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# *Study of Thermal Distortion in Thick Plate Using Finite Element Technique* *

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## Abstract

***The aim of the present study is to represent a numerical modeling of thermal distortion and stress distribution of welded plate by using submerged arc welding .The study is carried out using existing software, which is the ANSYS package. The distortion of welded plate is found to be a nonlinear problem in geometry and material; therefore, the finite element solution is based upon the thermo-elasto-plastic and large deflection theory.***

***The present work is an extension to a previous experimental work, where heat absorption paste (bentonite) was used to reduce distortion in welded plate, as a result of high local heating during welding process. The numerical results of distortion give reasonable indication with the distortion observed by Al-Dhamin [1].***

***Different rates of heat absorption are considered in this study over different area of cooling. The results show that, the distortion may be reduced significantly, by using cooling technique more efficient than the bentonite, as, using the cooling liquid of nitrogen. In this work, the optimum ratio of the cooling zone width (a) to the welded plate width (b), so as to minimize the distortion, is found equal to (a/b=0.2) for the plate at cooling temperature, equal to ($30C^{o}$, $0C^{o}$) and (a/b=0.4) for plate with cooling temperature equal to ($-30C^{o}$).***

***One of the experimental applications of this study is the formulation by heat source, as it is done with the structure of ships.***

## الخلاصـــــة

*يهدف البحث لإجراء تحليل عددي لحساب التشوه المرن-اللدن والإجهادات المتولدة نتيجة التأثير الحراري أثناء عملية اللحام لألواح ذات أسماك مختلفة.حيث تم التحليل العددي بواسطة إستخدام طريقة العناصر المحددة. حيث تم بناء برامجيات لهذا الغرض كما تم إستخدام الـ (**ANSYS**) في التحليل لكونه يعطي مرونة عالية أثناء العمل ونتائج أكثر إستقراراً. إن عملية التشوه للصفائح اثناء اللحام وجد أنها من المسائل الغير خطية في السلوك الشكلي وسلوك المعدن لذلك تم إشتقاق علاقات طريقة العناصر المحددة إعتماداً على نظرية التشوه المرن-اللدن للتشوهات الكبيرة اللاخطية.*

*إن العمل الحالي هو إمتداد لبحث سابق عملي تم إجراءه، حيث تم حساب التشوه وإستخدام (الطين خاوه) كطريقة لإمتصاص الحرارة وتقليل التشوه أثناء عمليات اللحام. إن النتائج العددية أعطت مؤشر جيد من النتائج العملية التي تم حسابها من قبل الباحث [١].*

*مختلف معدلات إمتصاص لحرارة اللحام قد تم إفتراضها أثناء هذه الدراسة بإفتراض إستخدام طرق تبريد أكثر كفاءة من الطين خاوه كإستخدام سائل النتروجين. بينت النتائج إن هناك نقصان في التشوه بنسب كبيرة. في هذه الدراسة تم إيجاد أفضل بعد نسبي ما بين عرض منطقة التبريد (**a**) إلى عرض اللوح المراد لحامه (**b**) بحيث يتم إعطاءه أقل تشوه، ووجد أن النسبة هي (**a/b=0.2**) عند درجة حرارة تبريد (**$30^oC$, $0^oC$**) وتكون النسبة هي (**a/b=0.4**) عند درجة حرارة تبريد (**$-30^oC$**) كما وجد أن زيادة منطقة التبريد أعلى من النسب أعلاه لا يقلل من التشوه الحراري.*

*ومن التطبيقات العملية لهذا البحث هو التشكيل بواسطة إستخدام مصدر حراري كما هو الحال في صناعة هياكل ومقدمة السفن.*


* Republished Paper (Accepted for Publishing in 2002)

## 1. Introduction

During the World War II, large numbers of ships were needed for war and to meet the urgent demands, United States started a large-scale program to produce instead of riveted ship for the first time in history. By that time the technique of welding steel plate had been established.

However, there had not been enough knowledge and experience regarding design and fabrication of large welded structures and their fracture characteristics. Enormous research effort was carried out due to structural failures of 20% of ships produced during the World War II, to establish a rigid technology for fabricating welded ships and other structures between 1954 and 1955.

Welding of parts is often carried out by holding with some kind of fixture, to keep them in the right position during welding. Welding without fixture may lead to large geometrical imperfections in the finished product. On the other hand, fixtures may affect the residual stress distribution in the weldment, so there is a need for an accurate simulation of the problem to determine the thermal distortion and stress developed in the welding zone. Multiple arcs are used in the automatic welding of long butt joints to reduce the time required for the welding operation. Different types of welding sequences are possible in such cases. A suitable sequence of welding will minimize the distortion [1].

