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Influence of the Butt Joint Design of TIG Welding on the Thermal Stresses

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Abstract

The aim of this paper is to demonstrate the influence of the single butt joint design of TIG welding on the thermal stresses for carbon steel type St-37. The butt welding was performed by V angles 30°,45°,60° and 90° and the thermal stresses analysis is based on the local moving heat flux. The numerical model developed by ANSYS12 software based on solving the three dimensional energy equation, considering moving heat source and temperature dependent material properties. Temperature and stresses distributions were obtained function of time. From the results, it is evident that the joint design has an important role in the welding process, when the edge angle of the welding region gets bigger, the faults get less due to increase of heat flux in the welding region. It can be concluded that the specimen with less than 6mm thickness can be welded without edge angle preparation, due to increase the thermal stresses when edge angle is evident and higher thermal stresses distribution was at edge angle 60° and lowest thermal stresses distribution was at 90°.

Keywords: Welding technology, Finite element method, Moving heat source, ANSYS12 software.

تأثير تصميم وصلة اللحام باستخدام قطب التنكستن على الاجهادات الحرارية

الخلاصة

في هذا البحث تم دراسة تأثير تصميم وصلة اللحام على الاجهادات الحرارية لفولاذ كاربوني نوع St-37 حيث تم اللحام بطريقة القوس الكهربائي باستخدام قطب التنكستن ووجود غلاف غازي للحصول على وصلات لحام تناكبية واجريت لها عملية تحضير بالزوايا V(30°,45°,60°,90°) من جهة واحدة، حيث ان تحليل الاجهادات الحرارية تم وفق مصدر حراري متحرك. لقد تم اعداد موديل عددي من خلال برنامج ANSYS12 ، أعتمد في النموذج العددي حل معادلة الطاقة ثلاثية الأبعاد ولمصدر حراري متحرك ، لمواصفات فيزيائية متغيرة مع درجة الحرارة، تغير الطور وباعتبار وجود مصدر حراري متحرك وخواص المواد معتمد على درجة الحرارة. ان توزيع درجات الحرارة والاجهادات الحرارية تم ايجادها لمنطقة اللحام دالة للوقت . وقد تم استنتاج ان تصميم حافة اللحام لها تأثير كبير على منطقة اللحام حيث كلما كبرت زاوية الحافة فان العيوب سوف تقل بسبب زيادة كمية الحرارة في منطقة اللحام . وقد تم الاستنتاج بانه يتم لحام الاسماك الاقل من 6 ملم بدون زوايا تحضيرية بسبب زيادة الاجهادات الحرارية التي تتولد نتيجة زوايا اللحام حيث ان اعلى توزيع حراري كان عند زاوية لحام 60° واقل توزيع كان عند 90°.

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Introduction

TIG butt welding is a process that is being widely used in industry for sheet joining purposes. Many applications of welding made of carbon steel (e.g. bridge structure, fuel tanks ..etc) are subjected to various stresses (mechanical, thermal ..etc). The toughness and resistance of the welded piece to failure depending on many factors such as shape, design of the welding piece, the method implemented for welding and the nature of the applied stresses. Estimation of the temperature field within a metal plate produced by a moving heat source subjected on its surface is obviously of a great practical interest for the study of welding processes. It is well known that the welding process relies on an intensely localized heat input, which tends to generate undesired residual stresses and deformations in welded structures, especially in the case of thin plates[1]. Therefore, estimating the magnitude of welding deformations and characterizing the effects of the welding conditions are deemed necessary. With modern computing facilities, the finite element technique has become an effective method for prediction and assessment of welding stresses[2]. Therefore, rapidly and accurately predicting welding induced distortion for real engineering applications is more challenging. Hani [3] (1998) explains the thermo-mechanical model which was developed using FE method to calculate temperature, stresses and distortions during elasto-plastic analysis. Lindergen et al [4] (2002) presented a thermo-mechanical Analysis in butt welding of copper canister for spent nuclear fuel. Anas And Abid [5] (2004) studied the finite element volume for modeling welds and it depicts a brief history of the Simulation of welds. Dragi and Ivana [6] (2009) studied the finite element analysis of residual stresses in butt welding of two similar plates. Hani and Khaiyria [7] (2010) studied experimentally and numerically the influence of single butt MIG welding shapes design on the microstructure and stresses of low carbon steel. Karima et al (2010) [8] studied the thermal distribution within metal plate subjected to moving heat source using finite element method. Many analytical 2D or 3D models have been developed in literatures [9,10,11,12] using integral transformations (a finite cosine Fourier integral transform), separation of variables and Jaeger's classical heat source method respectively. These models are principally based on several postulates regarding source term modeling methods (shape, source, distribution of energy) with or without surface cooling. The objective of this work is to study the thermal stresses of two metal plate subjected to a moving heat source during TIG welding process with different shape design.

Experimental

Choice of Metals

Low carbon steel St37 was chosen according to the Russian Standards (Gost) . Its chemical analysis is shown in Table (1).

Preparation of welding piece

- Selection metallic plates, 5 mm thick, 100 mm long and 30 mm wide.
- making preparation single V angle of 30°.
- The operation is repeated on the remaining pieces to make V angles of (45°, 60° and 90°).

Welding Process

Welding is done by electric arc (TIG) on the piece. The conditions for the process are indicated in Table(2) .The Input heat quantity is calculated by the following equation[1]:

$$Heat\ Input = \frac{IV \times 60}{S} \qquad (1)$$

where I .. current (amp.) , V.. Voltage (volt) , and S.. welding speed (m/min)

Welding Electrode

The welding electrode (316L) is used [13,14] with 2.8 mm diameter in which the chemical composition is shown in Table(3).

Classification of specimens

After preparation, the specimens were classified in the groups as shown below.

A	Butt welding single angle 30°
B	Butt welding single angle 45°
C	Butt welding single angle 60°
D	Butt welding angle 90°

Mathematical Model

Conservation of Energy

The three dimensional energy equation for an isotropic material is used to describe the plate thermal history [8,15].

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q^\bullet}{l} = \frac{1}{a}\frac{\partial T}{\partial t}$$

(2)

where

a is the thermal diffusivity of the metal at time t

$q^\bullet$ internal heat source per unit volume (existed when the is phase transformation otherwise it is vanished.

λ thermal conductivity of the metal. During phase transformation (i.e melting or solidification) then

$q^\bullet = r H \frac{\partial f_s}{\partial t}$ where H is the latent heat of fusion and ρ .. density.

