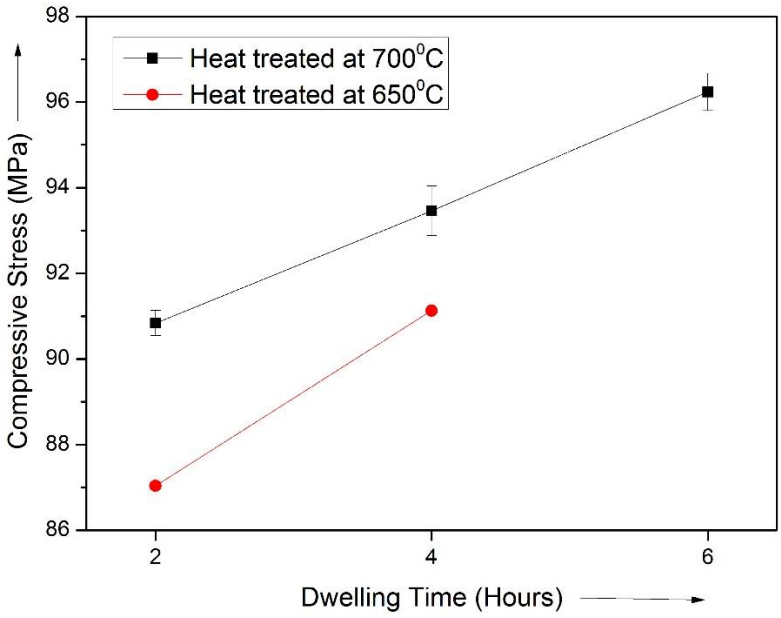
4.2.5 COMPARATIVE STUDY OF CRACK LENGTH AND COMPRESSIVE STRESS WITH RESPECT TO DWELLING TIME



(a)



(b)



(c)

Fig. 15 – (a) Average crack length vs Dwelling Time, (b) Average change in crack length vs dwelling time, and (c) Compressive Stress vs dwelling time

We can see from the Fig. 15 (a) that on increasing the dwelling time the crack length decreases rapidly. But the rate of decrease in crack length at 650°C is lower than 700°C. Fig. 15 (b) shows percentage change in crack length where it can be seen that a change of 45 % to 100 % of crack length takes place.

On increasing the dwelling time more time is available to the viscous glass to have a capillary rise to the crack depth. It first fills the crack tip and indentation where stress is very high. Then if further time is provided then spheroidization and cylinderization of crack takes place [8]. The depth of crack decreases results a lower uneven stress in that region.

Fig. 15 (c) shows the dependence of regenerated compressive stress with respect to dwelling time. As dwelling time increases there is an increase in compressive stress.

But compressive stress should depend on the rate of quenching. In this case there is a high viscous flow not only from the surface but also from the material below, a high dwelling time provides a higher amount of viscous glass on the surface and this extra amount of glass results into a high compressive stress.

4.3 FLEXURAL STRENGTH

The flexural strength of the glass samples, carried out by three point bending test, before thermal treatment is given in the Table – 4.

Sample	Width (mm)	Height (mm)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Maximum Load (N)
S1	29.90	3.82	51.4	19789	427.3
S11	24.12	3.82	62.4	21630	418.7

Table 4 – *Flexural Strength on intended glass samples without heat treatment*

The average flexural strength of the glass is **56.9 MPa**. This is due to presence of a crack on the surface of the glass. On heat treatment by thermal tempering method where regeneration of compressive surface stress occurs, the flexural strength of the glass samples is given in Table – 5.

Sample	Width (mm)	Height (mm)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Maximum Load (N)
S3	30.60	3.76	73.6	17382	607

S5	28.60	3.72	89.9	26614	678
S6	29.62	3.72	79.2	24153	618
S8	30.18	3.82	124.6	22946	1045
S12	26.68	3.72	39.58	19765	278.3
S13	27.60	3.74	68.5	22807	504
S10	28.54	3.72	74.5	22097	560.5
S9	27.80	3.74	110.1	19876	815.5
S15	28.64	3.74	83.2	23504	634.8

Table 5 - *Flexural Strength on intended glass samples after heat treatment*

The flexural strengths have greatly increased on thermal tempering of cracked glass. And this increase is directly proportional to the dwelling time. The change in flexural strength with respect to dwelling time is shown in Fig. 16.

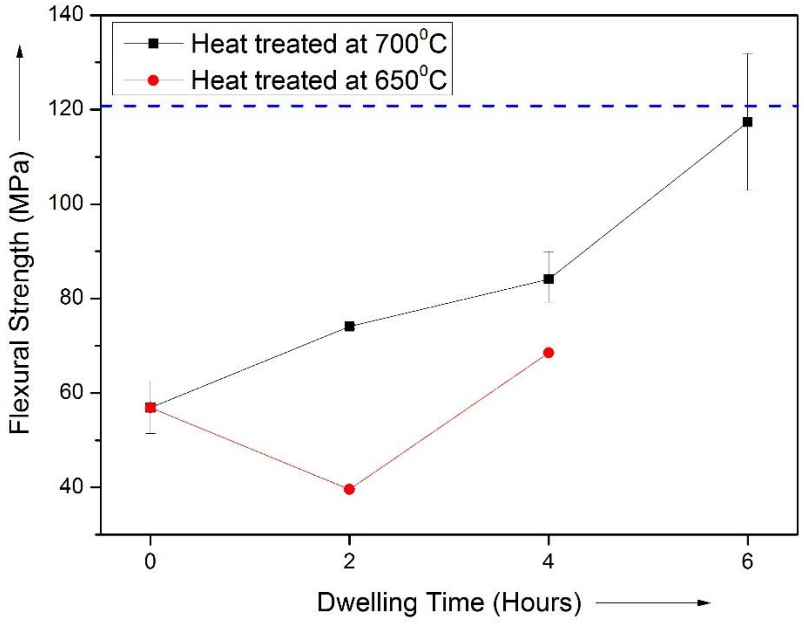


Fig. 16 – Flexural Strength vs dwelling time

As we can see from Fig. 16 that on heat treating at 650C the strength of the sample initially decreases and the increases. This is due to sharp crack tips on the glass surface which has not been blunt. This decreases the strength of the sample. As there is presence of very high compressive stresses, the flexural strength increases. When the crack is totally healed the flexural strength increases by two folds.

