MATHEMATICAL MODEL TO INVESTIGATE THE TEMPERATURE AND HARDNESS DISTRIBUTIONS DURING THE ANNEALING AND NORMALIZING TREATMENT

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ABSTRACT

Annealing and normalizing treatment are one of the most important heat treatment for the steel and its alloys. In the present work a mathematical model has been used to simulate this process, this model taken in account the variation in the physical material properties and heat transfer coefficient for the surface of metal. A numerical scheme based on control finite volume method has been used. A computer program with C++ language was constricted to found the final solution of the numerical equations.

The model was used to estimate the temperatures distribution and the hardness value at each point of the workpiece. Good agreement has been obtained when compared the result of the present model with other experimental published data.

KEYWORD: annealing and normalizing heat treatment, mathematical model, hardness predications

الخلاصة:

التخمير والتطبيع يعدا من المعاملات الحرارية المهمة للفولاذ وسبائكه، في هذا البحث تم اقتراح انموذج رياضي لوصف عملية الانتقال الحراري الذي يحدث خلال هذه المعاملات، هذا الانموذج المقترح ياخذ بنظر الاعتبار التغير في الخواص الفيزيائية للمعدن مع تغير درجات الحرارة خلال المعاملات الحرارية وكذلك التغير في معامل الانتقال الحراري لسطح المعدن. تم استخدام طريقة عددية لايجاد الحلول لهذا الانموذج وكذلك تم بناء برنامج حاسوب بالاستعانة بلغة البرمجة سي ++ لايجاد الحلول النهائية للمعادلات الخاصة بالانموذج.

استخدم هذا الانموذج لمعرفة توزيع درجات الحرارة على طول مساحة مقطع القطع المعاملة حرارية وكذلك حساب مقدار الصلادة في كل نقطة من المعدن للقطعة ، ايضا استخدم الانموذج لدراسة تاثير مساحة المقطع في هذه المعاملات الحرارية. تم الحصول على تطابق جيد عند المقارنة بين نتائج الانموذج مع نتائج عملية سابقة منشورة.

INTRODUCTION

It is well known that the heat treatment process of the steel is very old process technology of materials. In this process we can improve the mechanical properties of the steel. It’s involved a cycle of heating and cooling process in all heat treatment types. The mean difference between the types of this process is the cooling rate, for example high cooling rate used in quenching treatment while very slow in annealing treatment. During the heat treatment process there are coupled phenomena, such as thermal-mechanical coupled effect, temperature-microstructure coupled effect. So that it’s very important to study the temperature distributions in this process from this distribution we can expect the phase transformation and the microstructure as well as the thermal stress which is may occur in the workpiece during the heat treatment process.

In the recent years, the mathematical modeling of heat treatment process has been used in the world to reduce the offers in this process and to make the effective parameters for this process under the control.

[B.Shaheen.B.2010] developed a mathematical model to simulate the quenching treatment of viruses steel types. In this work a computer program was constricted to evaluate the temperatures distribution and to study the important parameters in the quenching treatment of steel with different quenching media and workpiece dimension.

[B.Smoljam etal 2006] a numerical simulation the quenching process have been carried out in this work, the relationship between the time from 800 ^{o}C to 500 ^{o}C and the distance from quenching end of Jumine- specimant have been studies to estimate the hardness distribution depending on the cooling rate or cooling curve for the workpiece.

[B.Smoljam etal 2009] a heat transfer model was used in this work to simulate the quenching treatment. The hardness distribution have been estimated based on the relationship between the cooling time from 800 to 500 and the Jumine- specimant.

[Haji Badrul etal 2009] in this work a heat transfer simulation to the quenching treatment using finite element software ANSYS workbench have been carried out to investigate the temperatures distribution. The hardness distribution have been predicated by using method based on the relationship between the Juminy distance versus cooling time to 500 ^{o}C and hardness versus Jominy distance.

A further work was carried out by [B. Liscic etal] to simulate the heat treatment process (quenching treatment). The temperatures distribution have been investigated, the hardness distribution also investigated by method based on the relationship Continuous-Cooling-Transformation (CCT) diagram of steel and the phase structure versus hardness diagram depending on the time to 500 ^{o}C .

In the present work a mathematical heat transfer model based on a computer program with C++ language have been carried out to simulate two kinds of the most important heat treatment process which is annealing and normalizing treatments. This work taken in account the variations in the physical properties for the workpiece metal which is occur during the treatment (increasing in the temperature of the workpiece) as well as the relationship between surface temperature and the heat transfer coefficient of the workpiece during the treatment.

MATHEMATICAL MODEL

The heat conduction equation in the middle of workpiece taken as in equation (1)

$$\frac{\partial}{\partial x}(K\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(K\frac{\partial T}{\partial y})=\rho C_p\frac{\partial T}{\partial t} \qquad (1)$$

Where **k** is the thermal conductivity and **C_p** the specific heat and **ρ** the density of the metal workpiece. From above model we can see that the temperature variation is with time and the coordinate x and y, also we assume that the maximum variation in workpiece temperature is taking place across the cross sectional area (X-Y) plane [B.Shaheen.B.2010] . The all thermal material properties i.e. thermal conductivity, specific heat, density are temperature dependent [ASM Handbook, Volume 1, 2005]

By using numerical scheme based on control volume method the nonlinear heat conduction equation eq. (1) will be discreted and we will obtain

$$a_p T_p = a_E T_E + a_W T_W + a_N T_N + a_S T_S + a_P^o T_P^o$$

Where

$$a_E = \frac{k_e \, \Delta y}{(\delta_x)_e} \qquad a_W = \frac{k_w \, \Delta y}{(\delta_x)_w} \qquad a_N = \frac{k_n \, \Delta x}{(\delta_y)_n} \qquad a_S = \frac{k_s \, \Delta x}{(\delta_y)_s}$$

$$a_{p^o} = \frac{\rho c_p \Delta x \Delta y}{\Delta t} \qquad a_p = a_E + a_W + a_N + a_S + a_{p^o}$$

Boundary Conditions

We can describe the boundary conditions in the present work a follows (see figure 1)

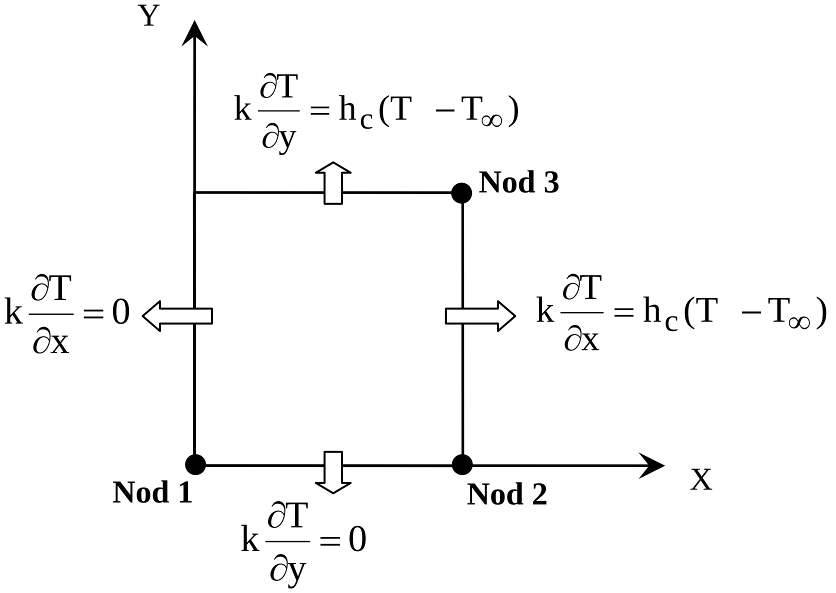


Figure (1). Geometry and the boundary conditions.