As an application of line heat of the plate forming, this method is currently used at most shipyards worldwide to fabricate the ships fore-and after body. The forming process consists of heating at a (steel) plate in predetermined pattern of lines by means of e.g. a gas torch so that the plate assumes a certain, curved shape. Thus, the method is an alternative or supplement to other forming methods such as pressing and rolling. Today, few skilful shipwrights are capable of performing the art of line heating, as the amount of heating and the position of the lines are entirely based on experience. A rational method for the determination of heating line patterns and heating amount would be very beneficial [2]. Therefore, a finite element method is used to determine the heating line patterns.

## 2. Literature Review

R. A. AL-Dhamin [1] studied distortion of welded plate by using submerged arc welding (S.A.W) and the effects of welding power on that distortion. His work was done experimentally where different thickness of plates (6, 8 and 10mm) was used and higher distortion rates were observed by using higher power input on the same plate thickness, lower distortion rates were observed by using larger plate thickness and heat absorption paste (bentonite was used to reduce distortion and reduction around 50% was observed in all plate thickness.

A. G. Kamtekar [4] studied the residual stresses caused by weld shrinkage in a plate containing a central longitudinal weld. A theoretical analysis was developed in which the weld was treated as a moving concentrated heat source. The equations were solved in finite difference form and the stresses were computed at discrete stage during welding and cooling.

## 3. The Numerical Modeling of the Thermal Distortion Process

As the first step in the analysis of the thermal distortion problem, the heat conduction problem is assumed to be unaffected by the stress strain field and therefore the temperature field can be evaluated beforehand. Then, the stress-strain field follows. Before the thermo-elastic-plastic analysis is applied, the steady state temperature distribution during the process should be determined. The temperature gradients cause residual stress and thermal distortion. The calculated temperature field is used as a loading condition that creates the residual stress.

### 3-1 Finite Element Modeling

The problem of thermal distortion of thick plate is assumed as three-dimension thermo-elasto-plastic large deflection condition [5,6]. Due to symmetry of the problem domain, transverse section "c-c", as shown in **Fig.(2)**, can only be considered in the solution and the three-dimension models are reduced to two-dimension plane strain condition without losing the accuracy of the results.

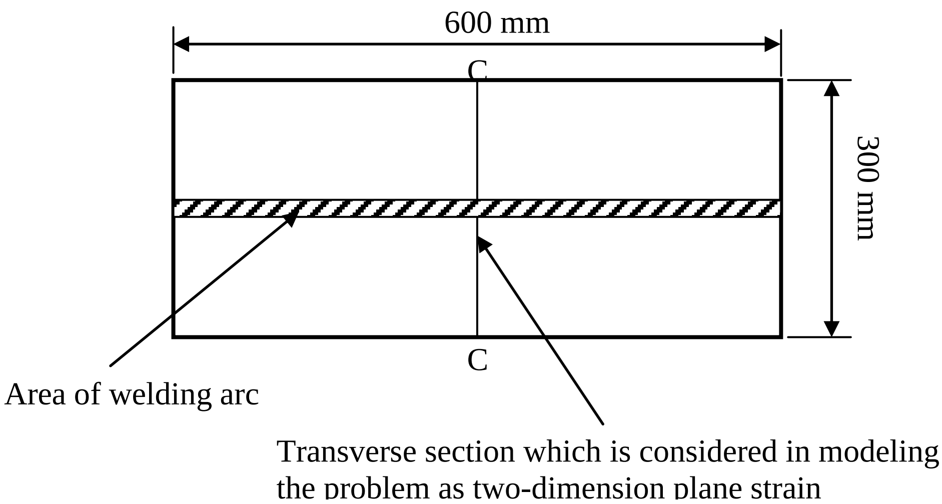


**Figure (2) The main dimensions of the welded plates**

**Figure (3)** shows the three-dimension discretization of the problem using "5400" elements of 8-node "hexahedral solid element 45" with "13237" nodes. While **Fig.(4)** shows two-dimension finite element mesh for a center line "c-c", where the problem is treated as plane strain condition and 8-node serendipity elements are used with 1000 nodes. The thermal loading due to welding process is considered as external zone temperature affected by value equal to 1650 $^{o}$C. The problem of the welded plate as shown in **Figs.(5,6,7)** is solved firstly, as steady-state heat transfer problem using the ANSYS package with the following boundary condition:

i) Essential boundary condition $\Gamma_1$ with temperature rose due to the local heating during welding process, $T_{wz}$ = 1650 $^{o}$C.

ii) Natural heat convection boundary $\Gamma_2$ with h= 4.5, and $T\infty$= 30 $^{o}$C.

iii) Cooling zone boundary condition $\Gamma_3$ $T=T_{cooling}$ =30 $^{o}$C,.

