Number 7 Volume 19 July 2013 Journal of Engineering

Numerical Simulation of Temperatures Distribution and Residual Stresses of High Melting Temperature Polymer

Dr. Nizar Jawad Hadi (Lecturer) / Faculty of Materials Engineering/ Babylon University
Email:nizarjawadhadi@yahoo.com

ABSTRACT:

This work predicts the effect of thermal load distribution in polymer melt inside a mold and a die during injection and extrusion processes respectively on the structure properties of final product. Transient thermal and structure models of solidification process for polycarbonate polymer melt in a steel mold and die are studied in this research. Thermal solution obtained according to solidify the melt from 300 to 30 $^{\circ}C$ and Biot number of 16 and 112 respectively for the mold and from 300 to 30 $^{\circ}C$ and Biot number of 16 for die. Thermal conductivity, and shear and Young Modulus of polycarbonate are temperature depending. Bonded contact between the polycarbonate and the steel surfaces is suggested to transfer the thermal load. The temperatures distribution produces in thermal model importing as load and boundary conditions to solve the structure model. 3D mold and die are built to simulate the thermal and structure behavior using ANSYS 12.1 program. The results show that the temperatures and residual stresses decreases with the distance from the center to surfaces for the mold ,while for the die the temperatures and stresses decreases with the distance from the inlet to the outlet. The temperatures and stresses decreases with the time increasing for both mold and die. Also the thermal strain compatible with the temperatures distribution in the mold and the die. The total deformation concentrated at the left and right edge of polycarbonate in the mold, while starting in the center of the polymer at the outlet and then transfer to the entry of the die with the time increasing.

KEYWORDS: Mold and Die, polymer melt, Thermal transient, and Residual stresses.

نمذجه عدديه لتوزيع درجات الحرارة والإجهادات المتبقية في اللدائن ذات درجات الانصهار العالية

د.نزار جواد هادي(مدرس)/ كلية هندسة المواد/ جامعة بابل

الخلاصة:

هذا البحث يخمن تأثير توزيع الحمل الحراري في منصهر اللدائن داخل قالب الحقن والبثق على المواصفات الميكانيكية للمنتج النهائي. يدرس في هذا البحث نموذج حراري وميكانيكي متغير مع الزمن لعملية تصلب منصهر البولي كاربونيت في قالب حقن وبثق مصنوع من الفولاذ. الحل الحراري يستنتج استنادا الى تصلب المنصهر من 300 الى 30م ورقم Biot 16 و112 على التوالي لقالب الحقن وتصلب من 300 الى 30م ورقم Biot 16 لقالب البثق. الموصلية الحرارية وثابت القص للبوليمر يتغير مع درجة الحرارة وتماس من نوع Bonded يحصل بين البولي كاربونيت والفولاذ لنقل الحرارة بين المادتين.توزيع درجات الحرارة الناتج في النموذج الحراري ينقل كحمل وظروف محيطية لحل النموذج الميكانيكي.قالب حقن وبثق ثلاثي الابعاد بني ليحاكي التصرف الحراري والميكانيكي باستخدام برنامج ANSYS 12.1. أظهرت النتائج ان الحرارة والاجهاد المتبقي يقل مع المسافة من المركز الى السطح للبولي كاربونيت ومع الزمن في قالب الحقن.اما بالنسبة لقالب البثق فان الحرارة والاجهاد يقل من المدخل الى المخرج ومع الزمن.كذلك الانفعال الحراري يتوافق مع توزيع درجات الحرارة لقالب الحقن والبثق في حين ان التشوه الكلي يتركز في الحافه اليمنى واليسرى وفي مركز مقدمة البولي كاربونيت في قالبي الحقن والبثق على التوالي.

الكلمات الرئيسية: قالب مغلق وقالب مفتوح، منصهر لدن، تغير درجة الحرارة مع الزمن واجهادات متبقية.

INTRODUCTION:

The relation between the quality and mass production of the final polymer products depends on the solidification process and cooling rate. The style of thermal behavior and temperatures distribution during cooling process strongly affected on the mechanical properties of polymer. Parts made of polymeric materials may be simulate in order to minimize the residual stresses.

Computer Aided Engineering analysis provides insights useful in designing parts mold and molding process[Alexandra,2003].During cooling the polymer from elevated temperature to room temperature, strain became" frozen-in" the material. These frozen in strains leads to residual stresses and distortions of the final product. A residual temperature field is introduced to describe the relationship between thermal history and frozen-in strains,[Vlado,2001].The state of internal stresses has been analyzed by means of photo elastic method (used stress viewer equipment) on the basis of layout and size of the isochromatics (field with the same color), which determine the pieces areas where the same value for the difference of main tensions, [Postawa,2006] .The most problems encountered when molding polymeric parts are the control and prediction of the components shape at room temperature. The resulting sink marks in final product are caused by the shrinkage of the material during cooling and curing. Warpage in the final product is often caused by processing conditions that cause unsymmetrical residual stress distributions through the thickness of the part. Thermoplastic parts most effected by residual stresses are those that are manufactured with injection molding process. The size of the frozen in free volume depends on the rate at which a material is cooling, high cooling rates results in a large free volume, also when the frozen in free volume is large the part is less brittle. When extruding amorphous thermoplastic profiles the material can be sufficiently cooled inside the die so that the extrudate has enough rigidity to carry its own weight, [Tim,2003].The solidification of molten layer of amorphous thermoplastic between cooled parallel plates is used the mechanisms of part warpage in the injection process. The model allows material to be added to fill the space created by the pressure applied during solidification, [Wit,1996]. The solidification of molten layer of amorphous thermoplastic between cooled parallel plates is used to model the mechanics of part shrinkage and the built up of residual stresses in the injection molding processes [Wit,1995]. The accurate prediction shrinkage warpage of injection molded parts is important to achieve successful mold design with high precision. The numerical analysis of shrinkage and warpage of injection molded parts made of amorphous polymers was carried out in consideration of the residual stresses produced during the packing and cooling stages of injection molding. The temperature and pressure fields were obtained from the coupled analysis of the filling and post filling stages. For residual stress analysis, a thermo-rheologically simple viscoelastic material model was introduced to consider the stress relaxation effect and to describe the mechanical behavior according to the temperature change, [Du,1999]. High density polyethylene specimens were obtained by standard extrusion and also by a procedure of solidification from a highly deformed melt in a wide range of temperature, time $^{\circ}C$,[Yu,1995]. The recoverable strain magnitude and the rate of strain recovery have been measured as a function of applied shear rate, temperature, and molecular weight. [Bryce,1979].Experiment on polystyrene coating cast from toluene have shown that residual internal stresses is independent of dried coating thickness and initial solution concentration.,[Croll,1979]. The larger removal method was used to measure the residual stresses at a thin walled test sample by milling machine. [Tong,2005].

Polycarbonate (PC) is an amorphous thermoplastic known for its stiffness, toughness and hardness, and its optical properties and high surface close. When injection molding PC , the pellets must be dried before molding for 10 hours at about 30 C . The melting temperature should be between 280 to 320 C, and the mold temperature between 85 to 120 C, typical applications for injection molded polycarbonate parts are telephone housing, lenses for glasses and optical equipment, camera housing, [Tim, 2003].

This work aims to predict the residual stresses in polymer during the solidification process in injection mold and extrusion die. Three dimensional model is built to simulate the transient heat transfer and t Line 2 structure behavior of polycarbonate polymer melt using ANSYS 12.1 program. Bonded contact between the melt and steel mold and die is suggest to transfer the heat and coupling technique used to importing the load from thermal to structure solution.

MODELING:

Table(1): Shows the nodes numbers, elements numbers, elements types name, and mechanical APDL name in the mold and die respectively**.** **Fig.(1,a and b)** represents mesh, boundary conditions and the geometry of steel mold 24*22*6 mm, and mesh, and the geometry of steel die 30*22*6 mm respectively. The dimensions of Polycarbonate melt 20*20*4 mm in the mold and 30*20*4 in the die . The specifications of the mesh can be obtained using the finite element modeler .

The setting of mesh: Physics preference = mechanical, relevance=100,
Relevance center, smoothing, and span angle center = medium., Minimum edge length= 4, Transition ratio=0.272 , Growth rate=1.2

Fig.2a,and b, show the cross section of the mold at the center along X coordinate and the cross section of the die at the center along Z coordinate. The qualitative results such as temperatures distribution, Von-Mises stresses, thermal strain, and total deformation at different times are obtained in these cross section for the mold and the die along **line 1 (4mm)** at x axis and **line1(30mm)** at z axis respectively. The relations between the temperature and Von-Mises stress and the dimensionless distance are drawing along **line (1)** in the mold, the behavior of the maximum temperatures and the maximum stresses at the same line with the time are obtained also. The temperatures and stresses behavior with the time at different locations along **line 1** at x axis starting from the center at x=0 to the surface at x=2mm are determined.

Initial and boundary conditions:
At time = 0, the temperature of polycarbonate melt =300 C, and the mold and the die= 85 C.
The boundary conditions at the surfaces of the mold and the die are producing by equating the Fourier and Newton's laws of cooling.