Where h_c The value of heat transfer coefficient and T is the surface temperature of the workpiece and T∞ is the cooling media temperature where this value in case of annealing treatment equal to the temperature of furnace and in case of normalizing treatment equal to air temperature.

The value of heat transfer coefficient (h_c) is taken as temperatures dependent. Table (1) shows these values for the two cases annealing and normalizing treatment [Brandon Elliott B. and Christoph Beckerman 2007].

Table (1) The heat transfer coefficient for the annealing and normalizing treatment

T ^{o}C	30	100	200	300	400	500	600	700	800	900	1000
h_c (w/m^2.C) Annealing	500	550	850	900	1054	1210	1300	1540	1650	1800	2000
h_c (w/m^2.C) Normalizing	500	500	600	650	700	725	800	850	950	980	1000

In the previous section we described the mathematical model and the numerical data needed, after this step we will used numerical scheme based on control volume method and iterative method known as (TDMA) also used to solve the system of equations which is consist of the boundaries equations and the medal equation finally computer program was constructed in this work based on C++ language to found the final solution for the proposed model and the out put of this program used in others computers program to show the results of the program.

HARDNESS VERIFICATION

It's very important to verify the result of the present model, so that a comparison between the values of hardness calculated in the present work and experimental published data [B.Smoljam etal 2006] [B.Smoljam etal 2009] as show in table (2) below:

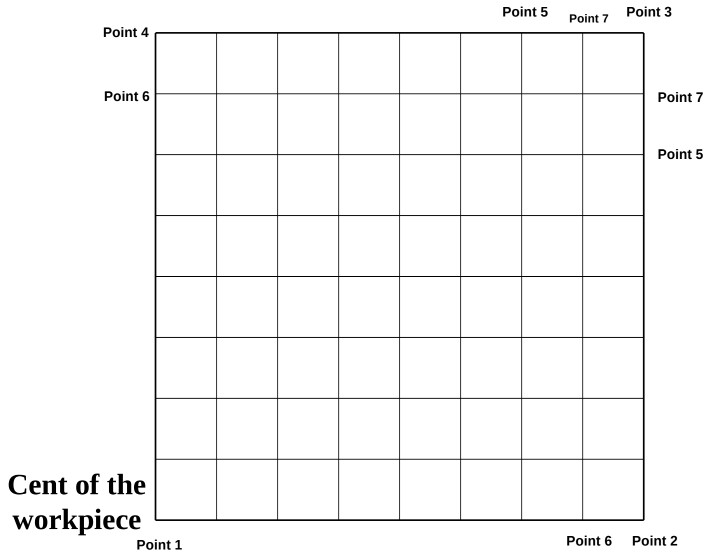


Figure (2) the nod points as described in the table (2).

Table (2) a comparison between the hardness calculated in the present work and [B.Smoljam etal 2006] [B.Smoljam etal 2009]

Point Node No	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Point 5**	**Point 6**	**Point 7**
Present work	**290**	**330**	**324**	**330**	**350**	**310**	**340**
[B.Smoljam etal 2006] [B.Smoljam etal 2009]	**311**	**349**	**340**	**349**	**368**	**324**	**379**

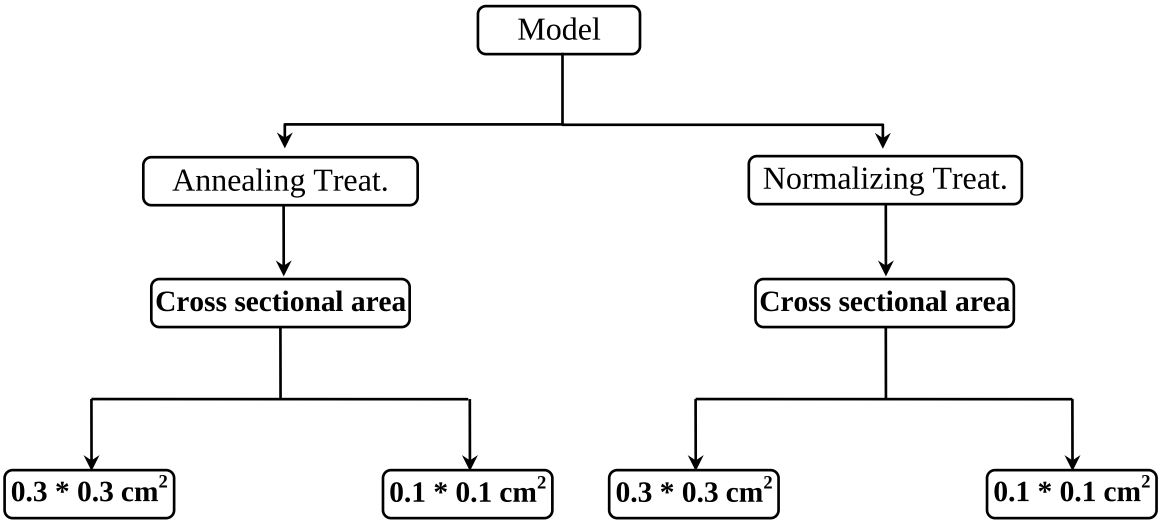
A further comparison has been made with [B.Smoljam etal 2009] to the point node no 2 which is equal to point 4 as show in table (3) below:

Table (3) a comparison between the hardness calculated in the present work and [B.Smoljam etal 2009]

	% F	% P	% B	% M	H. No
Present work	**5.2**	**8.5**	**73.8**	**12.5**	**330**
[B.Smoljam etal 2009]	**% F+ P**		**42-74**	**5-36**	**290-349**
	0-12				

RESULTS AND DISCUSSIONS

Different cases have been study in this work by the proposed model, figure (3) below shows a flow chart for these cases.



Figure(3). Case study by the proposed model in the present work for the steel type DIN 41Cr4.