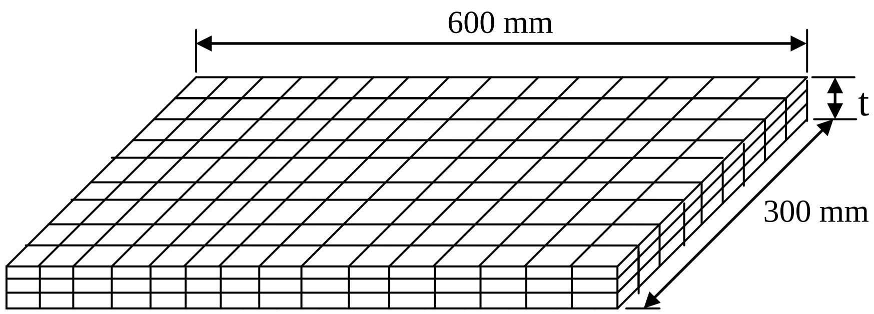


**Figure (3) 3-Dimension finite element mesh of the welded plate using 8-node hexahedral solid elements**

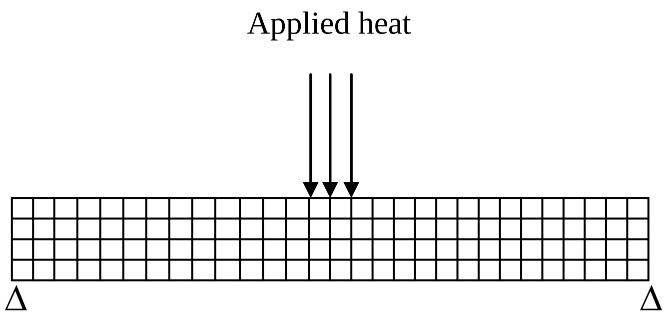


**Figure (4) 2-Dimension finite element mesh of the welded plate at the line of symmetry "c-c"**

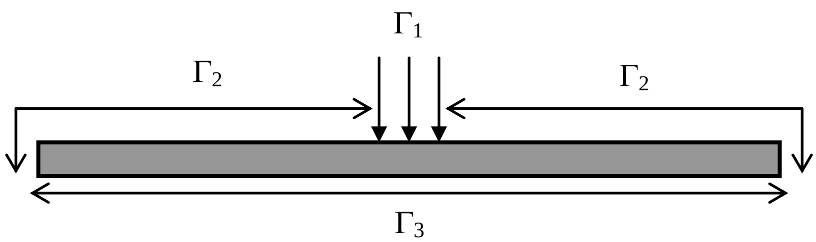


**Figure (5) Heat transfer boundary conditions**

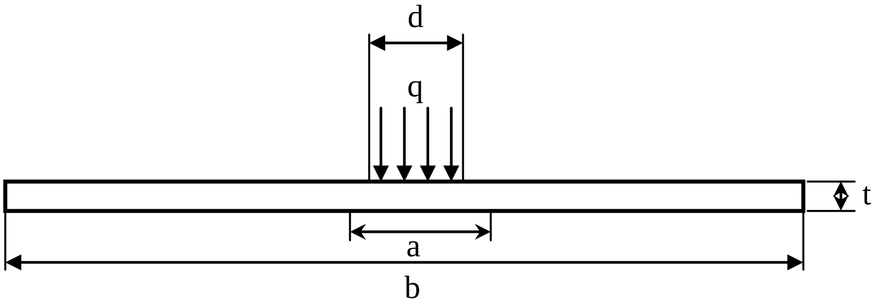


**Figure (6) Main dimension variables of the welded plate**

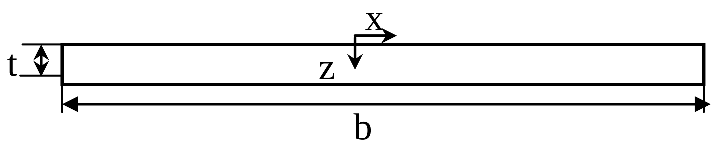


**Figure (7) Represents the location of the stress distribution**

Second step in the finite element solution is to apply the thermal loading which is raised due to the non-uniform, temperature distribution throughout the problem domain and the thermal deflection is found. The problem is solved as thermo-elasto-plastic large deflection.

## 3-2 Procedure of Finite Element Modeling Analysis

We performed both the temperature distribution analysis and the stress strain analysis sequentially. This procedure of solution using ANSYS package is shown in **Fig.(1)**.