Material Properties:

The thermal and mechanical properties of the steel and polycarbonate are illustrated in **Table2** and **Fig 3. a and b**.

THERMAL MODEL:

The thermal behavior is expressed mathematically in numerical analysis. This expression consists of initial condition, polymer response and interaction between the polymer and cooling fluid. The conventional energy conservation equation:

$$\frac{d}{dx}\int_V \rho cTdV = -\int_s n.qds + \int_v hvdV. \qquad (1)$$

Where V is the volume of polymer melt covered by surface S with outward normal vector n.T is temperature, c is specific heat capacity, ρ is density , q is heat flux vector and hv is the intensity of the volumetric heat source .The Fourier heat conduction law is:

$$q = -k\nabla T \qquad (2)$$

∇T is the temperature gradient vector:
Substitute eq.(2) in eq.(1) to find:

$$\frac{d}{dx}\int_V \rho cTdV = -\int_S n..(k\nabla T)dS + \int_V hvdV.) \qquad (3)$$

Eq.(3) integral form of energy conservation .The residual stresses prediction depends on the thermal history solution T(s,t) , where s any point at time instant t. In continuum mechanics, it is usually describe the energy conservation equation in the differential equation. The surface term in eq.(3) can be transformed into a volume term using of Gauss divergence theorem.[Guojun,2004 and Saso, 2008]

$$\frac{d}{dx}\int_V \rho cTdV = -\int_V n..(k\nabla T)ds + \int_V hvdV. \qquad (4)$$

$$\frac{\partial(\rho cT)}{\partial t} = \nabla.(k\nabla T)+hv \qquad (5)$$

Fourier law and Newton's law of cooling are equating to find the boundary conditions in x direction:

$$-k\frac{\partial T}{\partial x}+hT=0....at...x=-L \qquad (6)$$

$$k\frac{\partial T}{\partial x}+hT=0....at...x=L \qquad (7)$$

In sheet or plate polymer formation by injection mold the unsteady one dimension heat conduction equation is assumed for thermal transient solution. In present study unsteady three dimensions heat conduction equation is assumed to predict the temperature distribution.

$$\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}+\frac{\partial^2 T}{\partial Z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (8)$$

Where T= Temperature (K),t= Time (Second).,

α =Thermal diffusivity ($\frac{m^2}{S}$).

Thickness (X direction)of the polymer melt in the mold and length (Z direction) of the polymer melt in the die are used to test the temperatures and stresses distribution with distance and time. The Biot number (Bi) is used in heat transfer of the polymers as indicator of cooling rate value. High cooling rate produce high Biot number and low cooling rate produce low Biot number:

$$Bi=\frac{hL}{k} \qquad (9)$$

Where**:** h is heat transfer coefficient in watt/$m^2.\circ C$ and k is thermal conductivity coefficient in watt/$m\ .\circ C$ and L is the thickness dimension of polymer in mm(x in the mold and z in the die).

The heat conduction equation (1) is solved in two cases:

(a) For the mold at 85 C the polycarbonate melt solidifies from 300$^\circ C$ to 30$^\circ C$ with Biot number 16, and 112 at 0.1, 0.5, 2, 4, 8,16.20,28 and 40 second. The heat transfer coefficient of 0.001 and 0.007 watt/$m^2.\circ C$ respectively are used in this case.

(b)For the die the polycarbonate melt solidifies from 300 $^\circ C$ at the inlet to 30$^\circ C$ with Biot number 16, at 0.1, 2, 4, 8,16 and 40 second. The heat transfer coefficient of 0.001 watt/$m^2.\circ C$ is used in this case.

Water used as cooling liquid for the mold and the die. Bounded contact is activated between the polymer melt and steel .Qualitative and quantitative temperatures distribution are obtained at different times along line 1 for mold and die.

Coupling and Importing Load:

The solution is transfer from the thermal to structural model as shown in **Fig.(4a).** This process includes importing the load from the first to second model as indicated in **Fig.(4b).**

STRUCTURAL MODEL:

The qualitative and quantitative solutions of Von Mises stresses, along line 1 in the mold are predicted according to the temperatures distribution for each time in thermal solution**,** also the thermal strain and total deformation analyzed qualitatively. Free surface displacement and stress of polymer melt out of the steel die are investigated. While Von-Mises stress, thermal strain, and total deformation are predicted along line 1 in the die solution The residual stresses of thermoplastic polymer in solidification process is depend on temperature, space, thermal properties, elastic properties and time[Johanna,2011]:

$$\sigma=\sigma(T_i-T_f,T_g-T_f,L,X,\beta,K,h,\alpha,E,\nu,t) \qquad (11)$$

β thermal expansion coefficient, The final residual stress can be expressed as:

$$\frac{\sigma(1-\nu)}{E}=f(B_i,\overline{X}\ ,\varepsilon_T) \qquad (12)$$

$\overline{X}$ dimensionless coordinate: $\frac{X}{L}$,, T_g =Glass transition temperature,, T_f =Mold or die temperature.,, T_i =Initial temperature

ε_T thermal strain= $\beta(T_g-T_f)$

$T_f=T_g,,,,,,\varepsilon_T=0$

$T_i=T_g,,,,,,,\varepsilon_T=Maximum$

$\sigma = Stress$, $\nu =$ Poison ratio, E =Yong modulus

RESULTS AND DISCUSSION:

Injection Mold:

Fig.(5 and 6), show the temperatures, stresses , thermal strain, and total deformation distribution during the solidification process of polycarbonate melt at cross section along line 1 for 4 seconds cooling and Biot number 16 and 112 respectively .The maximum temperature, stress and thermal strain localized at the center of the mold and reduce gradually towards the surfaces of the polymer and the total deformation concentrated at the left and right edge. This behavior repeated at each time and decreases with time till reach the time were the polymer and the mold temperatures approximately the same. The most significant change in temperature , stress , thermal strain, and total deformation are across the thickness of the polymer along line 1 in x direction ,which is the lower distance and high heat flow compared with the other two dimensions.. The manner of temperatures change from the center to the surface produces a specific temperature difference and thermal gradient, which in turn strongly effect on the stress change from the center to the surface of the polymer .The maximum stress at the center generates tensile stress and minimum stress at the surfaces leads to compression stress and this may creates structural and mechanical defects for example cracks growth at the center of the polymer and bending moment. The temperatures, Von-Mises stress, thermal strain , and total deformation at Biot number 112 are less than that for Biot number 16 because of low Biot number produces slower cooling system for solidify the inside polymer zones than that of high Biot number. Slower cooling rate develops slower temperature gradient and stiffer regions than that of faster cooling rates.

Fig.(7 and 8), show the temperatures, stresses , thermal strain, and total deformation distribution during the solidification process of polycarbonate melt at cross section along line 1 for 16 second cooling and Biot number 16 and 112 respectively There is no change in general behavior in temperatures and stresses distribution and the inside regions of polymer slower cooling than surface due to the low thermal conductivity of polycarbonate. For the polymer the value of temperature and stress increased from the surface towards the center. Also the maximum value of thermal strain localized in a smaller zone than that at 4 seconds at the center of the mold and reduce gradually towards the surfaces and the total deformation again concentrated at the edges with desecrated zones. At the sixteenth second the temperatures, stresses, thermal strain , and total deformation at Biot number 112 are less than that for Biot number 16 due to the same reason in **figures 5 and 6**. Also the temperatures and stresses in 16 second is less than that for 4 seconds due to the time increasing. This results visualized qualitatively the effect of cooling rate and Biot number on the thermal and structural behavior.

Thermal strain distributions combatable with the temperatures distribution of the polycarbonate melt at 4 and 16 second.

Figs.9 and 10, show the temperatures variation with the dimensionless distance from the bottom to the top a long line 1 during the solidification process in the polycarbonate melt at 0.1, 0.5, 2,4, 8,16, 20 and 24 second for 16 and 112 Biot number respectively. The temperatures distribution indicates that the maximum value at the center of polymer melt and then decreases toward two ends of the polymer surface at each time. In general the temperatures decrease with the time increasing and the temperature gradient decreases with the time increasing from 0.1 to 24 second and towards the center in each times. The temperature gradient and the decreasing in the temperatures values in **Fig. 10**, are bigger than that in **Fig.9** due to the increasing in Biot number from 16 to 112.Also the drop of the temperatures from the center zone towards the surfaces at Biot number 112 is faster than that at Biot number 16 due to the high cooling rates.

Figs.11 and 12, show the stresses change with the dimensionless distance from the bottom to the top along line 1 during the solidification process in the polycarbonate melt at 0.1, 0.5, 2,4, 8,16, 20 and 24 second for 16 and 112 Biot number respectively. The stresses distribution indicates that the maximum value at the center and then decreases toward two ends of the polymer surface from 0.5 to 24 second, while for 0.1 second the stress decreased at the center . In general the stress decrease with the time increasing and the drop of the stress decreases with the time increasing from 0.5 to 24 second and towards the center in each times. The stresses distribution strongly affected by temperatures distribution , temperature gradient and cooling time. At 2,4,and 8 second the drop of the stresses are faster and the middle region are less stable at low time in **Fig.12** than that in **Fig.11**. Higher stresses induced along the line 1 at different times with Biot number 16 than that of Biot number 112. These results have a good agreement with that of [Vlado,2001].