Discretizition of equation(2) is adopted with FEM to give elemental matrices and vector. The assembly of these elemental matrices into global matrices and vector give first order transient simultaneous differential equations [3,15]:

Finally the plate surface exposed to specified heat flux q_s , can be formulated mathematically across the central segment of the upper surface as:

$$\lambda = \frac{\partial T_1}{\partial y}\Big|_{plate} = q_s \qquad (3)$$

$$C\dot{T} + KT = F \qquad (4)$$

The elemental matrices and vector can be computed from:

$$C^e_{ij} = \int_{\Omega^e} \rho c N_i N_j d\Omega \qquad (5)$$

$$K^e_{ij} = \int_{\Omega^e} \left(\lambda \frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + \lambda \frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y} \right) d\Omega + \int_{S^e} h N_i N_j d\Gamma \qquad (6)$$

$$F^e_i = \int_{S^e} N_i h T_\infty d\Gamma \qquad (7)$$

Finite Element Model

The general purpose FE package ANSYS12 is used for both the thermal and stress analyses performed directly with an appropriate couple elements [7,16]. The main features of the 3D model are the moving heat input, the element birth-and-death technique, the heat loss, the temperature-dependent material properties, and the application of ANSYS parametric design language (APDL) to model the moving heat source and adaptive boundary conditions (Appendix-A-). The element types used in the thermal and structural analyses are SOLID5 (Fig-1-). It is the 8-noded brick elements. The direct generation meshes used is shown in Fig.2 for different shapes design. The moving heat source is modeled by setting a heat flux to the elements of the fusion zone. The total heat input is evaluated according to the equation(1). The metal deposition is considered by using the element birth technique. This technique is based on deactivating and reactivating the elements of the fusion metal at a prescribed time as the deposition progresses. This is also the 'arrival' time for the heat input for the deposited elements. Consequently, the thermal mass and the heat flow conditions accurately portray the sequential deposition of the material. As it was mentioned earlier, the boundary conditions include convective heat loss. Since only the current outer surface of the partially completed deposit is a convecting surface at any given time, the boundary conditions are subject to the birth-death option. Also, the boundary conditions depend strongly on the position of the heat source[17]. The ANSYS steps can be demonstrated by our developed APDL program (Appendix -A-) to make the butt welding analysis.

Results and Discussion

By observed and calculated heat quantity as shown in Table (2), it is found that with increasing preparation edge angle of the welded plates, the heat quantity decrease, quantity of welding metal decreases, welding region possesses better quantities, greater heat transfer to adjoining region (which is effected directly by heat), while it can be shown that the heat quantity is equal with weld edge 30° V and 90° V, this is due to the same input parameters. Increasing of heat quantity contributes in growth of granules' volume with high ductility due to slow cooling of the metal during welding as well as weak mechanical properties (resistance to tension and hardness). Therefore, it is preferred that the welding angle be 30^o and 90° for homogenous heat distribution to it. Figs.(3,4,5,& 6) show the temperature distribution and the thermal stresses in the welded region due to moving heating flux, it can be seen that when the edge angle increased, the thermal stresses increased for angle 30°,45° and 60° while decreased in the 90° square butt welding. Weldability differs from one metal or alloy to another. It depends on its material properties (Table(4)), chemical composition and the method of welding. To insure good weld for the metal, the latter should be a good heat conductor, of little shrinkage and of small longitudinal expansion index. The more intense are the generated internal stresses, the greater would be the longitudinal expansion index and its shrinkage is greater. Evidently good welding quality would be better as the region adjacent to the seams of the weld is smaller. Weldability of low carbon steel down to 0.2% is very good. By increasing the carbon percentage, heat conductivity of steel decreases and the internal stresses in it are increased.

Conclusions

1. Higher thermal stresses distribution was at edge angle 60° and lowest thermal stresses distribution was at 90°.
2. It can be concluded that the specimen with less than 6mm thickness can be welded without edge angle preparation.
3. When the welding angle is increased, the stuffing material and its properties, have an influence on the properties of welding region.
4. The work presents the finite element model for numerical simulation of welding stresses in low carbon steel St-

37 butt welding. The welding simulation was considered as a direct coupled thermo- mechanical analysis.