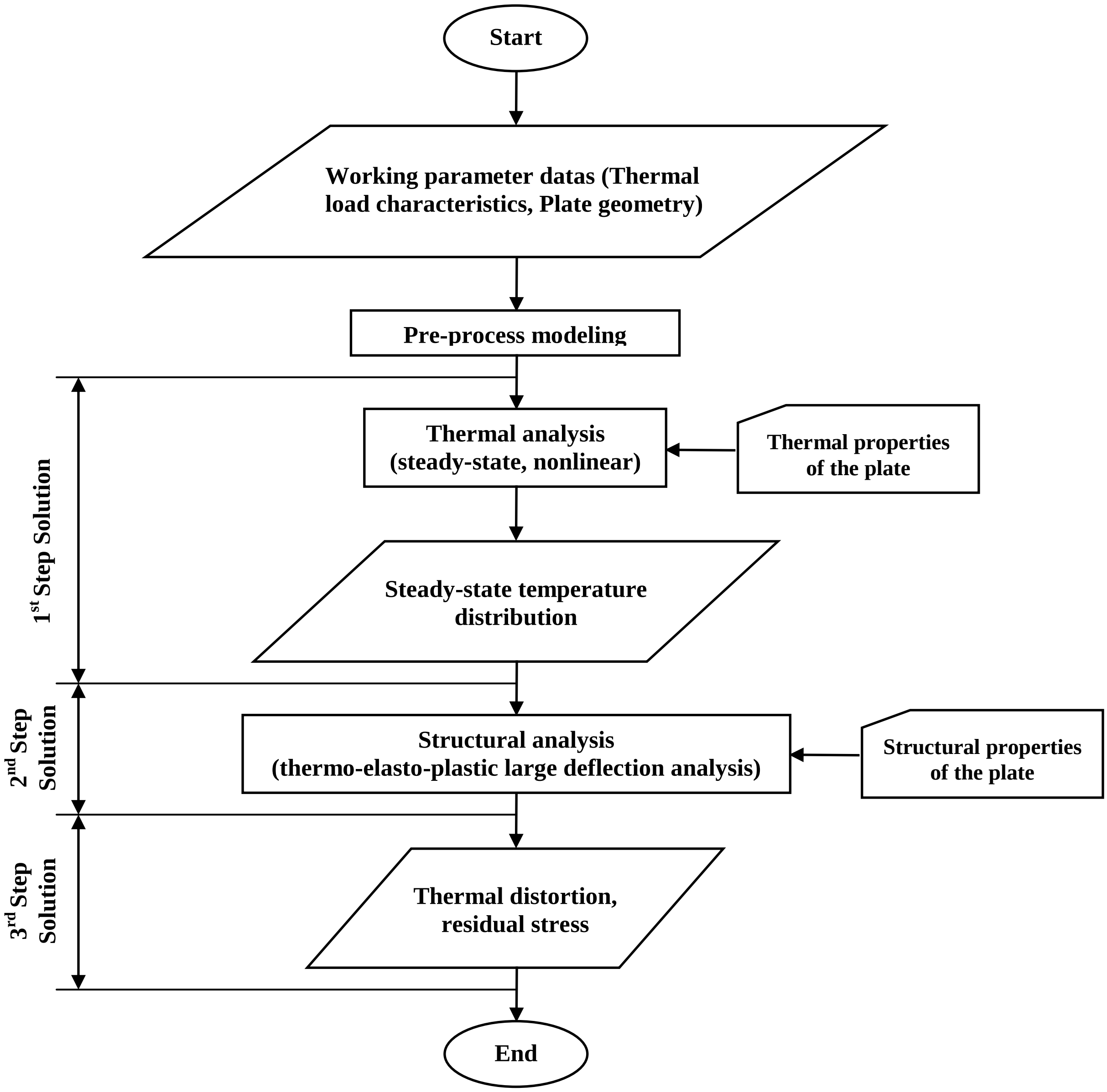


**Figure (1) Schematic diagram of the ANSYS analysis**

The main dimensions of the welded plates are shown in **Fig.(2)**. The material of the plate is taken from reference [2] which is the carbon steel. **Table (1)** shows the material properties used in the present work.

**Table (1) Shows the material properties of the carbon steel of the thick plate**

| Material properties | Value | Unit |
|---|---|---|
| E | 207E3 | MPa |
| $\nu$ | 0.3 | --- |
| $\alpha$ | 12E-6 | $1/^{O}C$ |
| $K_O$ | 44 | $W/\ m\ ^{O}C$ |
| C | 440 | $kJ/\ kg\ ^{O}C$ |
| $\sigma_y$ | 240 | MPa |
| $E_T$ | 20E3 | MPa |

There are many factors in welding process that affect the plate distortion in shape and magnitude. The following assumptions are taken through the numerical simulation:

i) The material properties are assumed independent to temperature especially at the welding zone of the welded plate.

ii) Heating line or Temperature welding zone with width equal to (20 mm) is assumed along the welding zone instead of the actual moving welding electrode.