The above cases were study to the steel **DIN 41Cr4** which have the chemical composition shown in table (4) [ASM Handbook, Volume 1, 2005]

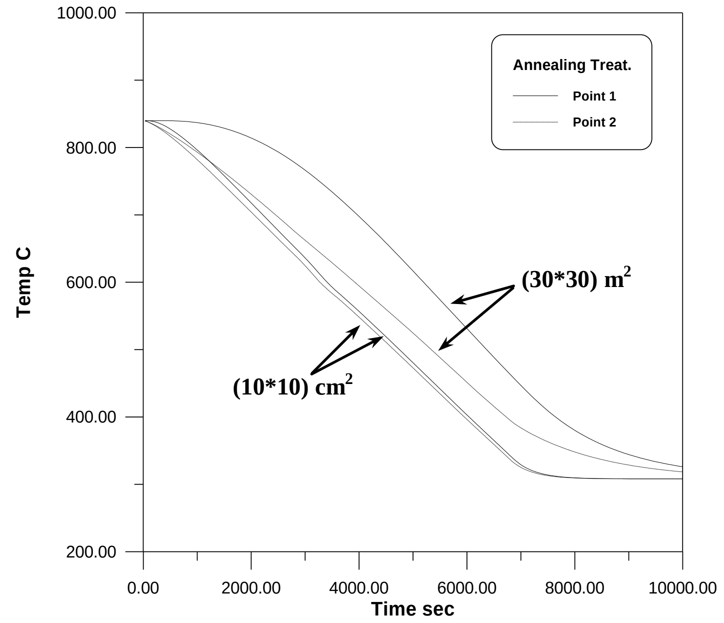
Table (4) Chemical Composition to the Steel DIN 41Cr4

Chemical Composition	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V
	0.44	0.22	0.80	0.030	0.023	1.04	0.17	0.04	0.26	<0.01

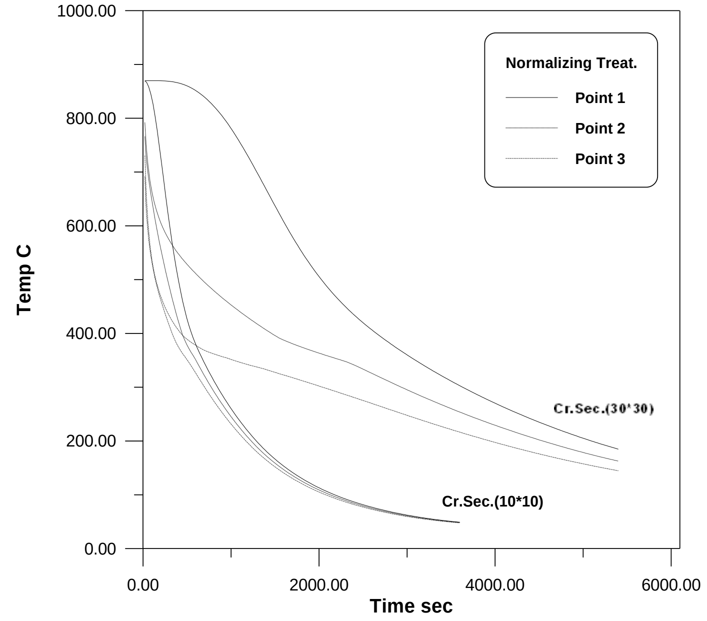
Figure (4) A, B shows the temperatures variation with time for the three points (points nod 1, points nod 2 and points nod3 see figure (1)) for the two cases which is annealing and normalizing treatment and when the cross sectional area is (**30 * 30) cm^2 , (10 * 10) cm^2 .**

In case of the annealing treatment fig (4)-A, we can see that the difference in temperatures between the described points is not high especially when the cross sectional area is (**10 * 10) cm**^{2}. The difference will increase with cross sectional area increasing. In general there is no high temperatures difference between the two cases of cross sectional area in the annealing treatment.

But these behavior is different in the normalizing treatment see figure(4)-B, where this figure shows that the temperatures difference between these points is increasing especially in case of (**30 * 30) cm^2** cross sectional area



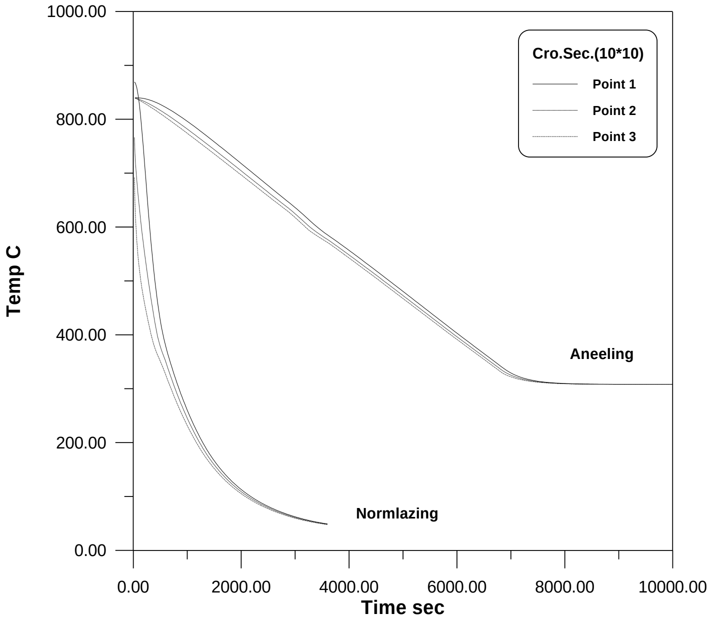
A-Annealing Treatment



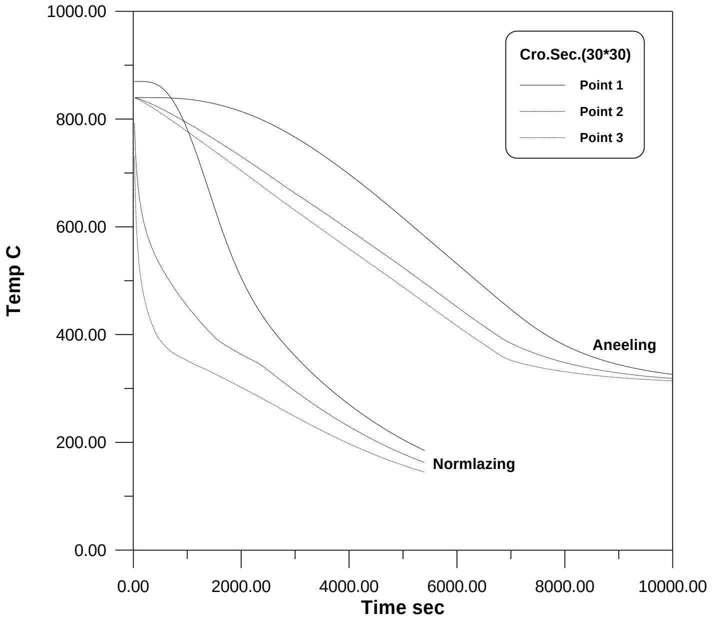
A- Normalizing treatment

Figure (4) Temperatures variations vs. time for at two cross sectional area with two cases, A-Annealing treatment and **B- Normalizing treatment.**

Figure (5) A, B shows a comparison between the annealing and normalizing treatment for three points in the workpiece and when the cross sectional area are (**10*10) cm^2** and (**30*30) cm^2**. It's very important to note that the thermal gradient in the normalizing treatment is more than in the annealing treatment, actually its come from the value of heat transfer coefficient and the environment temperature or the cooling media temperature which is different in the two treatment process (annealing and normalizing) as we described before.