Figs.13 and 14, show the maximum and minimum temperatures behavior with time during the solidification process of the polycarbonate melt for 16 and 112 Biot number respectively. For Biot number 112 the decreasing in the maximum temperatures is faster and the time consumed to be stable is lower (11.17second) than that for Biot number 16 (15 second) due to the increasing in Biot number. The minimum temperatures indicate more stability and starting with lower temperature in **Fig.14** than that in **Fig.13** due to high cooling rates .The time required to reach a certain temperature during cooling process can be predicted.

Figs.15 and 16, show the maximum temperatures behavior with time along line 1 during the solidification process of the polycarbonate melt at 0.1, 0.5, 2,4, 8,16, 20, 28 and 40 second for 16 and 112 Biot number respectively. The temperatures decrease with the time increasing from 0.1 to 40 second. The temperatures and thermal gradient rapidly drop from 0.5 to 16 second in **Fig.16** than that in **Fig.15** due to the increasing in Biot number and cooling rate, while the drop is slowly from 16 to 40 second.

Figs.17and 18, show the maximum stresses behavior with time along line 1 during the solidification process of the polycarbonate melt at 0.1, 0.5, 2,4, 8,16, 20, 28 and 40 second for 16 and 112 Biot number respectively. The stress increases with time increasing from 0.1 to 2 second and then decreases with the time increasing from 2 to 40 second. The stress rapidly drop from 2 to 16 second in **Fig.18** than that in **Fig.17** due to the increasing in Biot number while the drop is slowly from 16 to 40 second. For example at time 8 second with Biot number 16 the stress is above100, while at the same time and with Biot number 112 the stress is below 100, due to the slower cooling occurs at lower Biot number, which make the polymer stiffer than that in higher Biot number .

Fig.19 shows the temperatures decreasing with the time along x axis at line 1 (line1=4mm). The dropping in temperature increases with the distance increasing from center of line 1(x=0) to the surface of polymer due to the cooling rate around the surface and low thermal conductivity of polymer. The difference in temperatures between the center and the surface seems to be less after 16 second, while the maximum difference occurs between 2 and 4 second specially from x=1.5 to x=2mm, near the surface. The temperatures distribution in **Fig.19** is directly affected on stress decreasing with time in **Fig.20**. The difference in stresses became more stable after 16 second than that between 2 and 4 second .The high the stress difference obtained at the surface is due to the high temperature difference at the same region. The temperature is slowly decreases at x=0 than that at x=2mm,therfore the polymer is stiffer and induced higher stress value at x=0 than that at x=2mm.

Extrusion Die:

Fig. 21a, Indicates the temperatures distribution in the cross section along Z direction at 0.1, 2, 4, 8, 16,and 40 second and Biot number 16 . The temperature decreases from Inlet to outlet of the die for each time with distance increasing towards outlet. Also the drop of temperature increases with the time increasing at the starting region of the die as pointed in the figure after that the temperature more stable. **Fig.21b**, shows the Von-Mises stresses distribution at the polymer surface out of the die. The maximum stress concentrated at the top and bottom edges of the outlet of the die, while the minimum stress at the center region of the polymer surface, also the magnitude of the stresses decrease with the time increasing. The free displacement of polymer out of the die associated with the stresses distribution for each time due to temperature distribution .The displacement and volume of polymer out of the die decrease with the front stress decreasing due to the time increasing, and that confirms with the results of[Tim,2003].

Fig.22, show the Von-Mises stress, thermal strain, and total deformation behavior of the polycarbonate melt at 4 and 16 second and Biot number 16. At 4 second The magnitude of Von-Mises stresses are fluctuated and then decreased to minimum value outside the die at 4 second, while at 16 second the stress decreases from inlet to outlet of the die, due to the temperatures distribution in **Fig.22a**. The maximum stress for 4 second is concentrated at the upper and the lower edges of the outlet and for 16 second is observed at the region close to the entry. The minimum stress is indicated at the front center of the penetrated polymer for each 4 and 16 second and the stress at 16 second is lower than that in 4 second. Thermal strain for 4 and 16 second compatible with the temperatures distribution in **Fig.21a** because its depends directly on the temperature and coefficient of thermal expansion. The total deformation zone concentrated between the maximum stress regions, which is at the outlet of the die at 4 second and after the entrance of the die at 16 second. The value of the total deformation decreases due to the stress decreasing.

CONCLUSIONS:

1-ANSYS 12.1 has the ability to active the coupling between transient thermal and transient structural models in polymer melt.

2-The thickness along X coordinate direction of the mold, and the length along Z coordinate direction have the more significant change in properties.

3-The residual stresses produced in the mold are bigger than that in the die. The temperatures drop rapidly from the center towards the surfaces of the polymer in the mold as Biot number increasing.

4-The temperature and stress increase from the surface towards the center of the polymer across line (1) in the mold, while decrease from inlet towards outlet of the die. The stresses at the front zone center of penetrated polymer , and volume of penetrated polymer out of the die decrease with the time increasing.

5-The thermal strain compatibles with the temperatures distribution for mold and die, also its magnitude reduces with the temperature difference decreasing and with the time increasing.

6-The maximum magnitude of the total deformation localized at the left and right edges of the mold and at the center zone of the penetrated polymer out of the die. The maximum total deformation zone discredited at the mold, while transferred to the entry in the die with the time increasing .

7- In thermal solution the temperature drops rapidly at low cooling time , while drops slowly with time increasing. The thermal and mechanical stresses is higher in the fast cooling than that in slow cooling.

8-The time required to reach the specific thermal and mechanical properties can be predict in this study. Different materials, cooling style, die and mold geometry and boundary conditions can obtained different properties.

9-The procedures of this work can be applied with the other polymer and metal materials.

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Table (1): Nodes numbers, elements numbers, elements types name, and mechanical APDL names for polymer and steel in the(a) mold model ,(b) die model.

a

(a) Bodies Summary

Body Name	**Nodes**	**Elements**
POLYMER	22915	4836
STEEL	29067	17106

Generic Element Type Name	**Mechanical APDL Name**
Quadratic Tetrahedron	Mesh200
Quadratic Hexahedron	Mesh200
Quadratic Quadrilateral Contact	Conta174
Quadratic Triangular Target	Targe170

b

(b) Bodies Summary

Body Name	**Nodes**	**Elements**
POLYMER	69111	15264
STEEL	64147	12291

Generic Element Type Name	**Mechanical APDL Name**
Quadratic Hexahedron	Mesh200
Quadratic Quadrilateral Contact	Conta174
Quadratic Quadrilateral Target	Targe170

Table(2): Thermal and mechanical properties of polycarbonate and stainless steel.

Materials	Stainless Steel	Polycarbonate
Thermal conductivity $W/m.^{\circ}C$	15.1	(Temperature Dependent) Fig.(3a)
Specific heat $J/kg.^{\circ}C$	480	552
Density (kg/ m^3)	7750	1200
Coefficient of Thermal expansion (C^{-1})	1.7E-0.5	0.00017
Young Modulus (Pa)	1.93E+11	(Temperature Dependent) Fig.(3b)
Poison ratio	0.31	0.43
Shear Modulus	7.3664E+10	(Temperature Dependent)

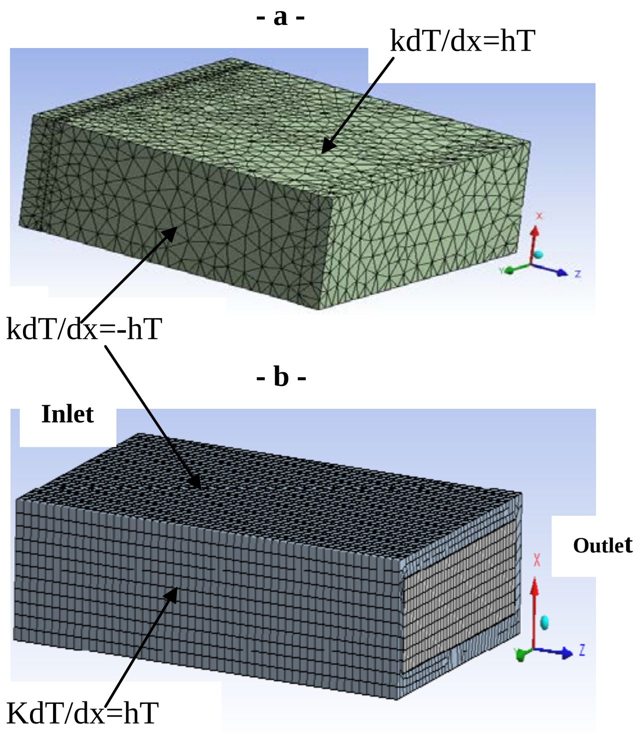
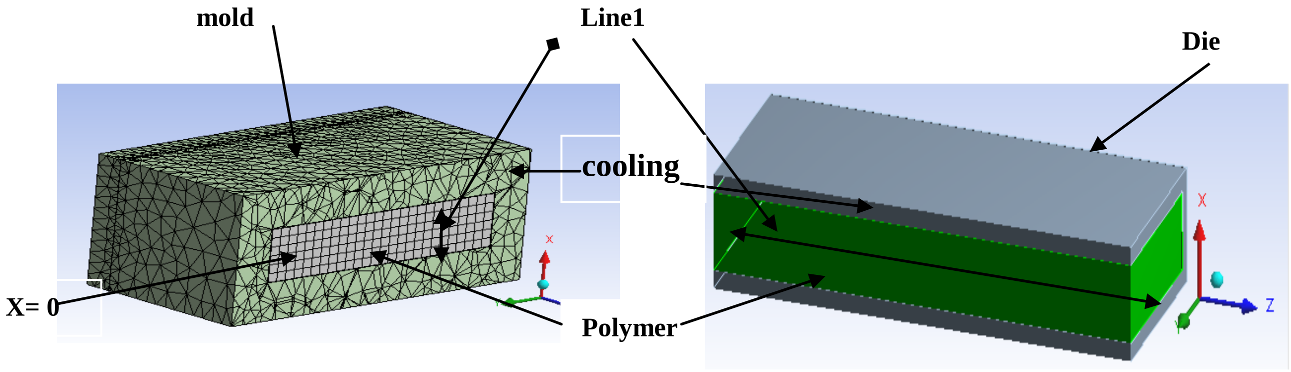