## 4. Case Study

The case with plate thickness equal to (t = 4, 6, and 10 mm) and temperature welding zone ($T_{wz}$) equal to (1650 $^oC$) is considered Different (a/b) ratios (a/b = 0.05, 0.08, 0.1, 0.15, 0.2, 0.4, 0.8, 1) are considered where the cooling temperature is equal to ($T_{cooling}$ = 30 $^oC$, or zero or -30 $^oC$).

**Figures (8)**, **(9)**, and **(10)**, show the distortion magnitude at different (a/b) ratios. One can find out that, when the area of cooling increases, the magnitude of deformation will decrease gradually. Where spot cooling is used at the beginning, then by increasing the area of cooling .The magnitude of deformation will decrease gradually until the cooling area reaches the value of (a = 6 cm "a/b =0.2") where the deformation remains constant, i.e. after this value any increasing in the cooling area does not affect the magnitude of the deformation. The value of (a/b=0.2) is considered as an optimum value for this case and for all plate thickness.

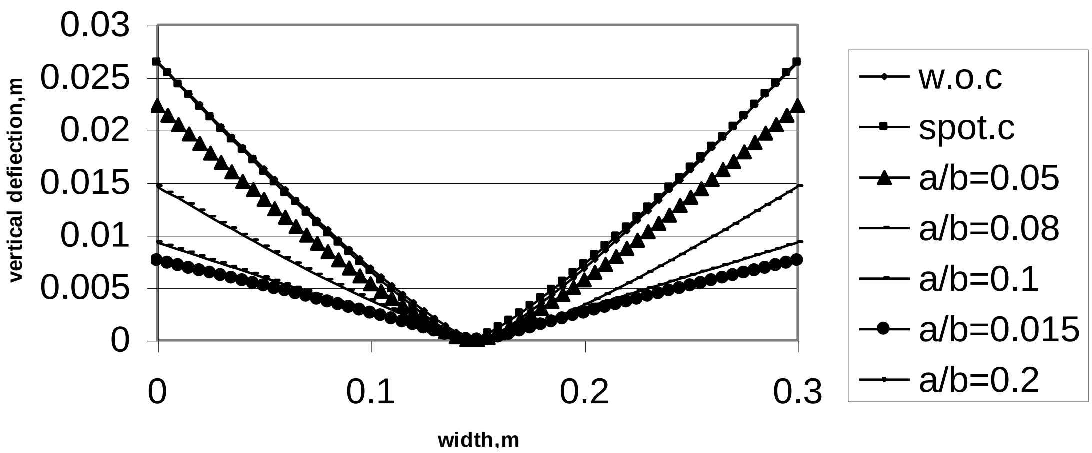


**Figure (8) Vertical deflection with out cooling and variable cooling area cooling temperature (30C) (t=4mm)**

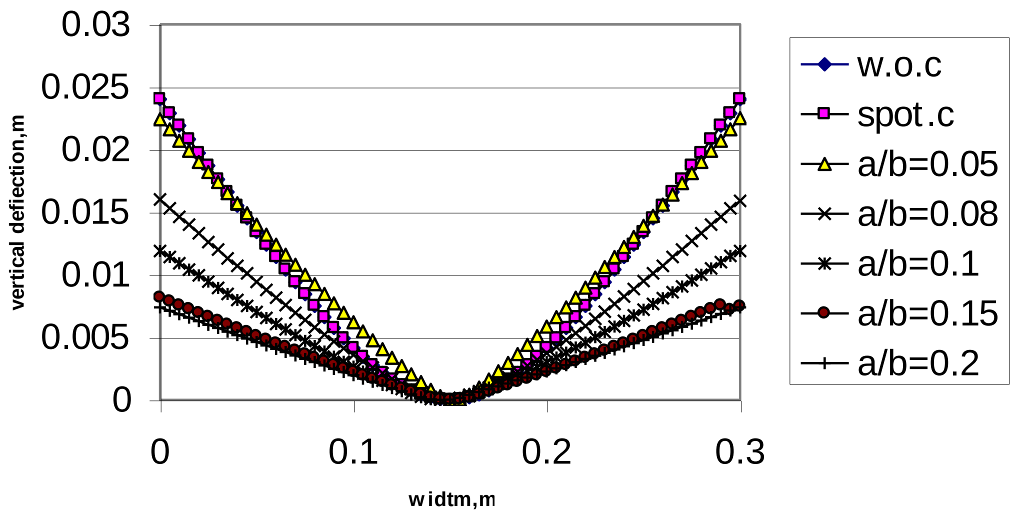


**Figure (9) Vertical deflection with out cooling and variable cooling zone area cooling temperature (30C) (t=6mm)**

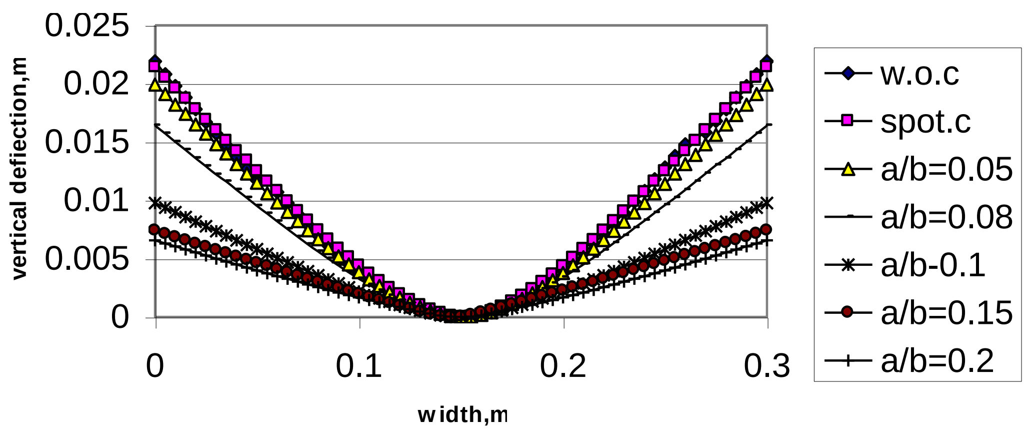