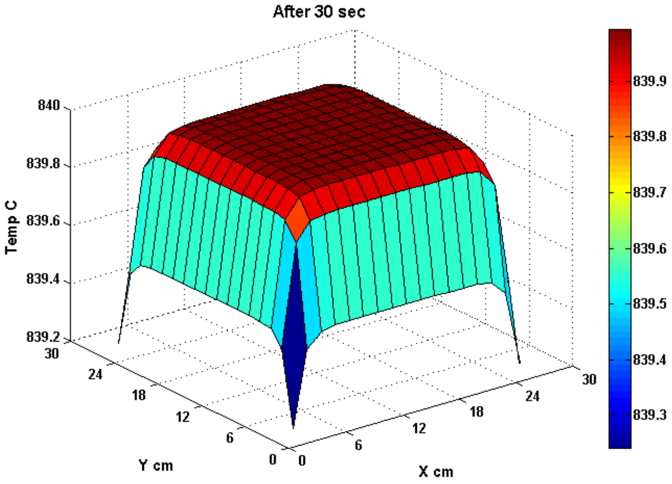
A-Cross sectional area (10*10) cm^2.



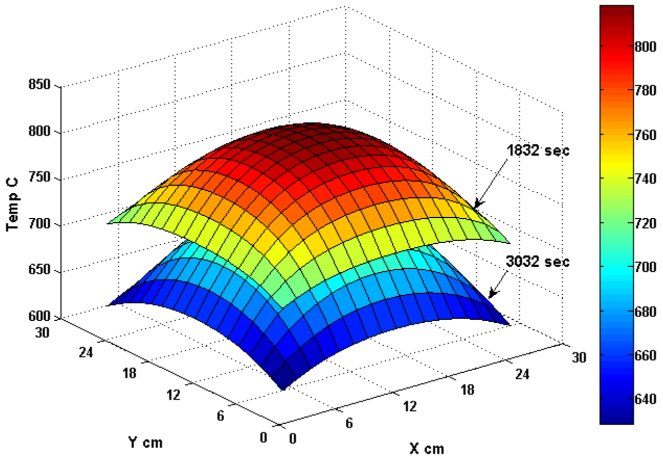
B- Cross sectional area (30*30) cm^2

Figure (5) Temperatures vs. time in a comparison between annealing and normalizing treatment for three points at two cases A-Cross sectional area (10 * 10) cm^2, B- Cross sectional area (30*30) cm^2

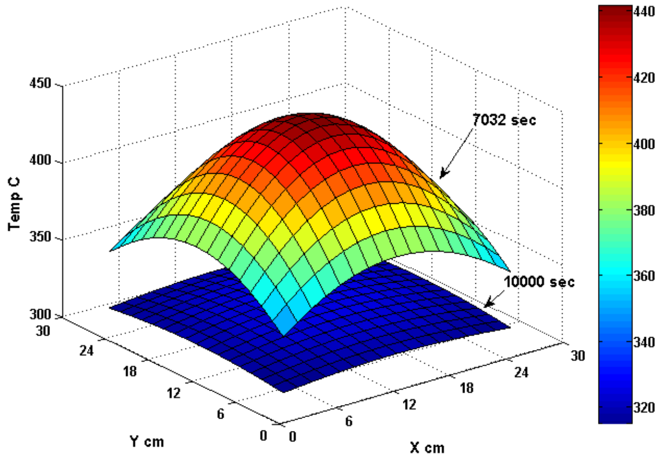
Figure (6)-A,B,C show the temperature distribution for the annealing (0.3*0.3 m^2) at different time 30, 1832,7032 and 1000 sec, from this figure we can se that the thermal gradient throe the cross sectional area is changing with time, in the first time step the thermal gradient not high but with increasing time this gradient increase until reach same point (specific time) then this gradient will decreasing with time increase this mean there is a specific critical time point before which the gradient increase with time and after which the gradient decreasing with time increase.



A- After 30 sec



B- After 1832 and 3032 sec



C- After 7032 and 10000 sec

Figure (6)-A,B,C The temperature distribution for the annealing for (0.3*0.3 m^2)

Another case shows in figure (7), which described a comparison between temperatures distribution for the normalizing treatment when the cross sectional area is (0.3*0.3 m^2) at different time (30, 330, 1832 and 3032) sec. From this figure we can see that the thermal gradient increase with time increase from 30 to 330 sec after this time the thermal gradient will be decrease with time increase.