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Appendix-A-

```
/view,1,1,1,1
/prep7
et,1,5,0
! properties of plate
mp,dens,1,7880:mp,kxx,1,60:
mp,c,1,480:mp,ex,1,210e9:
mp,nuxy,1,0.3
mp,alpx,1,1.15e-5
! plasticity coef.
TB,bkin,1:                    tbtemp,80:
tbdata,1,380e6,210e9*0.85
!properties of fusion area in the plate
mptemp,1,0,100,200,400,600,800,1000
,1200,1400,1550
mpdata,c,2,1,480,500,520,650,750,100
0,1200,1400,1600,1700
mpdata,kxx,2,1,60,50,45,38,30,25,26,2
8,37,37
mpdata,dens,2,1,7880,7880,7800,7760,
7600,7520,7390,7300,7250,7180
mpdata,alpx,2,1,1.15e-5,1.2e-5,1.3e-
5,1.42e-5,1.45e-5,1.45e-5,1.45e-
5,1.45e-5,1.45e-5,1.45e-5
mpdata,Ex,2,1,210e9,200e9,200e9,170
e9,80e9,35e9,20e9,15e9,10e9,10e9
mpdata,nuxy,2,1,0.3,0.3,0.3,0.3,0.3,0.3,
0.3,0.3,0.3,0.3
type,1 :  mat,1
n,1,0,0,0     :        n,2,0,0,0.025     :
n,3,0.03,0,0.025: n,4,0.03,0,0
n,5,0,0.0025,0:      n,6,0,0.0025,0.025:
n,7,0.03,0.0025,0.025:
n,8,0.03,0.0025,0
en,1,1,2,3,4,5,6,7,8:        n,9,0,0.005,0:
n,10,0,0.005,0.025:
n,11,0.03,0.005,0.025
n,12,0.03,0.005,0:
en,2,5,6,7,8,9,10,11,12:
n,13,0.06,0,0.025: n,14,0.06,0,0
n,15,0.06,0.0025,0.025                :
n,16,0.06,0.0025,0:
en,3,4,3,13,14,8,7,15,16
n,17,0.05785641,0.005,0.025:
n,18,0.05785641,0.005,0
en,4,8,7,15,16,12,11,17,18                :
n,19,0.093,0,0.025:  n,20,0.123,0,0.025
n,21,0.123,0,0      :      n,22,0.093,0,0:
n,23,0.093,0.0025,0.025
n,24,0.123,0.0025,0.025                   :
n,25,0.123,0.0025,0                       :
n,26,0.093,0.0025,0
en,5,19,20,21,22,23,24,25,26:
n,27,0.093,0.005,0.025                    :
n,28,0.123,0.005,0.025
n,29,0.123,0.005,0:
n,30,0.093,0.005,0:
en,6,23,24,25,26,27,28,29,30
n,31,0.063,0,0.025    :    n,32,0.063,0,0:
n,33,0.063,0.0025,0
n,34,0.063,0.0025,0.025:
en,7,31,19,22,32,34,23,26,33
n,35,0.06514359,0.005,0.025:
n,36,0.06514359,0.005,0
en,8,34,23,26,33,35,27,30,36
*do,i,1,24,1
n,36+i,0.06,0,0.001*i
*enddo
*do,i,1,24,1
n,60+i,0.063,0,0.001*i
*enddo
*do,i,1,24,1
n,84+i,0.06,0.0025,0.001*i
*enddo
*do,i,1,24,1
n,108+i,0.063,0.0025,0.001*i
*enddo
en,9,14,37,61,32,16,85,109,33:
en,10,37,38,62,61,85,86,110,109
en,11,38,39,63,62,86,87,111,110:
en,12,39,40,64,63,87,88,112,111
en,13,40,41,65,64,88,89,113,112:
en,14,41,42,66,65,89,90,114,113
en,15,42,43,67,66,90,91,115,114:
en,16,43,44,68,67,91,92,116,115
en,17,44,45,69,68,92,93,117,116:
en,18,45,46,70,69,93,94,118,117
en,19,46,47,71,70,94,95,119,118:
en,20,47,48,72,71,95,96,120,119
en,21,48,49,73,72,96,97,121,120:
en,22,49,50,74,73,97,98,122,121
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en,23,50,51,75,74,98,99,123,122 :
en,24,51,52,76,75,99,100,124,123
en,25,52,53,77,76,100,101,125,124 :
en,26,53,54,78,77,101,102,126,125
en,27,54,55,79,78,102,103,127,126 :
en,28,55,56,80,79,103,104,128,127
en,29,56,57,81,80,104,105,129,128 :
en,30,57,58,82,81,105,106,130,129
en,31,58,59,83,82,106,107,131,130:
en,32,59,60,84,83,107,108,132,131
en,33,60,13,31,84,108,15,34,132
*do,i,1,24,1
n,132+i,0.05785641,0.005,0.001*i
*enddo
*do,i,1,24,1
n,156+i,0.06514359,0.005,0.001*i
*enddo
type,1
mat,2
en,80,16,85,109,33,18,133,157,36 :
en,85,85,86,110,109,133,134,158,157
en,90,86,87,111,110,134,135,159,158 :
en,95,87,88,112,111,135,136,160,159
en,100,88,89,113,112,136,137,161,160
:
en,105,89,90,114,113,137,138,162,161
en,110,90,91,115,114,138,139,163,162
:
en,115,91,92,116,115,139,140,164,163
en,120,92,93,117,116,140,141,165,164
:
en,125,93,94,118,117,141,142,166,165
en,130,94,95,119,118,142,143,167,166
:
en,135,95,96,120,119,143,144,168,167
en,140,96,97,121,120,144,145,169,168
:
en,145,97,98,122,121,145,146,170,169
en,150,98,99,123,122,146,147,171,170
:
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en,160,100,101,125,124,148,149,173,172
:
en,165,101,102,126,125,149,150,174,173
en,170,102,103,127,126,150,151,175,174
en,175,103,104,128,127,151,152,176,175
en,180,104,105,129,128,152,153,177,176
:
en,185,105,106,130,129,153,154,178,177
en,190,106,107,131,130,154,155,179,178
:
en,195,107,108,132,131,155,156,180,179
en,200,108,15,34,132,156,17,35,180 :
D,all,ux: D,all,uy: D,all,uz
Allsel,all
finish
/SOLU
ANTYPE,trans
TRNOPT,FULL
NROPT,AUTO, ,
EQSLV,
SOLCONTROL,ON
AUTOTS,on
KBC,1 !step
OUTRES,ALL,ALL,
! moving heat flux
V=380 ! voltage (volt)
I= 130 ! Current (amp.)
S=2 ! welding speed (m/min)
qw=V*I*60/2
!load step 1, initial conditions 25 C
TIME,0.001
DELTIM,0.001,0.001,0.001
TUNIF,25,
solve
!load step 2..... , apply moving heat flux
j=1
*DO,i,195,85,-5
 TIME,j
 DELTIM,0.11,0.11,0.11,
 SFEDELE,i+5,6,HFLUX
!delete heat flux of previous step
 SFE,i,6,HFLUX, ,qw, , ,
!apply heat flux, face 6
 eplot
 solve
 j=j+1
*ENDDO
finish
```

Table(1) The Chemical Properties of the used Metal St 37

Wt% of element	C	Si	Mn	Cr	Mo	Cu	Co	V	W	Ai	Ni	P	S
Actual value %	0.2	0.009	0.65	0.011	).004	0.041	0.004	0.0009	0.003	0.001	0.012	0.09	0.05
Standard value %	0.18 - 0.23	0.01	0.3-0.6	-	-	-	-	-	-	-	-	0.04	0.05

Hardness (HB) =125

Table(2) Conditions of the Welding process(V=380 volt, welding speed, S=2 m/min, thickness= 5mm)

	Current I (Amp)	No. of passes	Input heat quantity (Joule)
30° V angle	130	1	804726000
45° V angle	120	2	742824000
60° V angle	123	2	761394600
90°	130	3	804726000

Gap (root) is made = 1mm for all joint design

Table(3) The Chemical composition of welding wire 316L

element	C	Si	Mn	Co	Ni	Cr	Cu	Mo
Wt%	0.03	0.5	1.5	0.19	10	17.1	0.22	1.510

Diameter of wire=2.8mm

Table(4) Material Properties[6]

Temperature (^oC)	Specific Heat (J/kg^oC)	Conductivity (W/m^oC)	Density (kg/m^3)	Yield Stress (MPa)	Thermal Expansion Coefficient (10-5/^oC)	Young's modulus (GPa)	Poisson's
0	480	60	7880	380	1.15	210	0.3
100	500	50	7880	340	1.2	200	0.3
200	520	45	7880	315	1.3	200	0.3
400	650	38	7760	230	1.42	170	0.3
600	750	30	7600	110	1.45	80	0.3
800	1000	25	7520	30	1.45	35	0.3
1000	1200	26	7390	25	1.45	20	0.3
1200	1400	28	7300	20	1.45	15	0.3
1400	1600	37	7250	18	1.45	10	0.3
1550	1700	37	7180	15	1.45	10	0.3

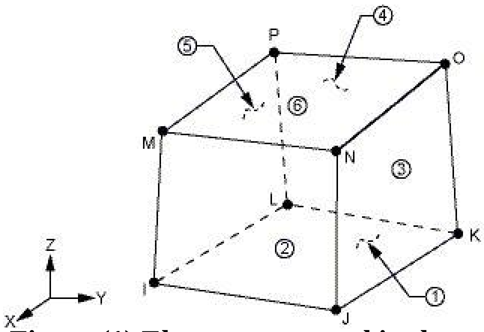


Figure (1) Element type used in the analysis(Solid5)