**Figure (10) Vertical deflection without cooling and variable cooling zone area cooling temperature (30C) (t=10mm)**

## 4-1 Temperature Distribution

The temperature distribution has been calculated for the plate with thickness equal to (4mm) without cooling, also it is calculated with cooling operation with different areas, when a/b is (0.05,0.1 and 0.2), and temperature cooling is 30 centigrade. The external welding temperature is applied to the upper surface in the middle of plate, whose area is (20mm), so as to be very close to the experimental work. The temperature welding zone ($T_{wz}$) is taken as 1650ºC and the temperature distribution is calculated on the upper and lower surfaces of the welded plate.

**Fig.(11)** shows the temperature distribution for plate thickness (4mm) without cooling. It is noticed that the temperature distribution satisfies the essential and natural boundary conditions. It is seen that the decrease of temperature is gradual at the upper and lower surfaces. Half of the plate is considered due to symmetry in the loading and geometry.

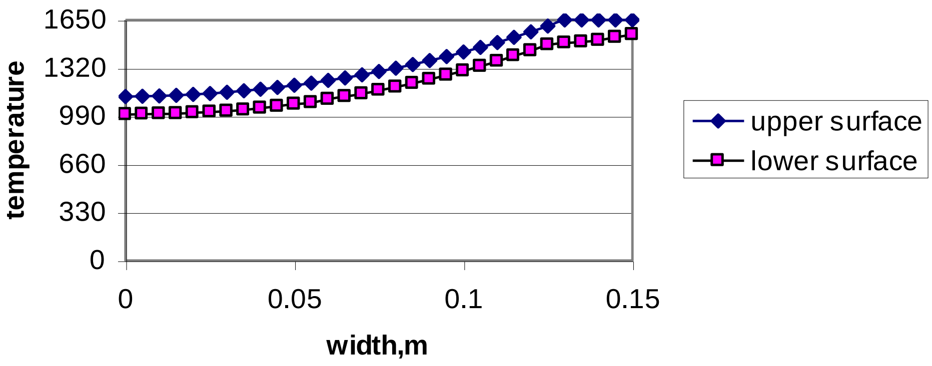


**Figure (11) Temperature distribution without cooling (t=4mm)**

In **Fig.(12)** the cooling ratio (a/b) = 0.05, [i.e. the cooling area is (1.5cm)]. It is noticed that the temperature distribution on the upper surface has been affected by cooling process that the temperature decreases gradually till the edge of plate with temperature equal approximately to 1100ºC. Also the lower surface temperature increases from 30Cº till it becomes at the end of the plate 500ºC.