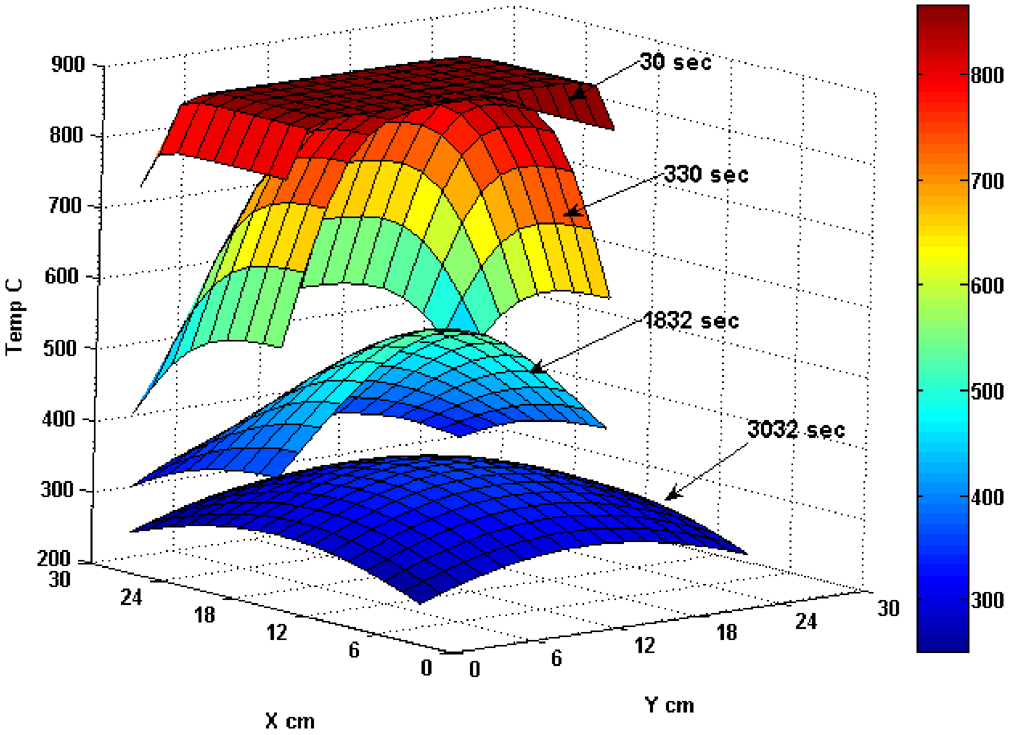
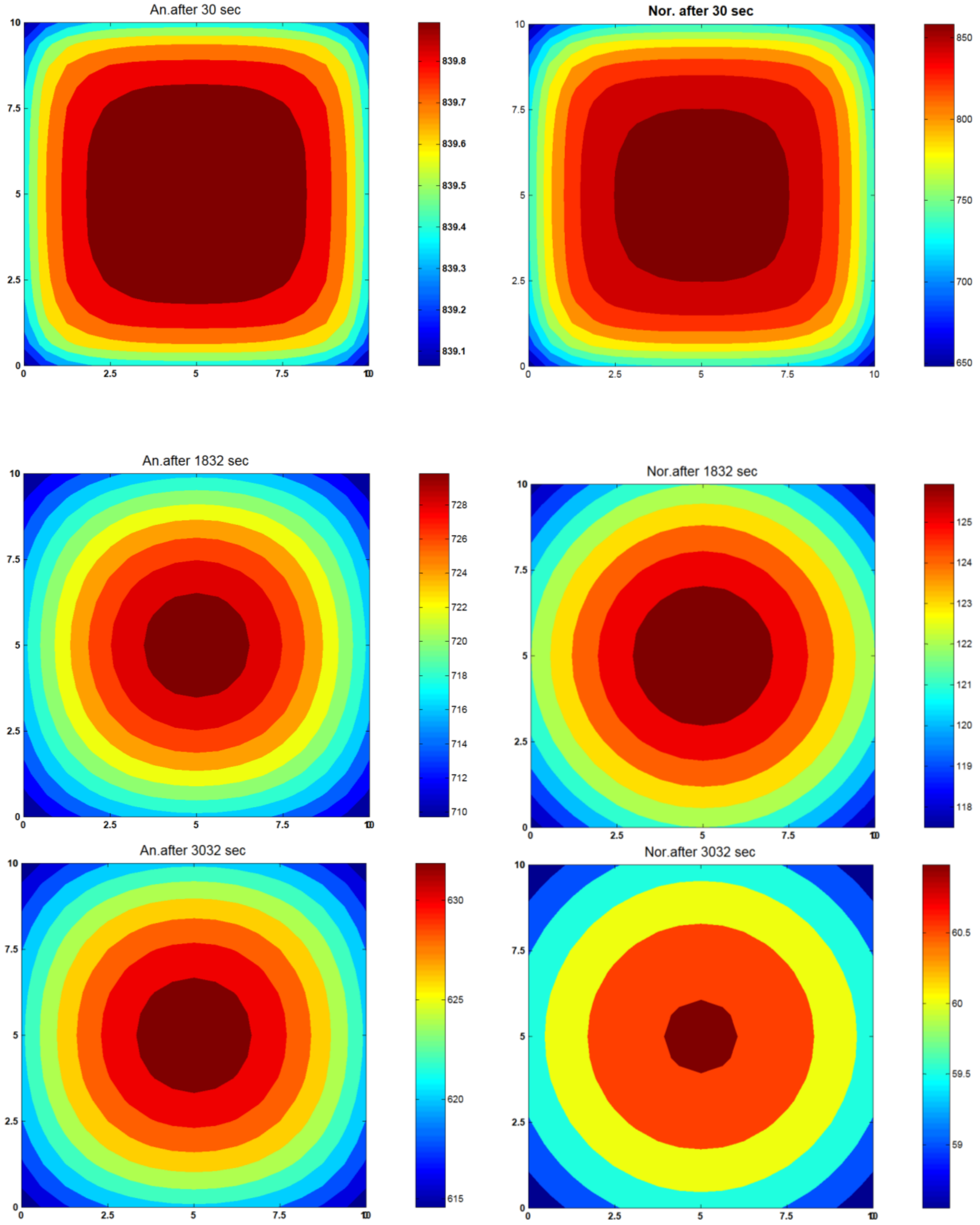


Figure (7) - The temperature distribution for the normalizing treatment for (0.3*0.3 m^2)

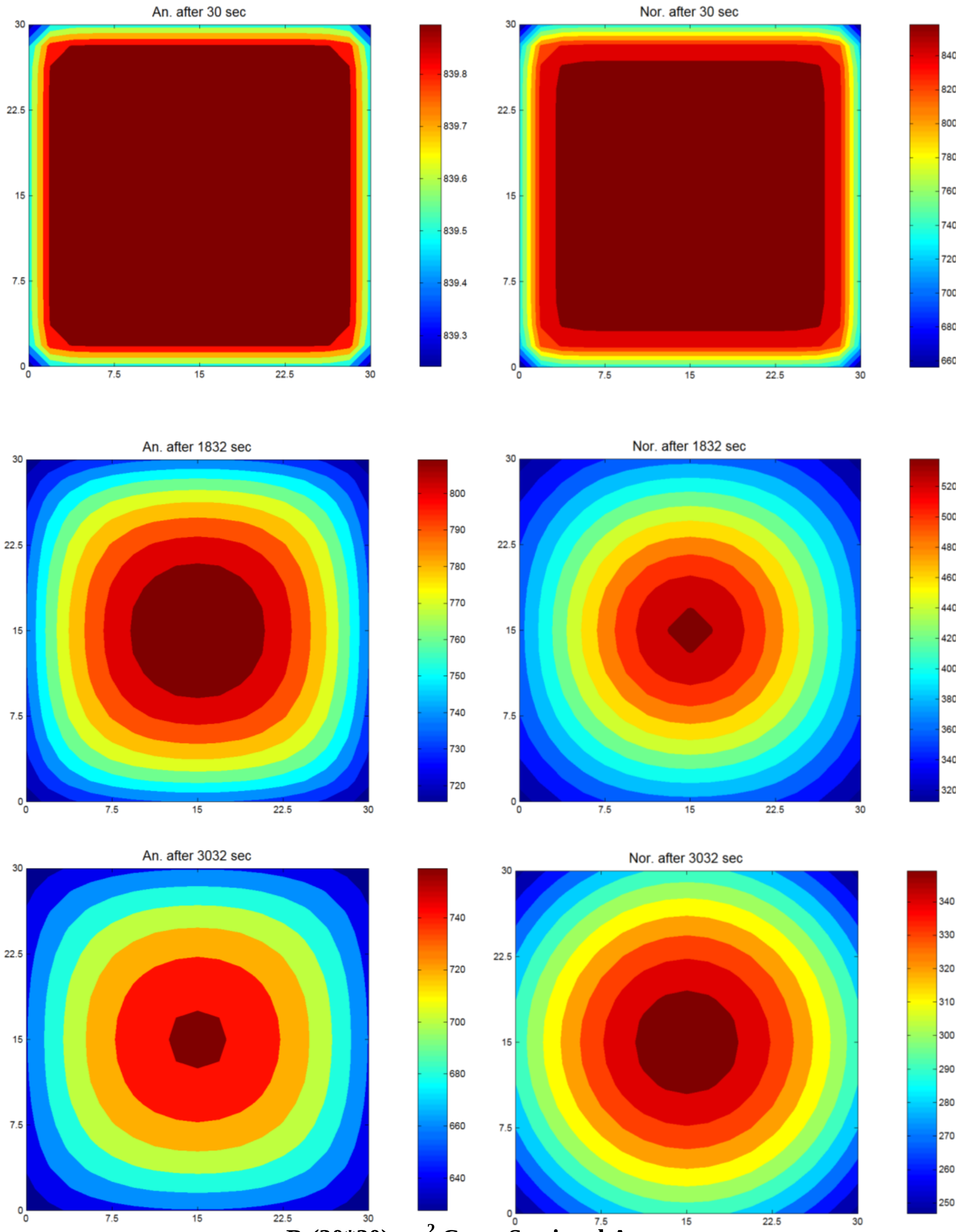
Actually there is a specific time point at which the thermal gradient is maximum, before this point (this time) the thermal gradient is increase with time increase and after this point the gradient is decrease with time increasing as we mention that before.