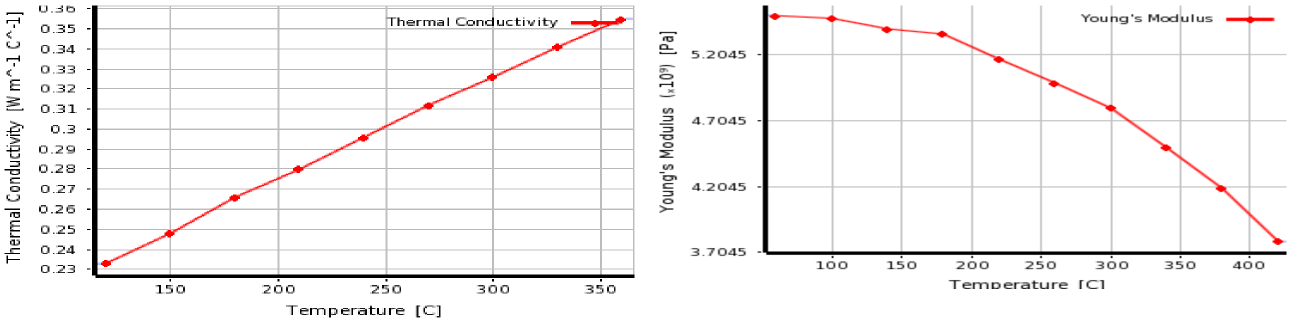
Fig.(1): Mesh, geometry and boundary condition of (a) mold, (b) die.



a

b

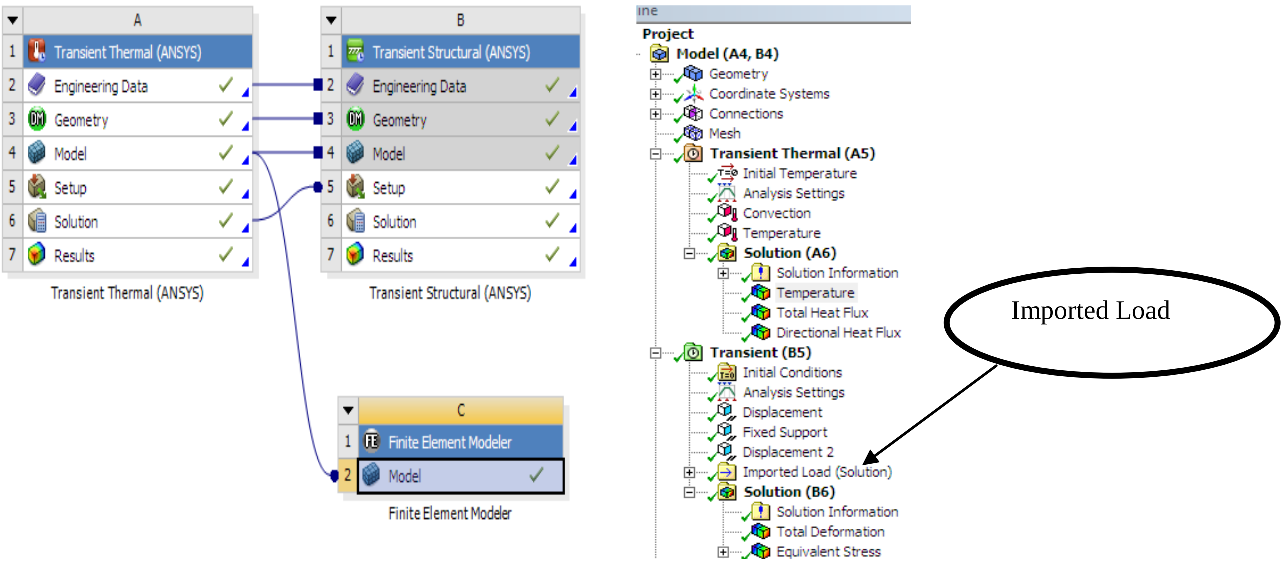
Fig.(2) (a) Cross section of the mold at the center along X axis (line 1=4mm) (b) Cross section of the die at the center along Z axis (line1=30mm),with locations of polymer melt, and cooling zones for mold



-a-

-b-

Fig.(3): (a) Thermal conductivity vs temperature, and (b) Young Modulus vs temperature, for polycarbonate melt.



-a-

-b-

Fig.(4): (a) Project schematic of transfer the solution from the thermal to structural model (b) Outline of the project includes importing load.

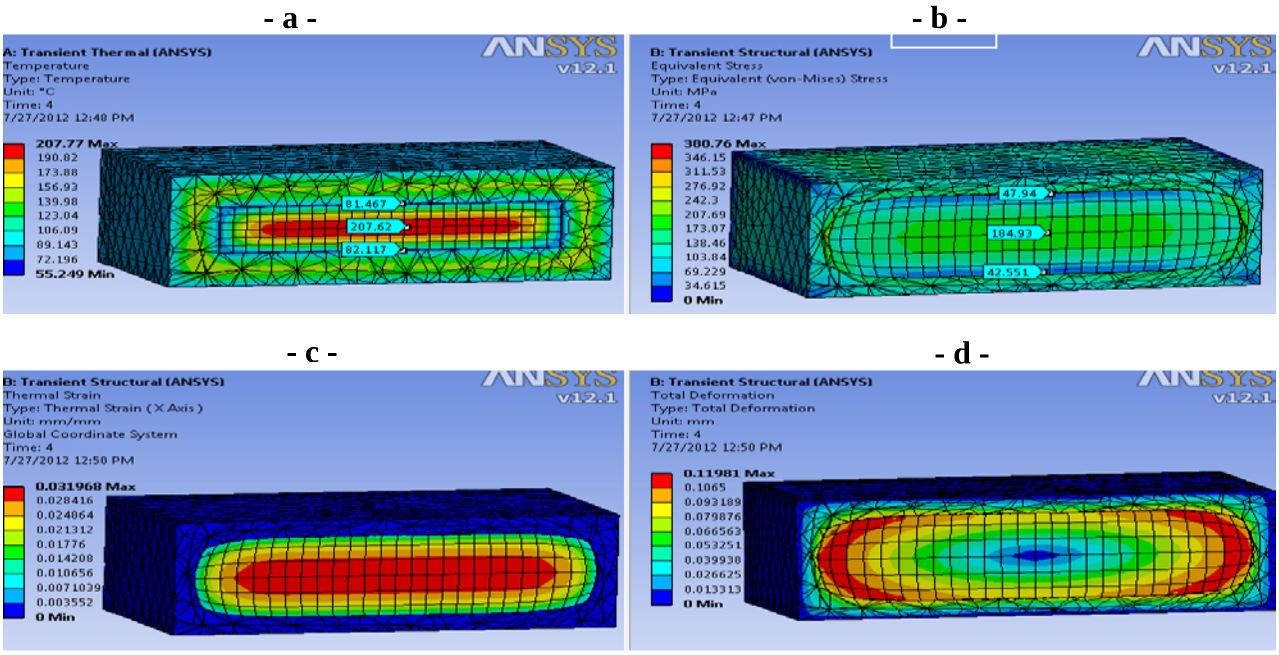


Fig.(5): Illustrates the(a)temperature, (b) Von-Mises stress,(c) thermal strain, and (d) total deformation contours at the cross section along line (1) of injection mold during the solidification of polycarbonate at 4 second and Biot number 16.