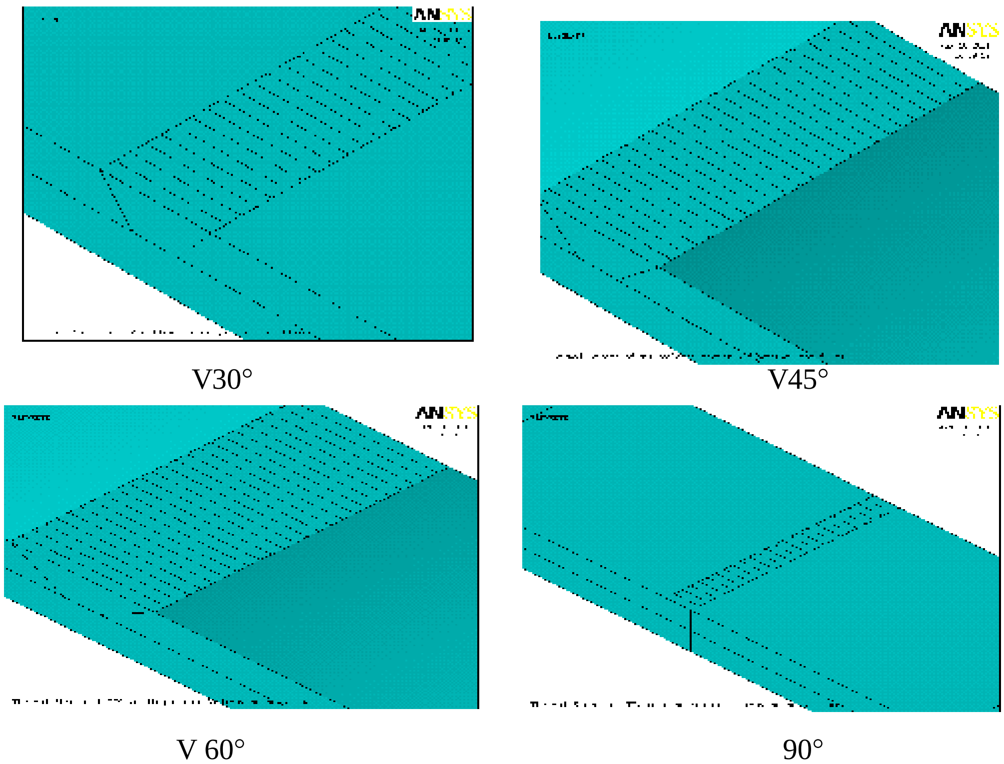
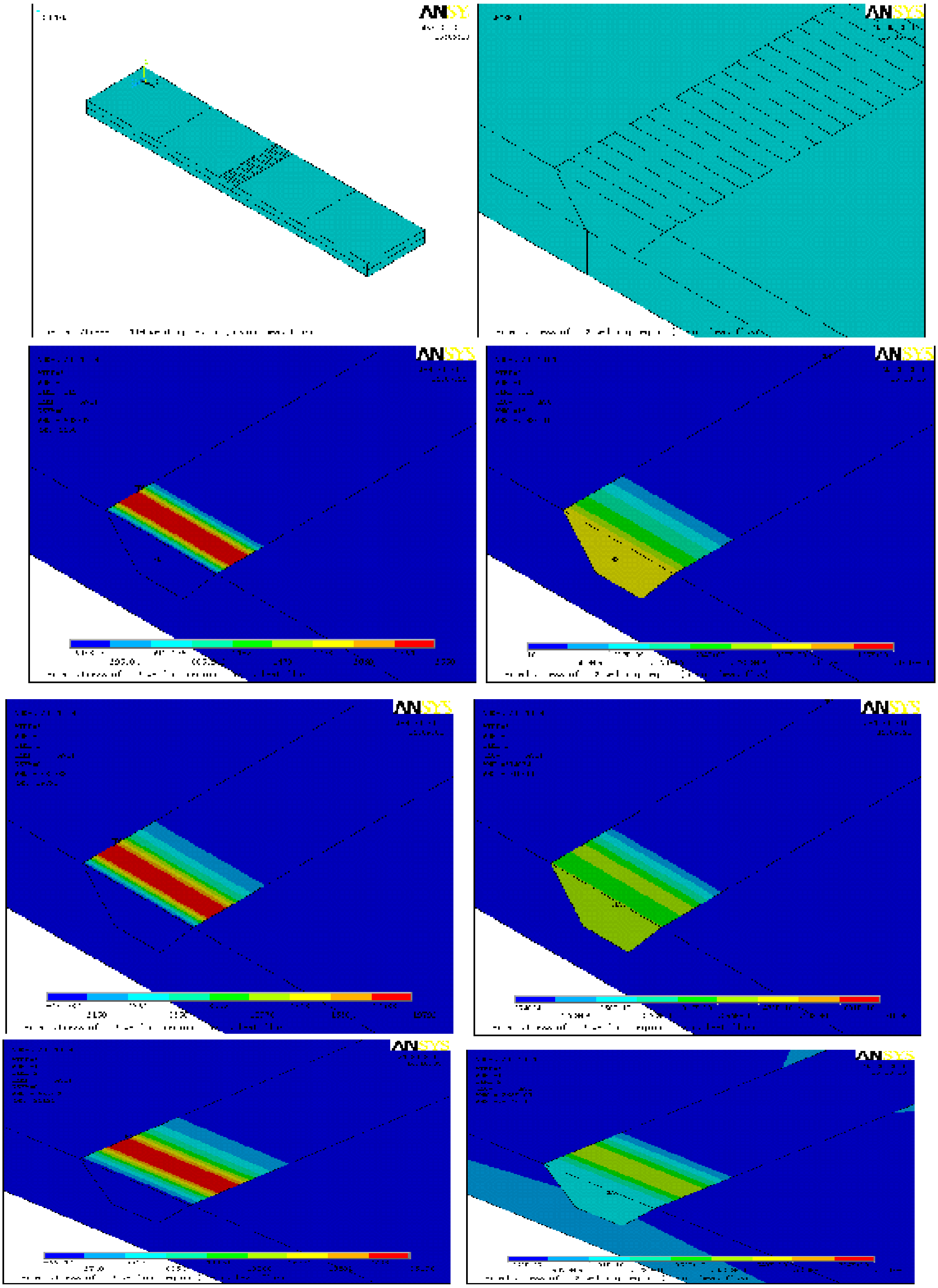
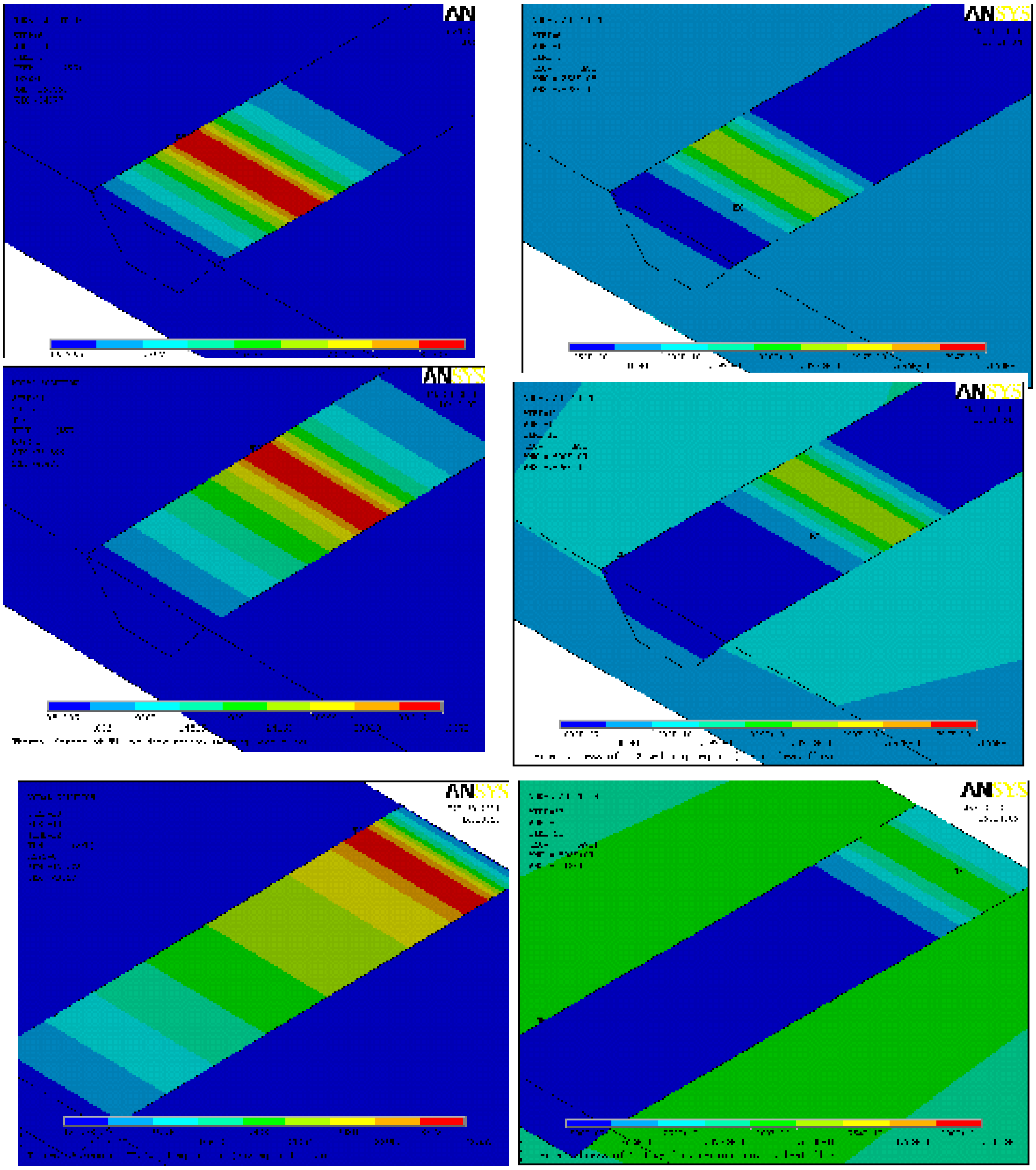