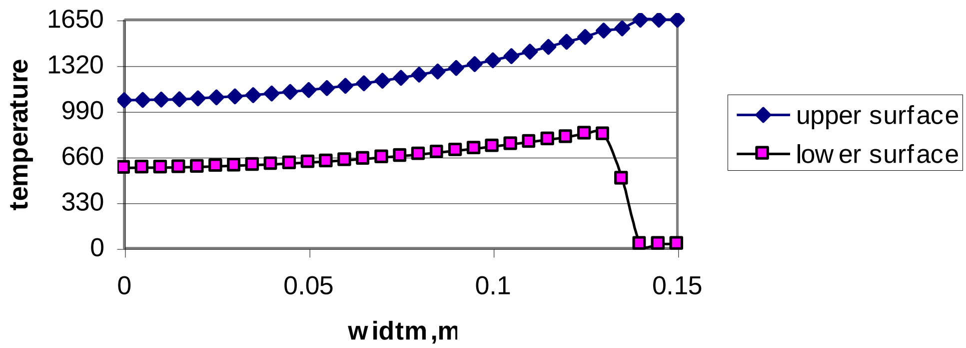


**Figure (12) Temperature distribution with cooling (a/b=0.05) (T=30c) (t=4mm)**

In **Fig.(13)** for the ratio (a/b)=0.1, the high effect of cooling process on the temperature distribution is indicated at the upper and lower surfaces, where the temperature decreases after limited time and becomes equal at two surfaces, which to approximately 110ºC. This is due to the fact that the cooling area is larger than the applied temperature area, and the small thickness has effects.

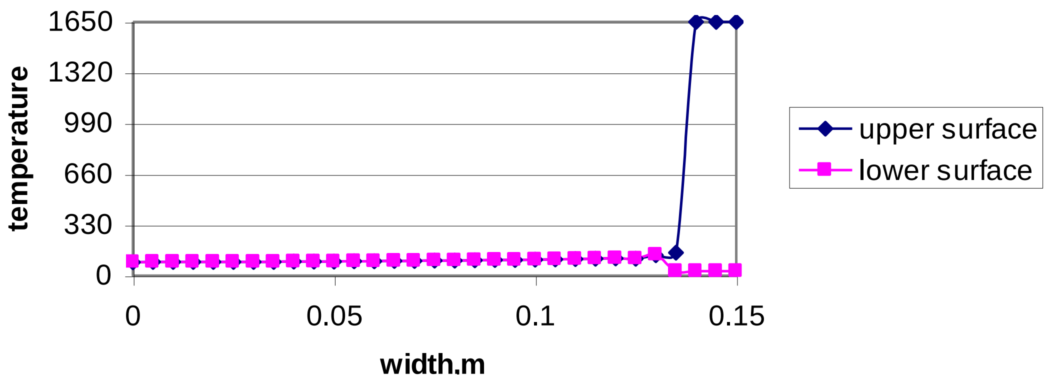


**Figure (13) Temperature distribution with cooling (a/b=0.1) (T=30c)**

In **Fig.(14)**, for the ratio (a/b)=0.2,the material becomes in (satisfied) situation. Then the material is not affected by increasing the cooling area. And the high difference between the cooling area and the applied temperature area is noticed. The temperature decreases at upper surface, and gradually the same with the lower surface.

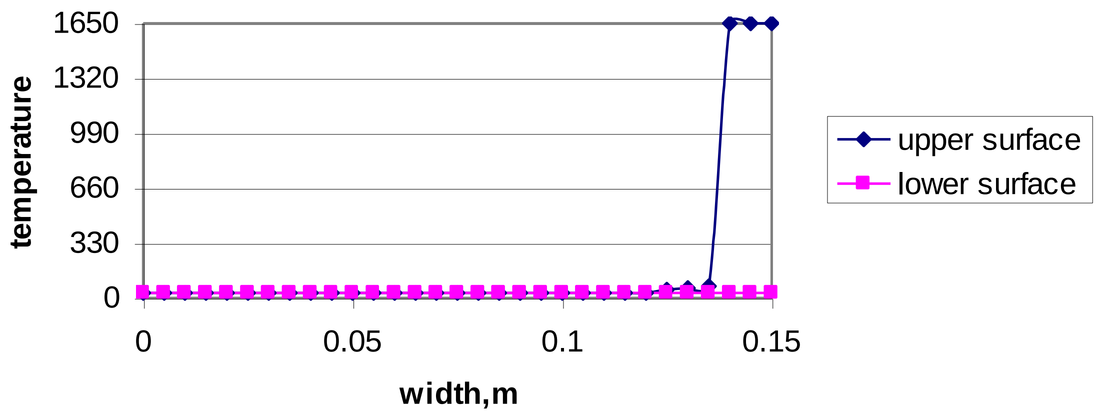


**Figure (14) Temperature distribution with cooling (a/b=0.2) (T=30c)**

## 4-2 Residual Stress Distribution

**Figures (15)** and **(16)** show the stress distribution through the plate thickness from the center of the plate to the free end, as shown in **Fig.(15)**. The distribution of residual stress in the x-direction ($\sigma_x$) is only considered for case with cooling temperature equal to 30ºC and (a/b=0.2), as a sample of the results. It can be seen that, for the case without cooling, the distribution of $\sigma_x$ varies in nonlinear manner and it changes from tension above the neutral axis to compression under the neutral axis. The point of inflection is displaced at the value (z/t=0.5) of that in the case of cooling ratio (a/b=0.2). It means that for case without cooling, the neutral axis is displaced from its elastic position i.e. the plate is in the elasto-plastic condition. The results of the pervious data have shown that the stresses decrease as the distance from the applied heat load increases for all cases.