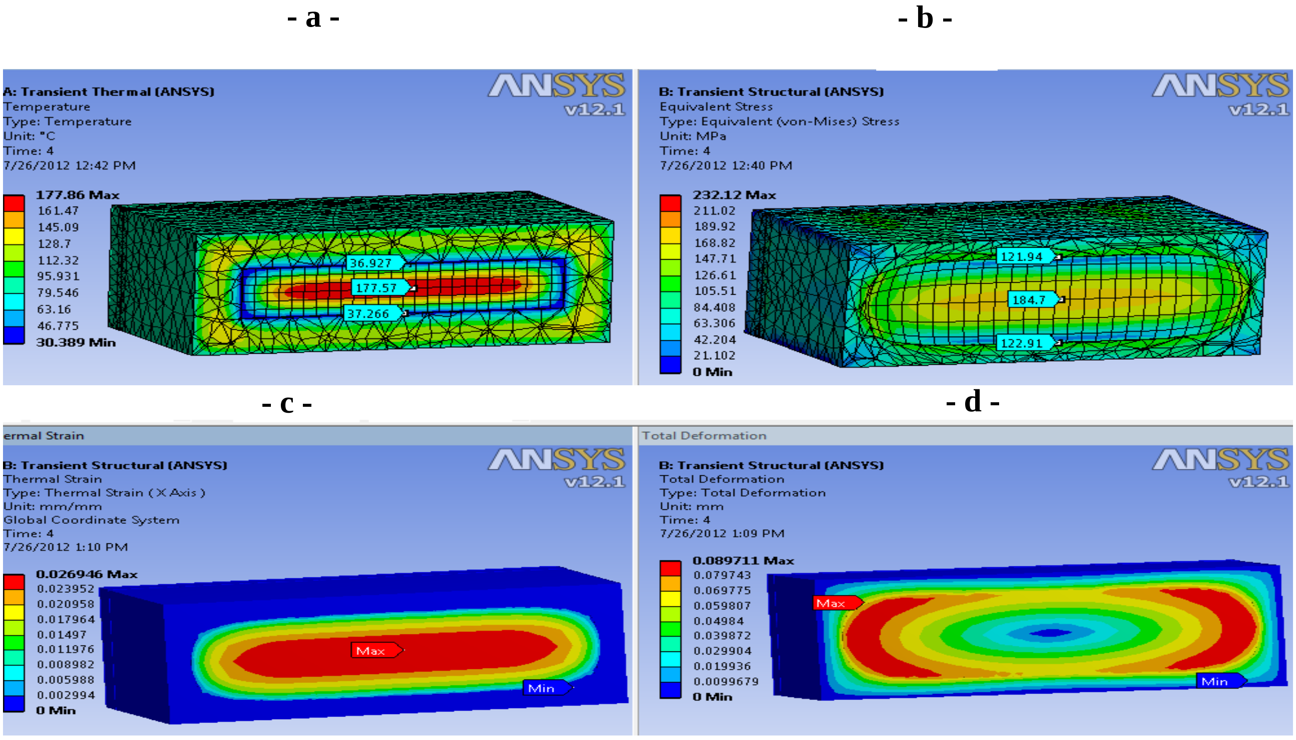


Fig.(6): Illustrates the(a) temperature,(b) Von-Mises stress, (c) thermal strain, and (d) total deformation contours at the cross section along line (1) of injection mold during the solidification of polycarbonate at 4 second and Biot number 112.

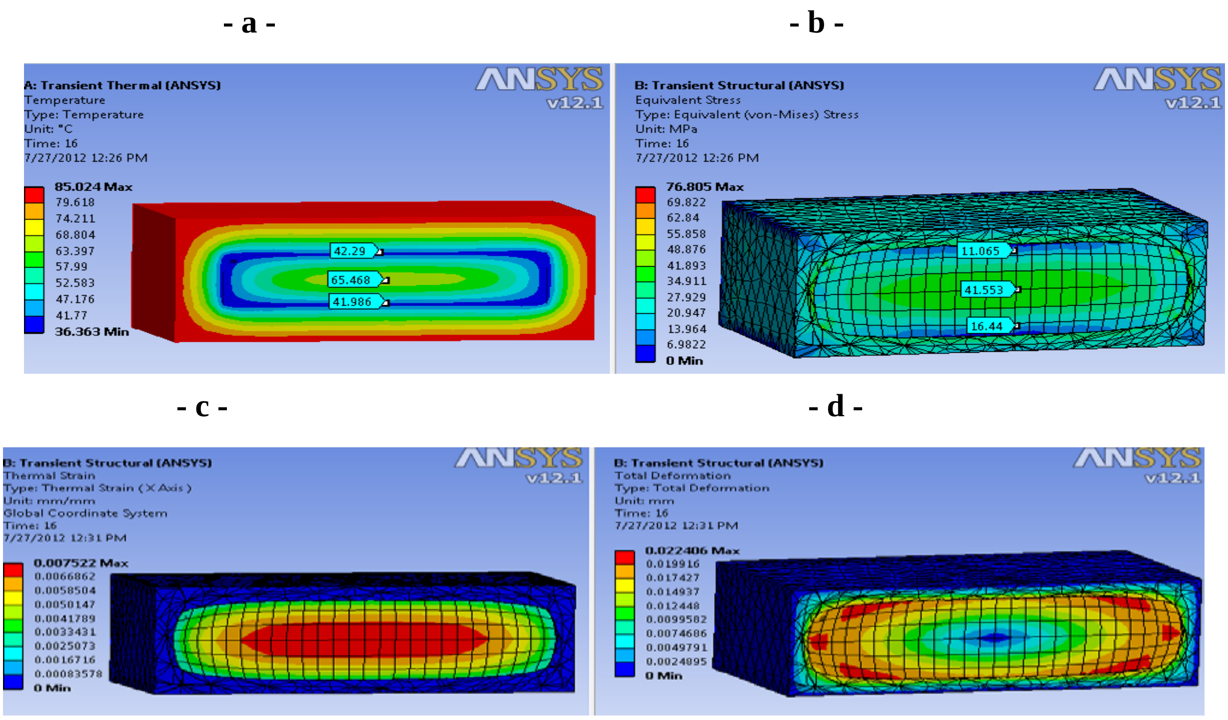


Fig.(7): Illustrates the (a) temperature, (b) Von-Mises stress, (c) thermal strain, and (d) total deformation contours at the cross section along line (1) of injection mold during the solidification of polycarbonate at 16 second and Biot number 16.

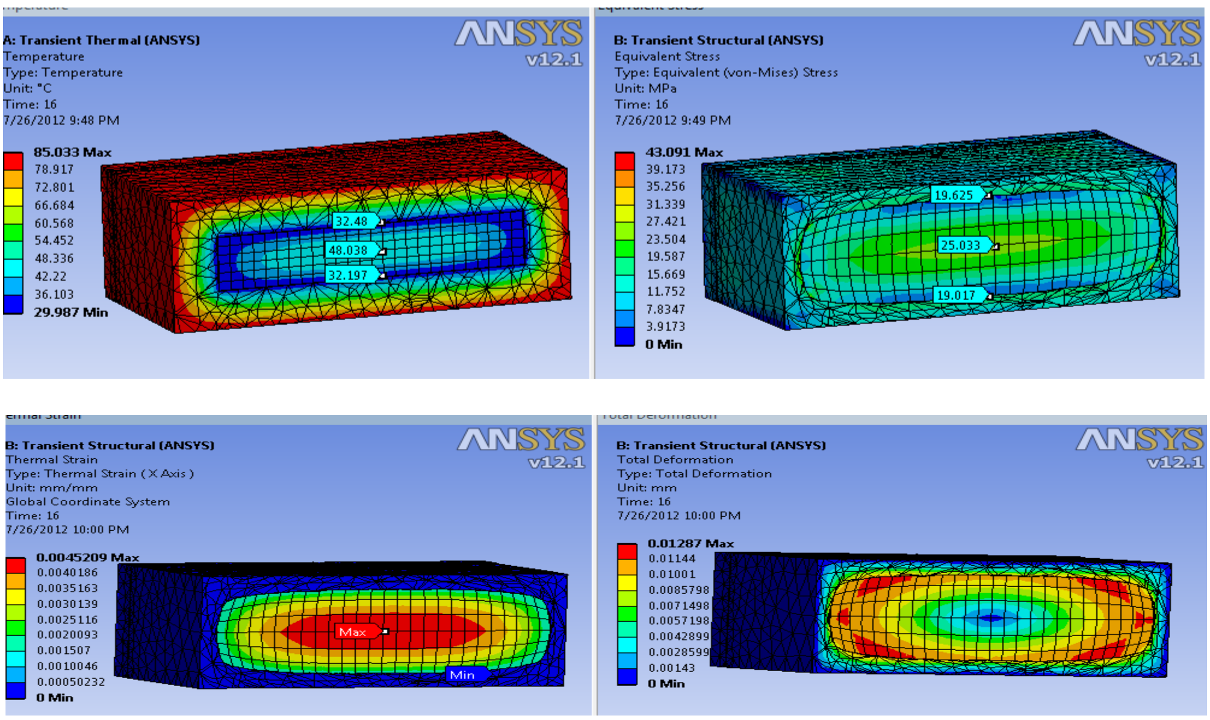


Fig.(8): Illustrates the (a) temperature,(b) Von-Mises stress, (c) thermal strain, and (d) total deformation contours at the cross section along line (1) of injection mold during the solidification of polycarbonate at 16 second and Biot number 112.