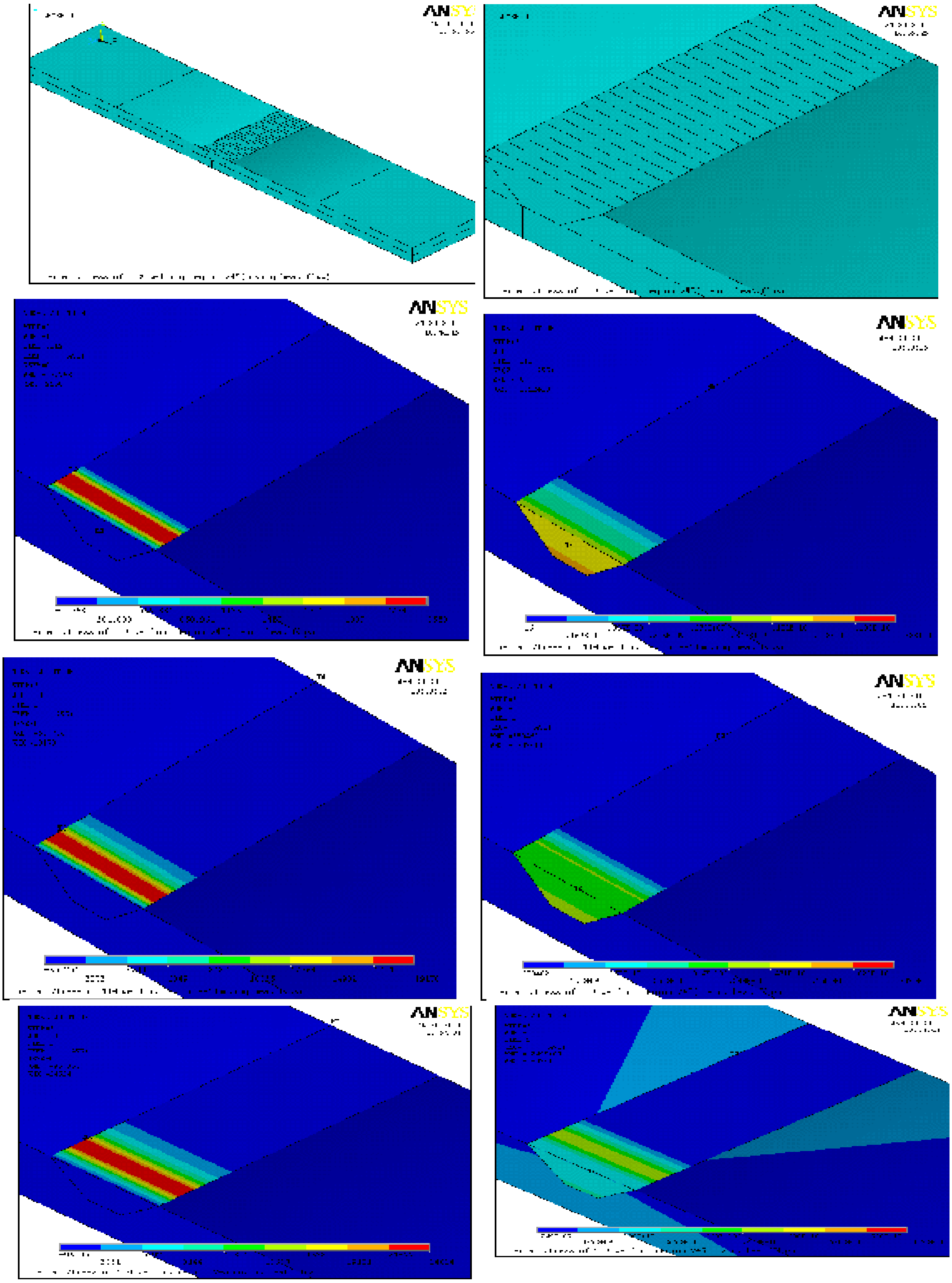
Figure (2) Models used in the TIG welding analysis