4.4 COMPARATIVE STUDY

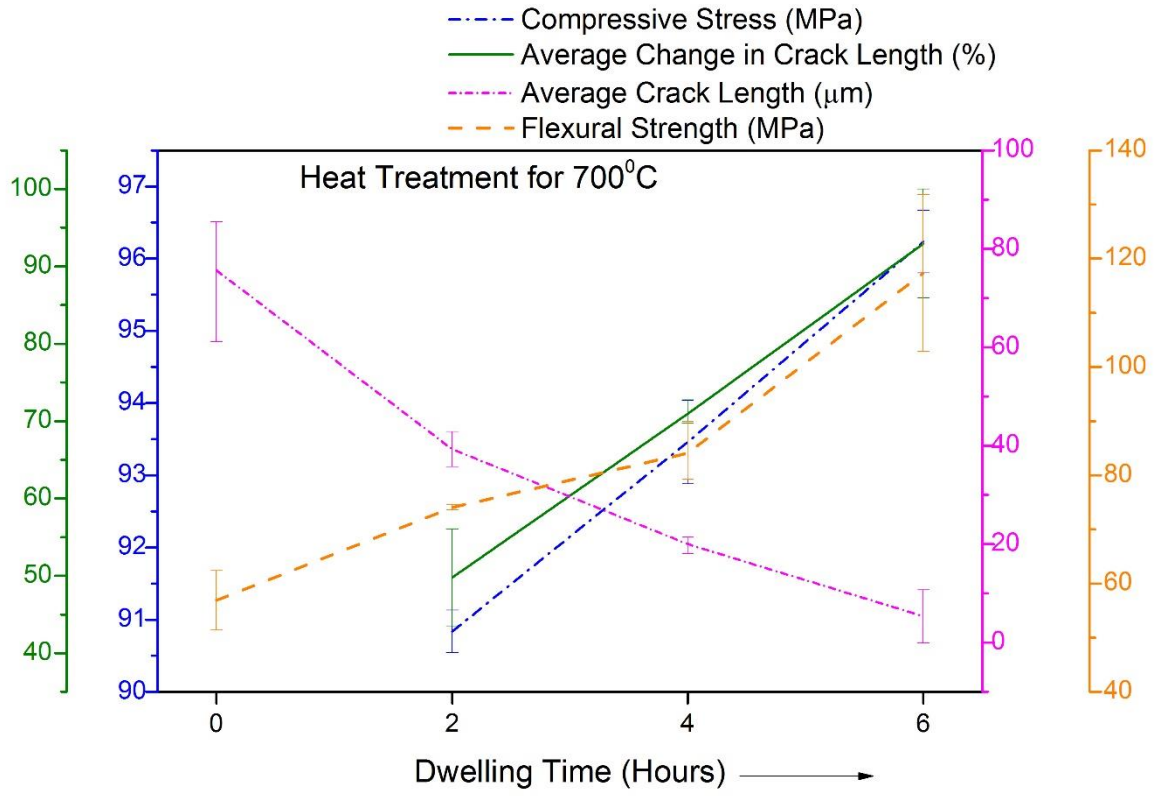


Fig. 17 – Comparison of compressive stresses, average crack length, average change in crack length and flexural strength with respect to dwelling time on heat treatment at 700C

Fig. 17 shows an overall comparison of crack length, flexural strength, and compressive stress with respect to dwelling time. It can be seen that flexural strength, average change in crack length and compressive stress is directly proportional to the

dwelling time. When dwelling time is 6 hours there is complete crack clouser. Flexural strength is increased by two times which suggests that there is both crack clouser and formation of toughened glass. The stress on the surface is higher in the centre of the glass and corners have the lowest stress. Due the irregular surface of the crack, viscous glass flows to the crack depth, by gradient in surface glass concentration, causing fill up of cavities results in crack clouser. This phenomenon is assisted with the help of sudden quenching that arrests those structures kin that position. Hence a high dwelling time causes lowering of viscosity of glass and increase in capillary pressure for rounding off the fine crack tip occurs.

5

CONCLUSION

From the present work it can be concluded that

1. Tempering method can effectively be used for healing of the crack
2. There was low viscous flow on the surface of glass due to high viscosity at 650°C
3. At 700°C the crack tips tend to blunt and spheroidization of crack occur
4. On increasing the dwelling time there was more viscous flow on the edges of the crack that result into the pinching of the crack tip
5. The sample S8 shows a full crack clouser and showed strength nearly same as the original glass which was heat treated at 700°C for 6 hours
6. This was a result of both viscous flow on the surface of glass and generation of compressive stresses
7. The thermal treatment method requires minimum 24 hours for full crack clouser but in thermal tempering 6 hour dwelling at 700° results a full crack clouser

5

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