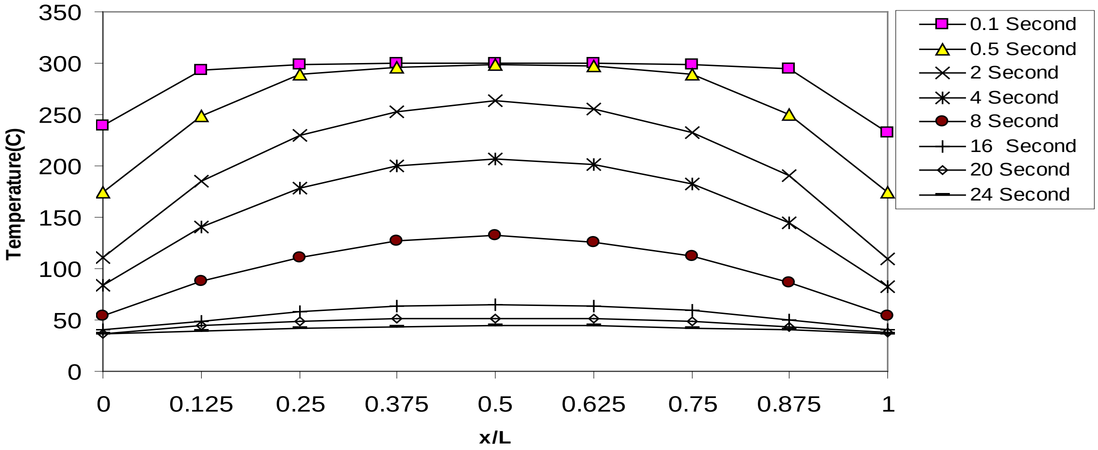


Fig.(9): Temperatures distribution a long line (1) in the injection mold during the solidification process of polycarbonate from 300 C to 30 C and Biot number 16 at 0.1, 0.5, 2, 4, 8, 16, 20 and 24 second.

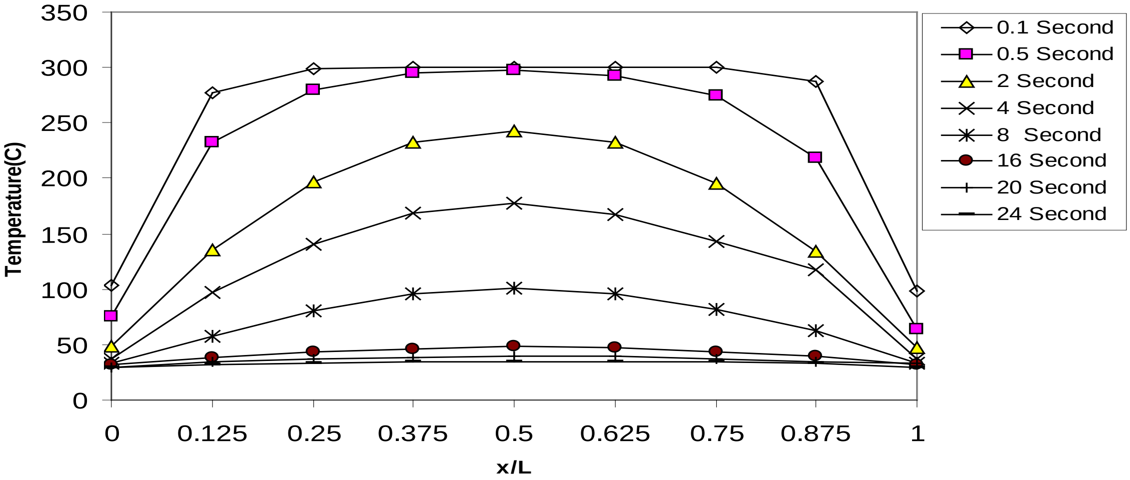


Fig.(10): Temperatures distribution a long line (1) in the injection mold during the solidification process of polycarbonate from 300 C to 30 C and Biot number 112 at 0.1, 0.5, 2, 4, 8, 16, 20 and 24 second.

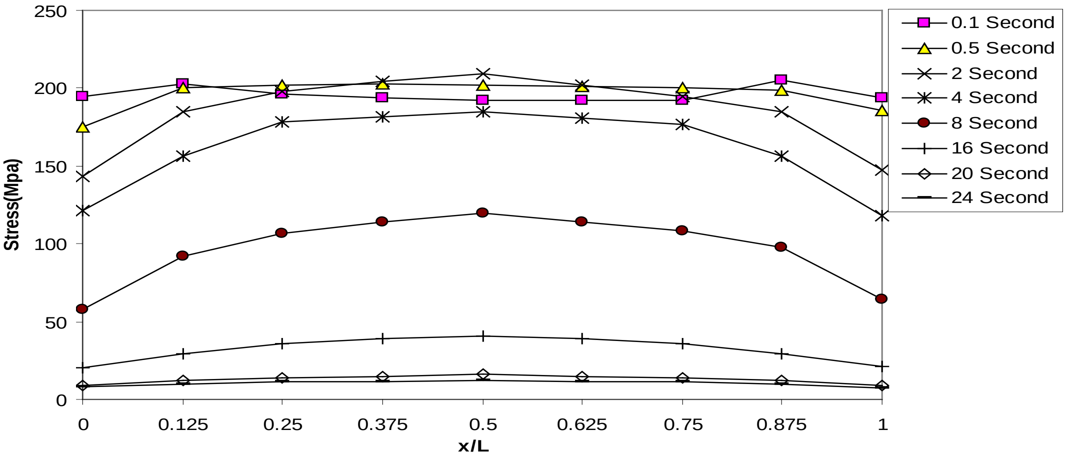


Fig.(11): Stresses distribution a long line (1) in the injection mold during the solidification process of polycarbonate from 300 C to 30 C and Biot number 16 at 0.1, 0.5, 2, 4, 8, 16, 20, and 24 second.

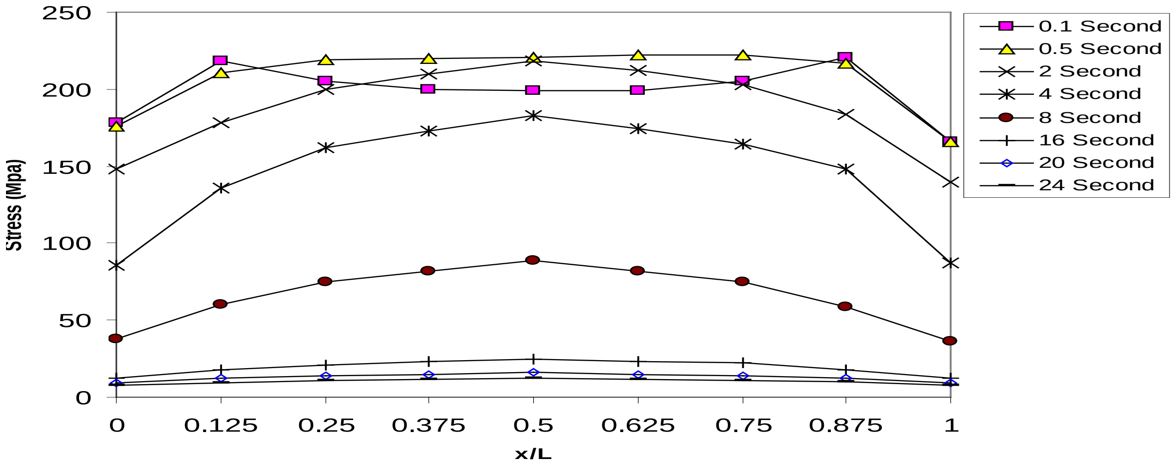


Fig.(12): Stresses distribution a long line (1) in the injection mold during the solidification process of polycarbonate from 300 C to 30 C and Biot number 112 at 0.1, 0.5, 2, 4, 8, 16, 20, and 24second.

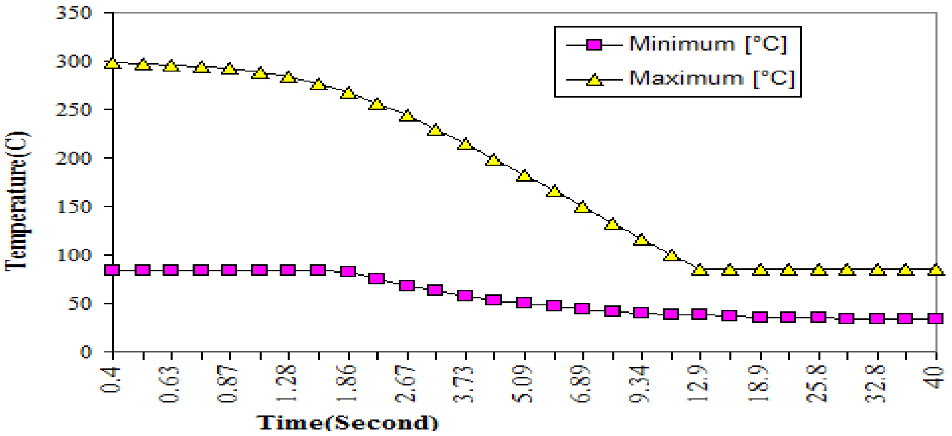


Fig.(13): History of maximum and minimum temperatures during the solidification process of polycarbonate at Biot number of 16.