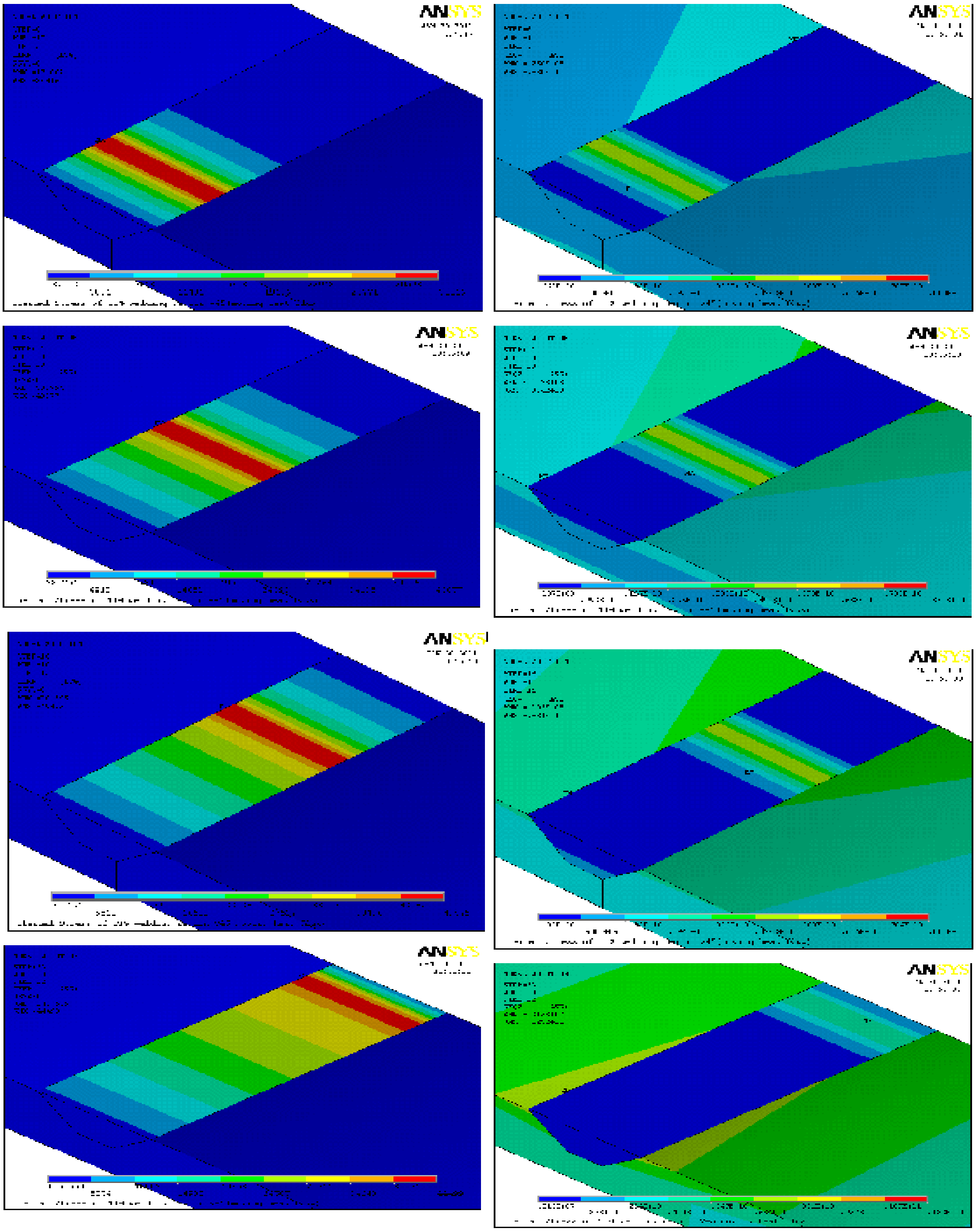




Temperature distribution Thermal stresses distribution

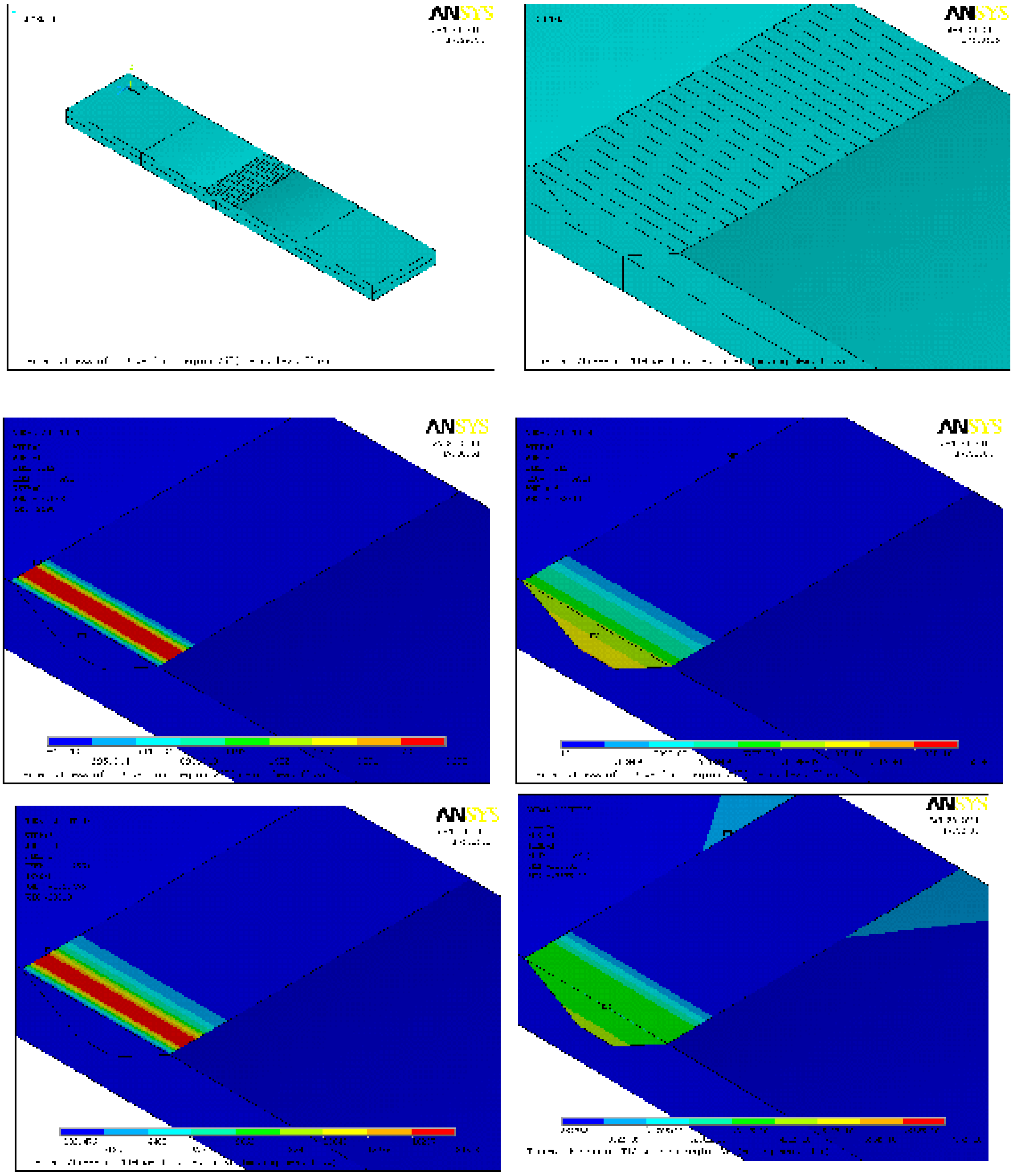
Figure(3) Moving heat source on the specimen group – A –