We can described this point as (**Time of Maximum Thermal Gradient**) (**$T_{M.T.G}$**). Value of **$T_{M.T.G}$** is effected by many parameters such as the cross sectional area, temperature of heat treatment and heat treatment type. Thermal stress or crack may be occurring due to high thermal gradient so that it's very important to specify this point in the heat treatment process to avoid these defects. A special cooling process can be used to eliminate the effect of this phenomenon.

Another comparison shows in figure (8)-A, B, where figure (8)-A shows a comparison between the temperatures distribution for the annealing and normalizing treatment process at different time (30, 1832, 3032) sec, when the cross sectional area (0.1*0.1 m^2) while figure (8)-B shows the same case but for the cross sectional area (0.3*0.3 m^2). It's very important to noted that there is many differences between the temperatures distribution for the annealing and normalizing we can see that from the contours line of temperatures distribution and the temperature bar, this difference is increasing with time increase and with cross sectional area decrease. This is due to the value of heat transfer coefficient and the cooling process in the heat treatment process type.



A-(10*10) cm^2 Cross Sectional Area



B-(30*30) cm^2 Cross Sectional Area

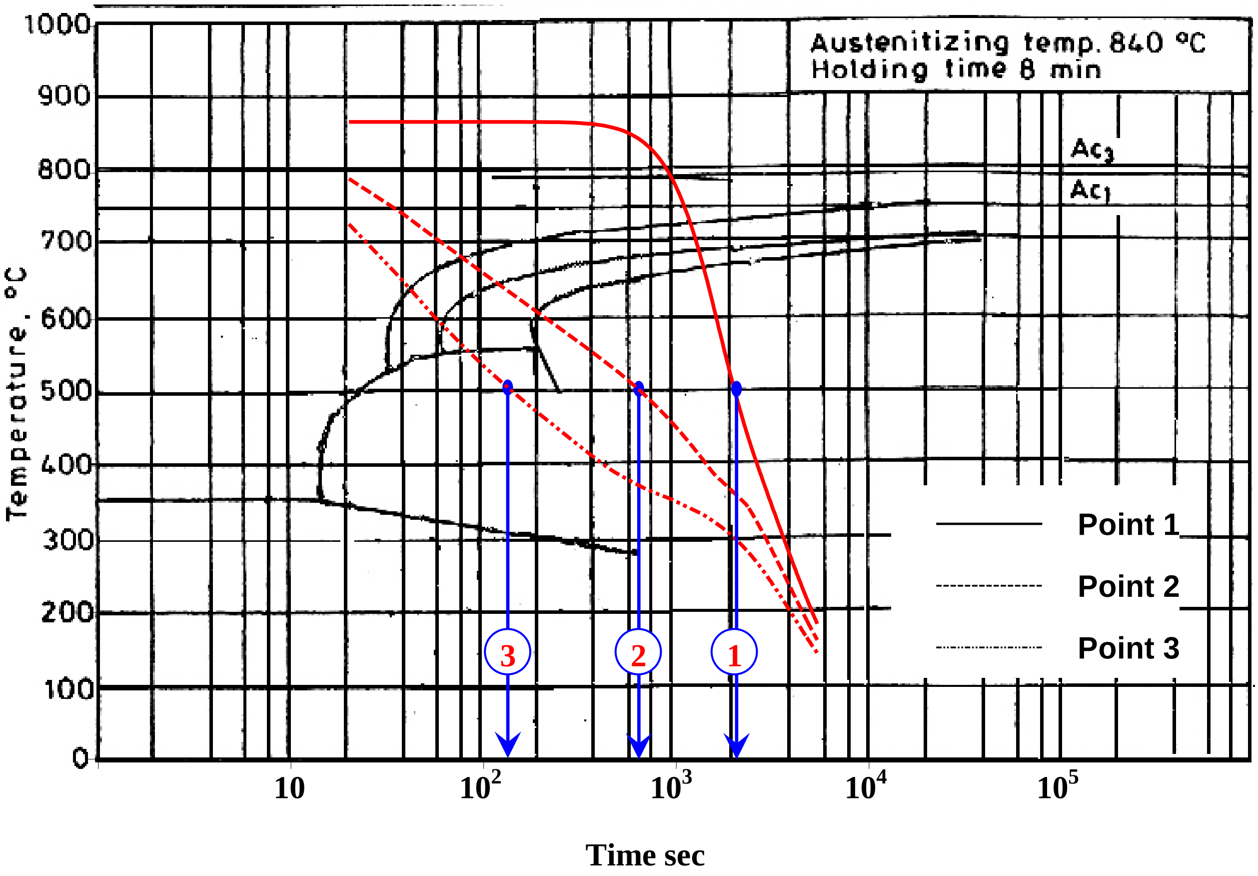
Figure (8)-A, B, comparison between the temperatures distribution for the annealing and normalizing treatment