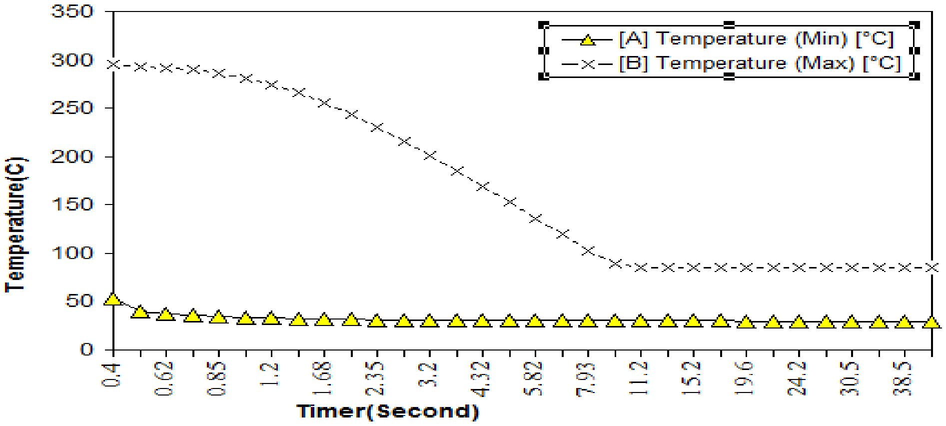


Fig.(14): History of maximum and minimum temperatures during the solidification process of polycarbonate at Biot number of 112.

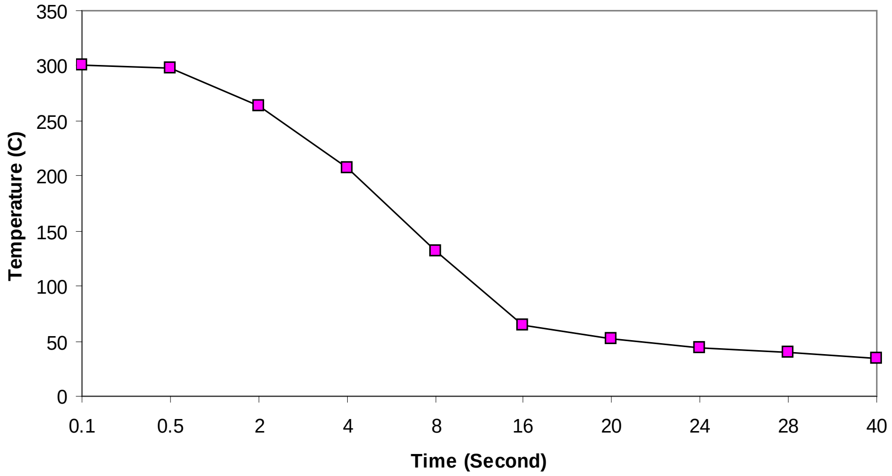


Fig.(15): History of maximum temperatures a long line 1 during the solidification process of polycarbonate at Biot number of 16.

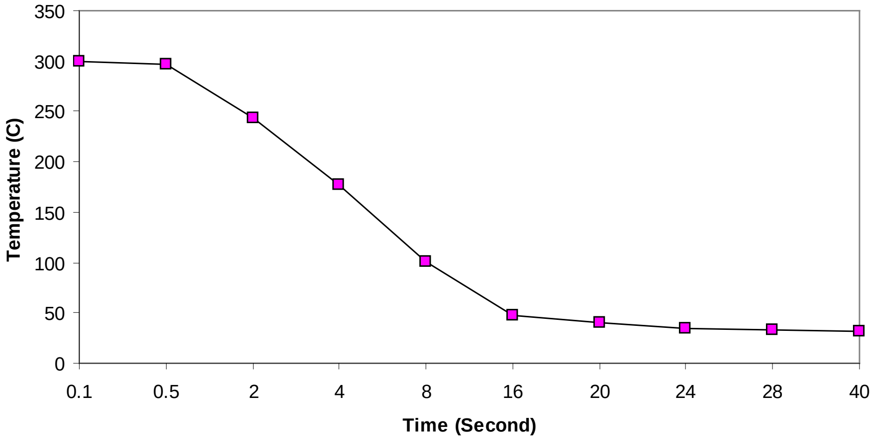


Fig.(16): History of maximum temperatures a long line 1 during the solidification process of polycarbonate at Biot number of 112.

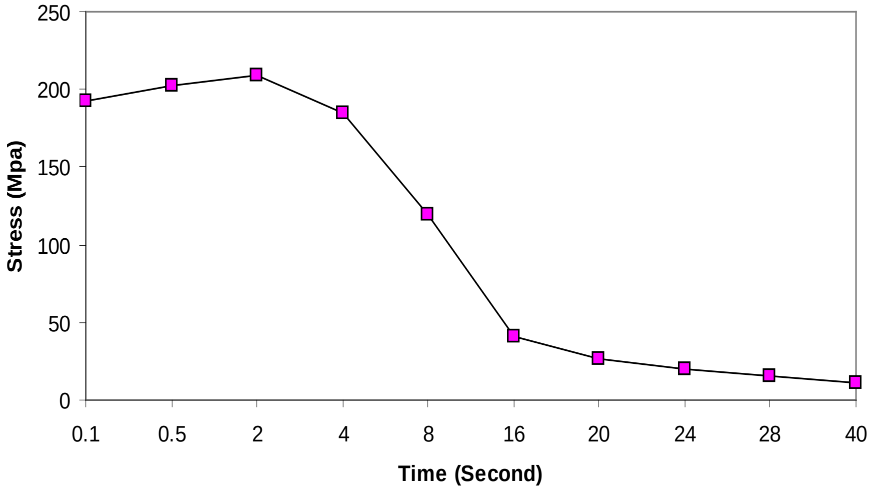


Fig.(17): History of maximum stresses along line (1) in the mold during the solidification process of polycarbonate at Biot number of 16.

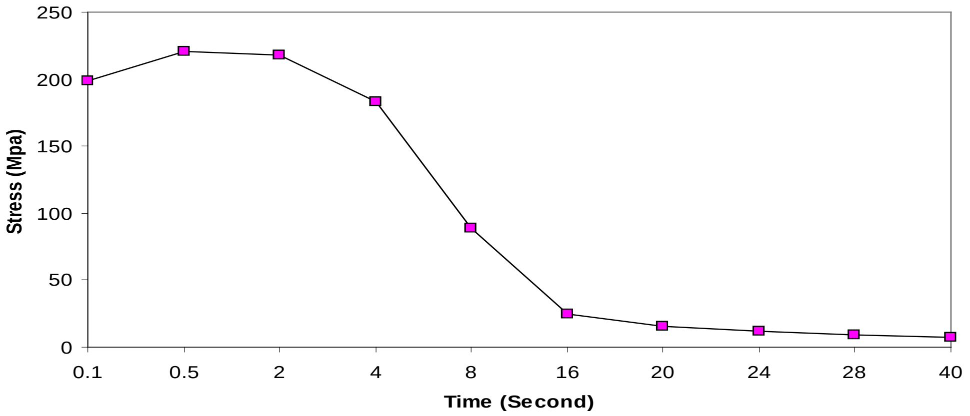


Fig.(18): History of maximum stresses along line (1) in the mold during the solidification process of polycarbonate at Biot number of 112.

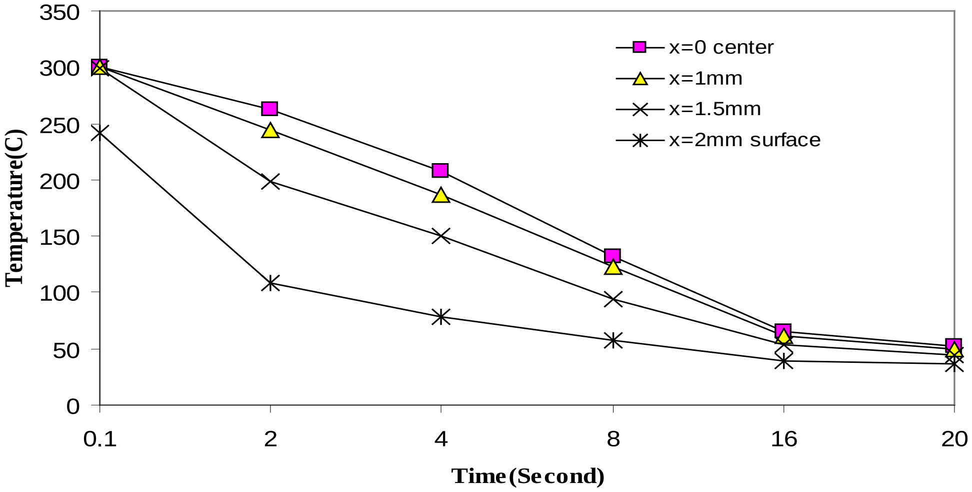


Fig.(19): Temperature history of the polymer in the mold along the line 1 at x axis starting from the center(x=0) to the surface at Biot number 112.