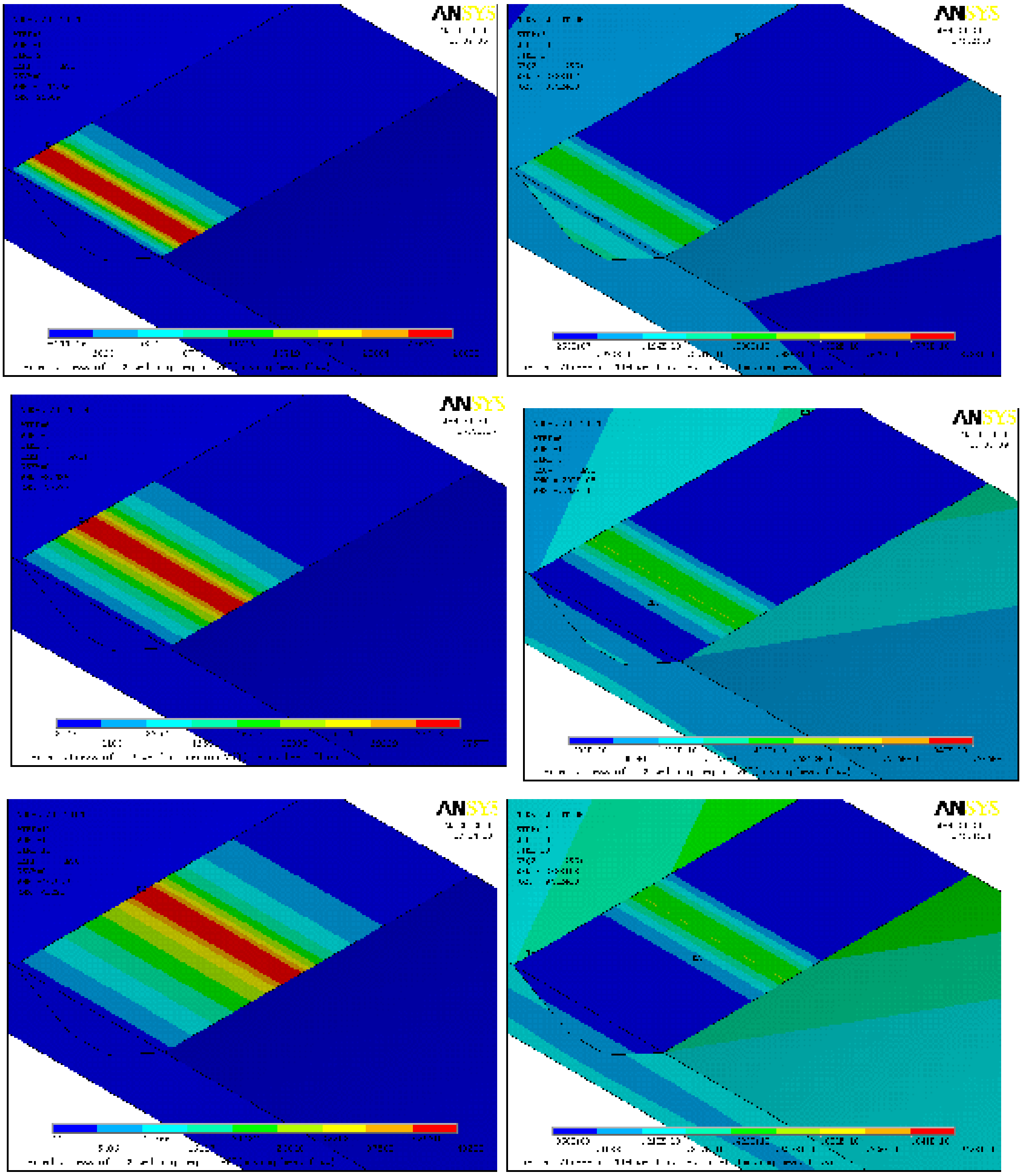


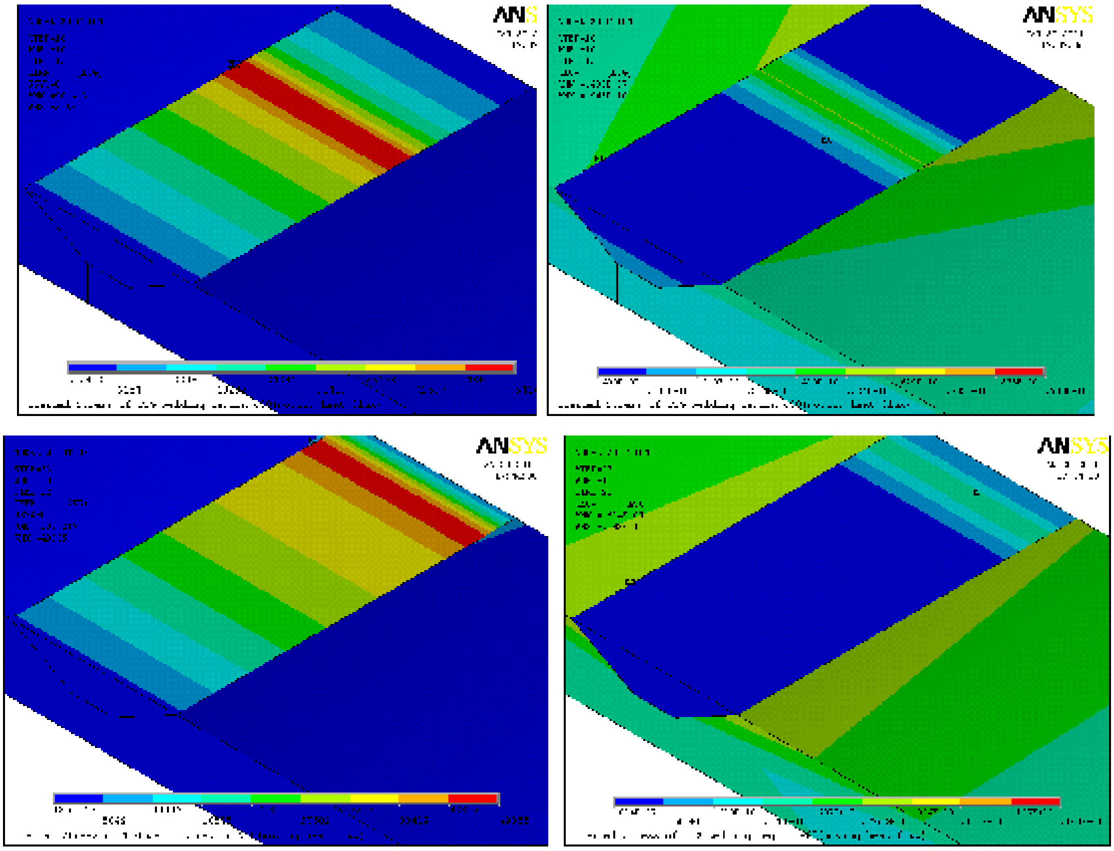


Temperature distribution Thermal stresses distribution