THE HARDNESS PREDICATION

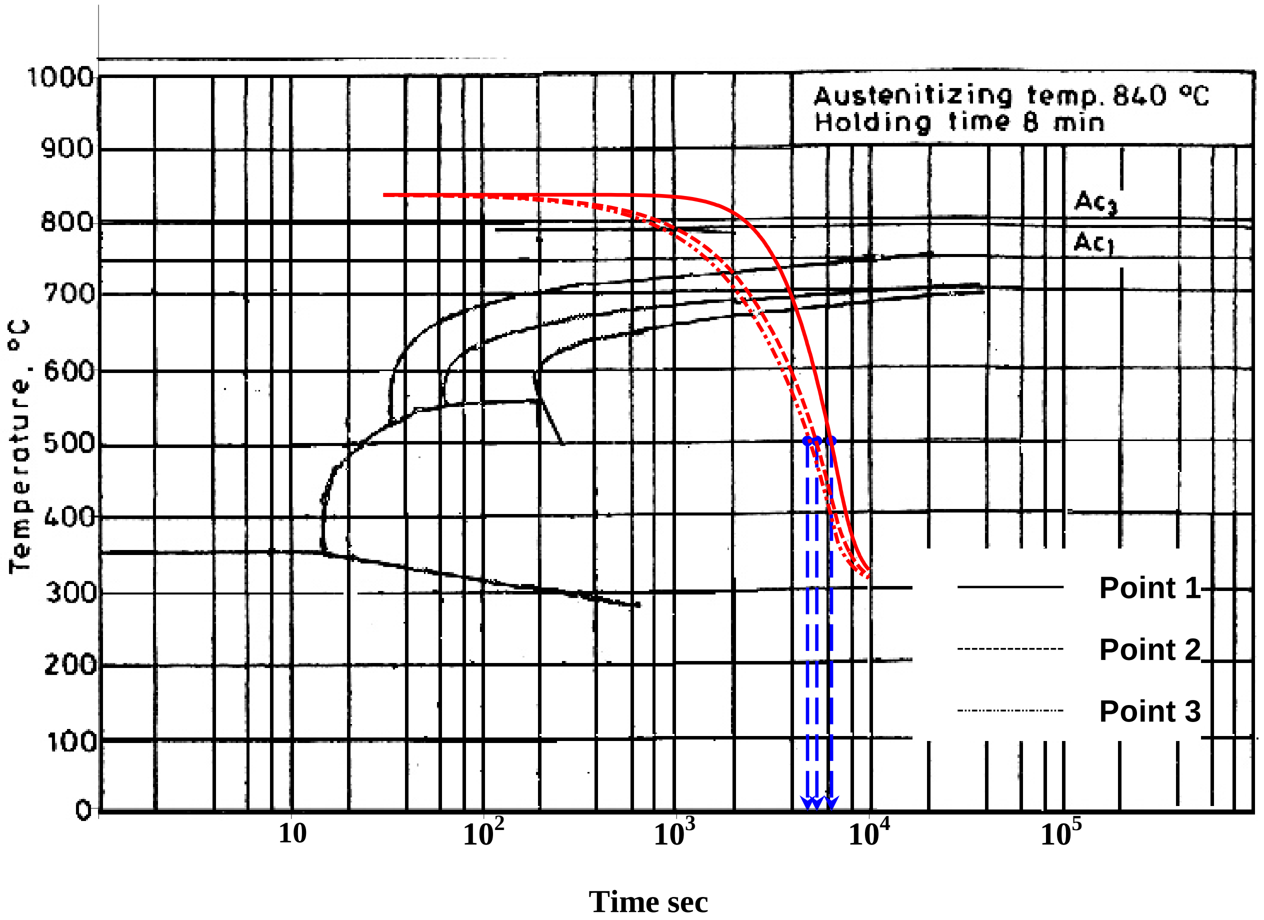
After we calculate the temperature distribution in the previous section we will used this data to investigate the phase transformation and the value of the hardness in each point in the workpiece by using a method consist of the below steps.

By using the continuous-cooling-transformation (CCT) diagram we can determined time required to reach the temperature 500 ^{o}C (by intersection with the isothermal line 500 ^{o}C), this step will be use to examination each point in the workpiece and determined the required time to reach the temperature 500 ^{o}C for each point.

For example figure (9) A, B shows the cooling curve for the three point (point nod 1, point nod2 and point node 3 see figure 1) for the normalizing and annealing treatment respectively and when the cross sectional area is **(30*30) cm^{2}** , from figure (9)-A we can see the time required to reach the isothermal line 500 ^{o}C (to the three points) this time can be noted as 1, 2 and 3, from these value we can see that the time required to each point is different from point to other this lead to different phase structure and mechanical properties. Figure (9)-B shows the same case but for the annealing treatment. It's very important to noted that the different between time required to reach the isothermal line 500 ^{o}C for the three point (point nod 1, point nod2 and point node 3) in the annealing case are less than that for the normalizing treatment, this case lead to uniform phase structure in the annealing treatment more that that for the normalizing treatment.



A-Normalizing Treatment



B-Annealing Treatment

Figure (9) Continuous-Cooling-Transformation (CCT) Diagram and steps to determined the required time to reach the isothermal line 500 °C for the two cases **A-Normalizing, B-Annealing**

After we determined the time for each point in the workpiece we will use this value to determine the phase structure and the hardness at each point by using figure (10), which shows the relationship between the time and the phase structure and the hardness value in HRC.