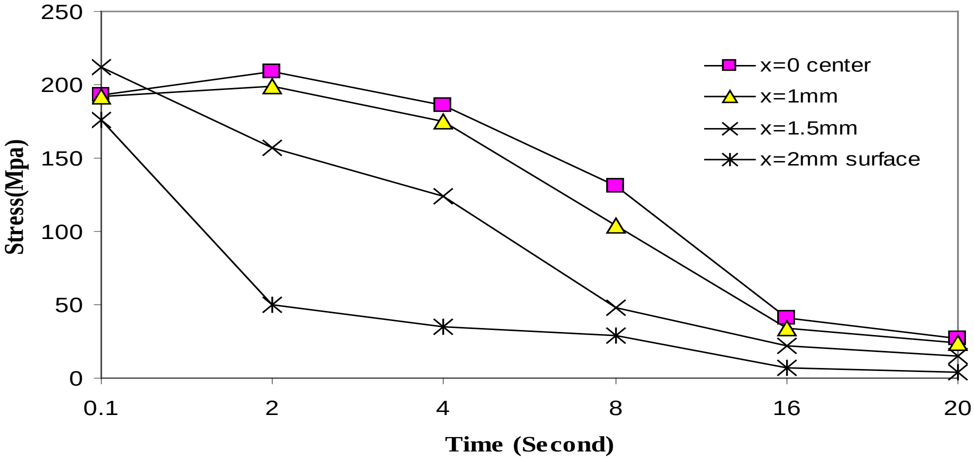
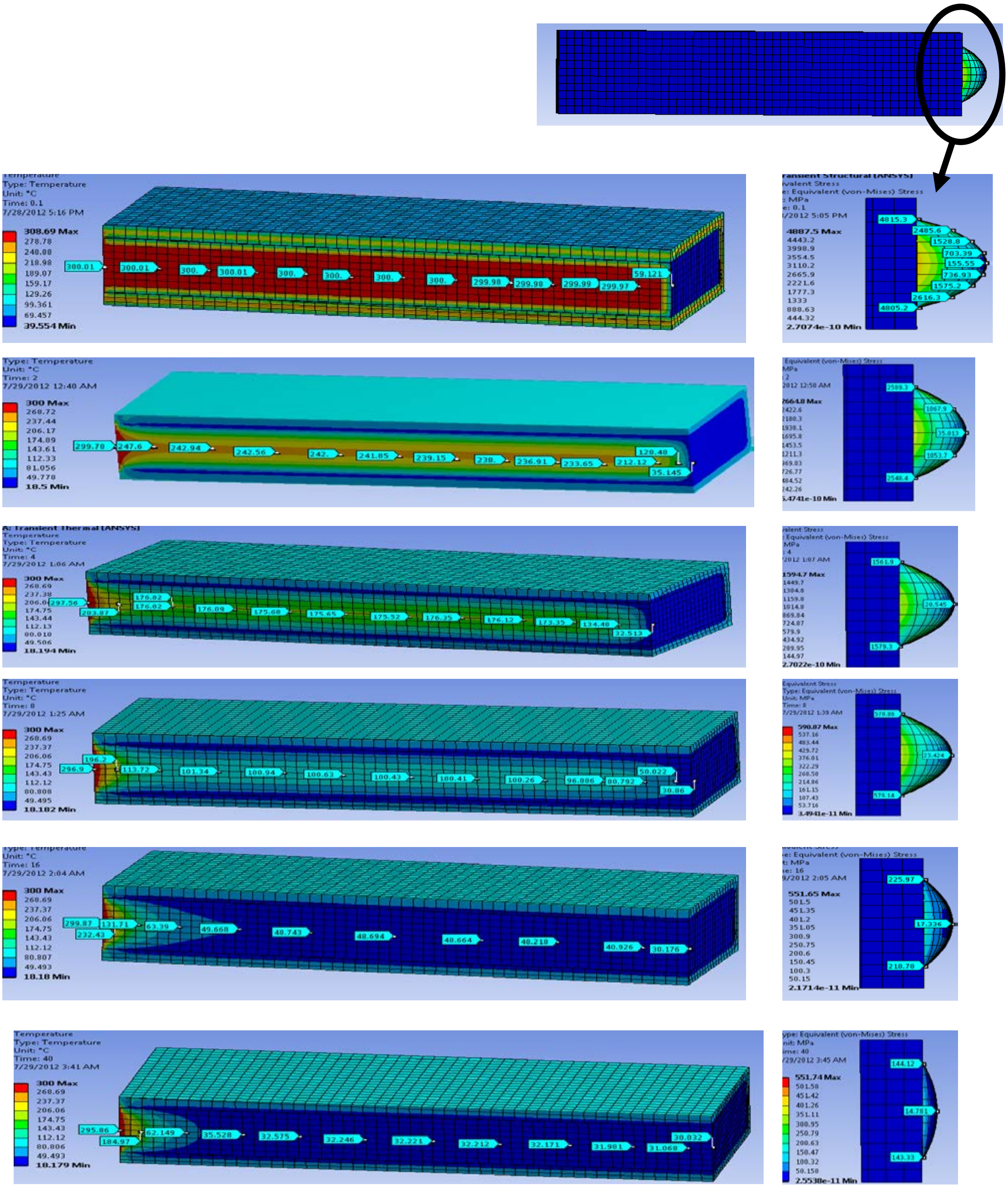
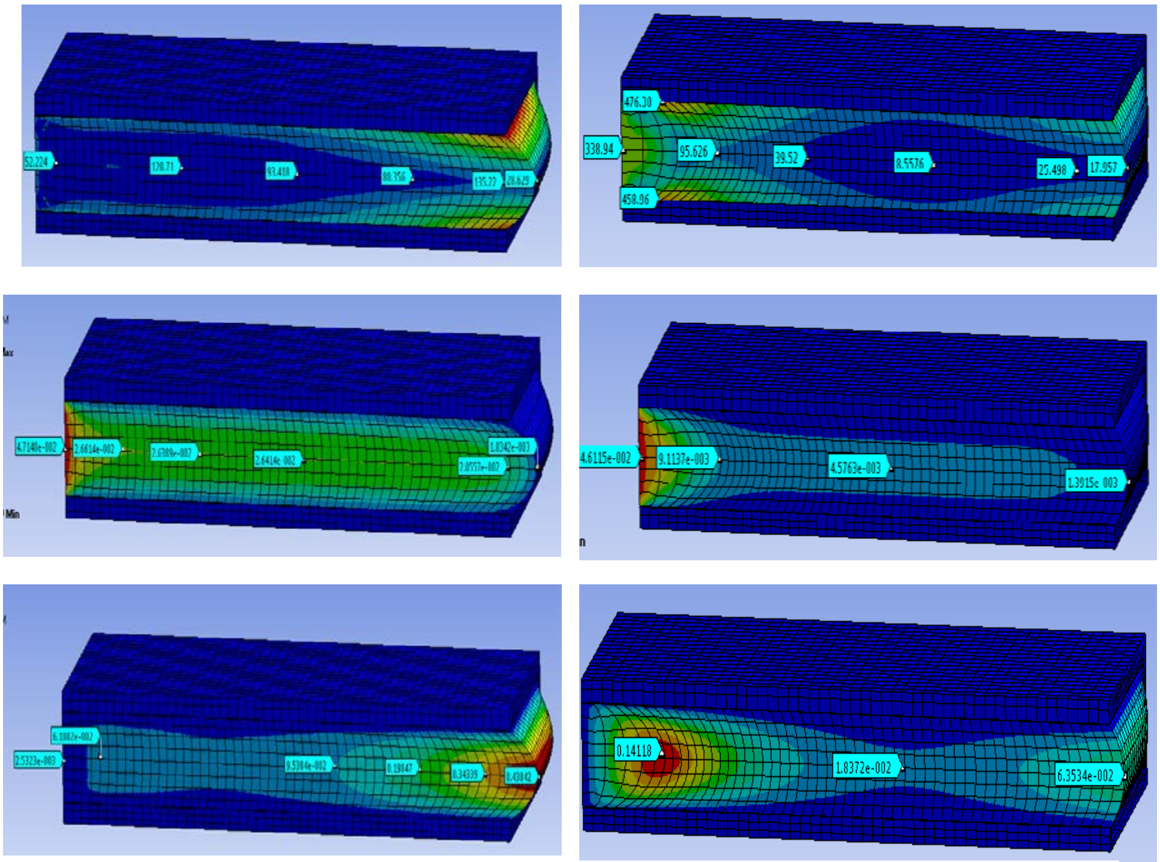


Fig.(20): Stress history of the polymer in the mold along the line 1 at x axis starting from the center to (x=0) the surface at Biot number 112.



-a- -b-

Fig.(21): (a)Temperatures distribution in cross section along line 1 of the die and (b) Von-Mises stress at front of the polymer in the outlet region, at 0.1, 2, 4, 8, 16 and 40 second and Biot number 16.



-a- **-b-**

Fig.(22):Von-Mises stress, thermal strain, and total deformation contours respectively at Z cross section along line 1of the die at Biot number 16, (a) 4 seconds,(b) 16 second