Because of the localized heating and cooling operation, the uneven expansion and contraction of the effective area cause residual stress. The mid region is subjected to elevated temperature; whereas, the plates are essentially at ambient temperature. For steady-state condition the heat from the effective area is dissipated to the plate while the mid region is kept at constant temperature, the heat from the effective area is dissipated to the plate while the mid region is assumed at these effects because residual stresses distributed. Since there are no external forces acting on the plate, the tensile and compressive forces due to these stresses must balance each other.

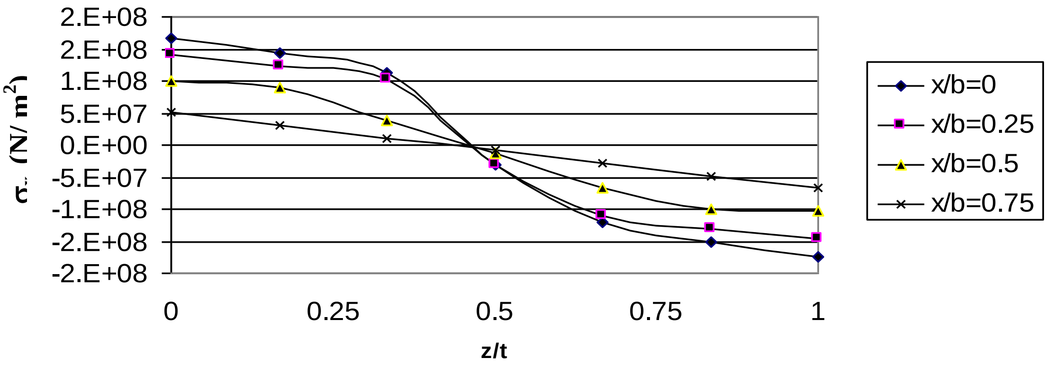


**Figure (15) Residual stress distribution through thickness without cooling (t=6mm)**

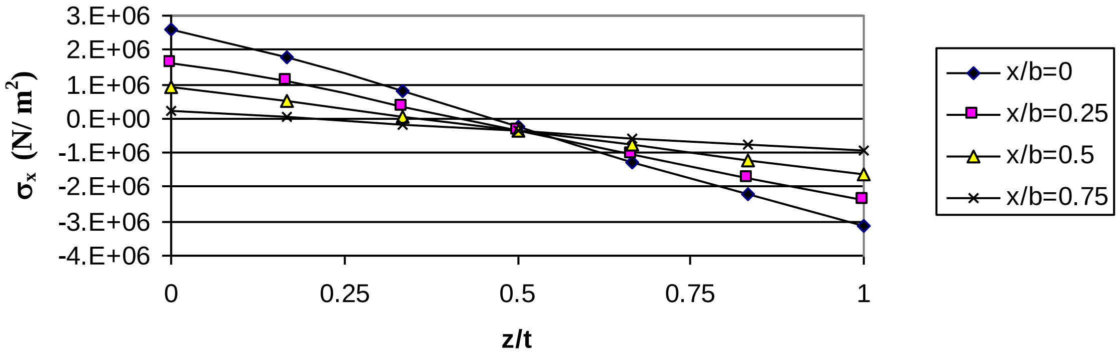


**Figure (16) Residual stress distribution through thickness with cooling (a/b=0.2) (t=6mm)**

## 5. Conclusions

In view of the results obtained, the conclusions that can be drawn are listed below:

1. The deflection is found to be directly proportional to the heat source input for the same plate thickness.
2. The deflection is found to be inversely proportional with plate thickness, when heat source input is constant.
3. The deflection reduced with increasing the cooling area but it is reached to a stable fixed value.

From the previous discussion, the following points can be clearly carried out for the future works as follows:

1. Temperature has great influence on the material properties, while during the present work it is assumed that the "modulus of elasticity, yield stress and tangential modulus of elasticity" are independent of temperature. Therefore, a Finite Element formulation can be extended to include the temperature influence.
2. Transient temperature distribution must be used in the thermal analysis, since the nature of the line heating process is a thermal transient process.
3. The modeling of the heating source must be modeled as moving torch flame.
4. Cooling temperature at T= -60˚C, -100˚C is to be investigated.

## 6. References


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