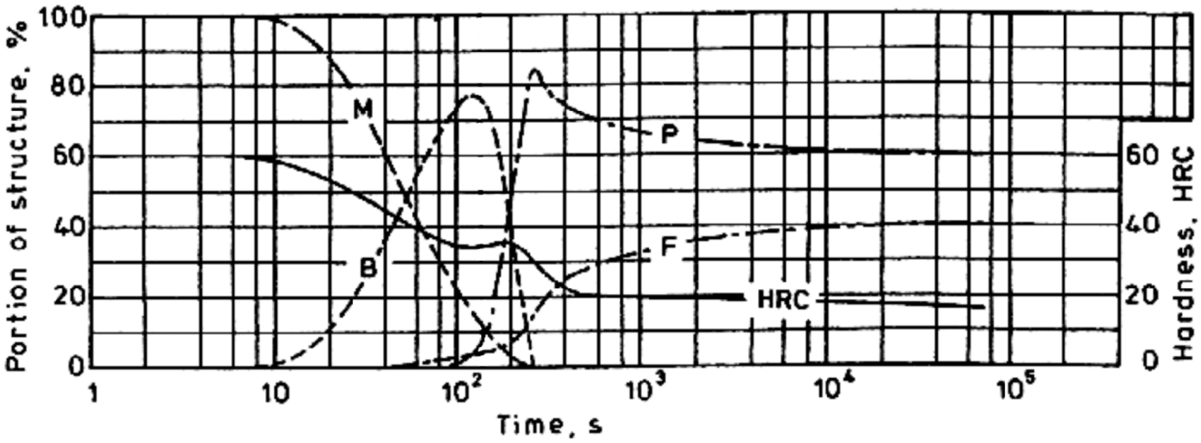


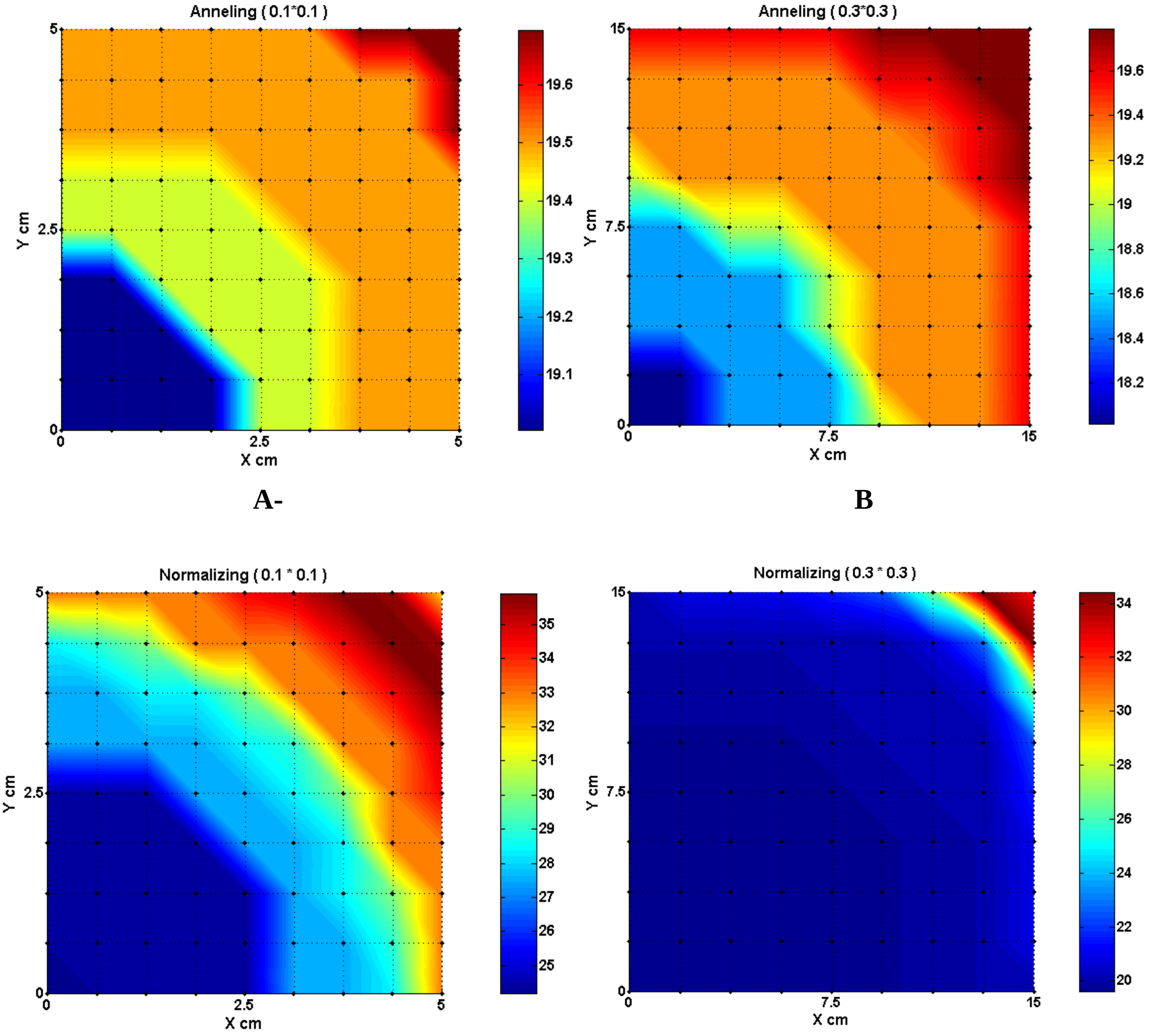
Figure (10) The relationship between the time and phase fraction and hardness in HRC [5].

Table (5) shows the phase structure and the hardness no in HRC for same point for the annealing and normalizing treatment and with two cross sectional area which are **(10*10) cm^2** and **(30*30) cm^2** .

Table (5) The phase structure and the hardness no in HRC

Treatment Type	Nod Point	%F	%P	%B	%M	HRC
Annealing Treatment (10*10) cm^2	Nod 1	38	62			19
	Nod 2	37.2	62.8			19.5
	Nod 3	37	63			19.7
Annealing Treatment (30*30) cm^2	Nod 1	39	61			18
	Nod 2	37	63			19.7
	Nod 3	36.6	63.4			19.8
Normalizing Treatment (10*10) cm^2	Nod 1	25	75			24.1
	Nod 2	12	78.5	9.5		33
	Nod 3	5.2	8.5	73.8	12.5	31.9
Normalizing Treatment (30*30) cm^2	Nod 1	36.6	63.4			19.8
	Nod 2	31	69			20
	Nod 3	6	9.5	72.5	12	32.5

After we used the above methods to determined or predicate the hardness distribution for the workpiece for the two cases of heat treatment process these hardness value show in figure (11)-A,B,C and D, where this figure show the hardness distribution in HRC for the annealing and normalizing treatment process with (10*10 cm^2) and (30*30 cm^2), from this figure we can see there is a hardness difference between each point in workpiece, in fact this is duo to differences in the microstructure or phase structure which is depending on the cooling rate of each points from the workpiece, from figure(11)-A, we can see that the difference is not high between the inner and the boundary of the workpiece, these difference is increase with cross sectional area increasing see figure (11)-B, figure (11)-C shows the hardness value and distribution which is more that that for annealing treatment , and the hardness increment when the cross sectional area increase is more than that in the annealing treatment see figure (1).



A- B

C D

Figure (11) the hardness distribution for the workpiece

CONCLUSIONS

1-During the cooling process in the heat treatment there is a specific time at which the thermal gradient through the cross sectional area is maximum we can note it as (**T$_{M.T.G}$**) (**Time of Maximum Thermal Gradient**), before this time (**T$_{M.T.G}$**) the thermal gradient is increase with time increase and after this time the gradient is decrease with time increasing. Thermal stress or crack may be occurring duo to high thermal gradient (which is occurs at this point) so that it's very important to specify this point in the heat treatment process.

2-The possibility of thermal stress and crack during the normalizing treatment is more than that in the annealing treatment also the high cross sectional area tend to this defect more than the small cross sectional area.

3-Generally the hardness is a function for (phase type and phase percent), and this hardness value decrease when the cooling time increase, but this behavior is change between the times from (120 to 200) sec where the hardness value at this cooling time range will increase with time increasing, even with phase portion change so that the hardness of point nod 3 (P3) is less than the hardness of point 5, point 4, and point 7. Also in the cooling time range (440 to 3100) sec there is no effect to the cooling time on the hardness even with increasing the %F phase and decreasing the %P phase.

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