Figure (4) Moving heat source on the specimen group – B -

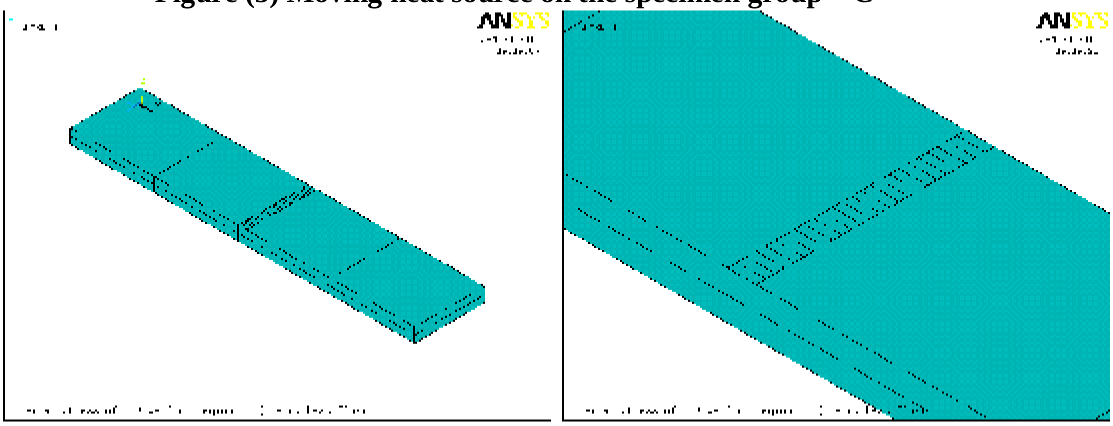


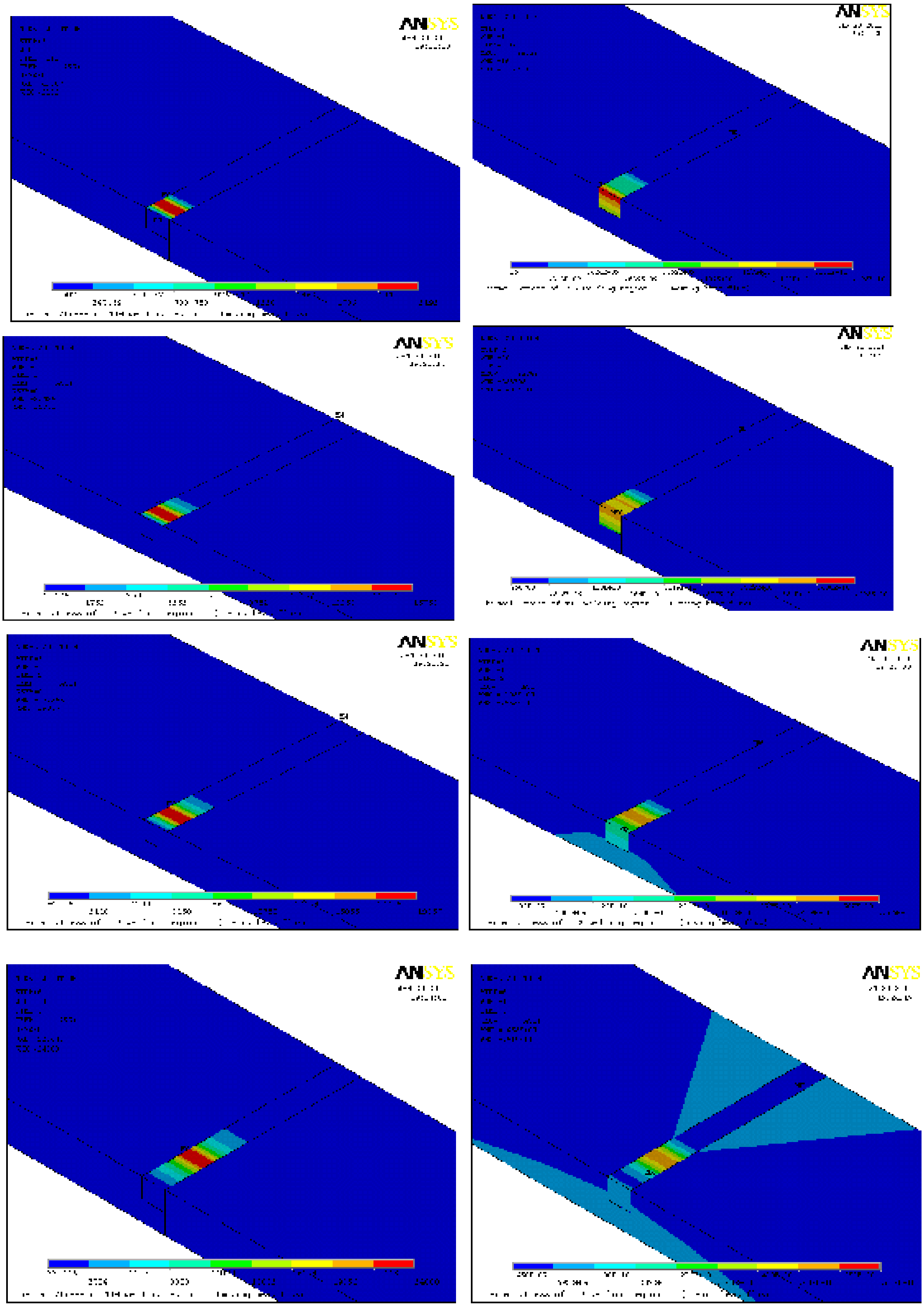


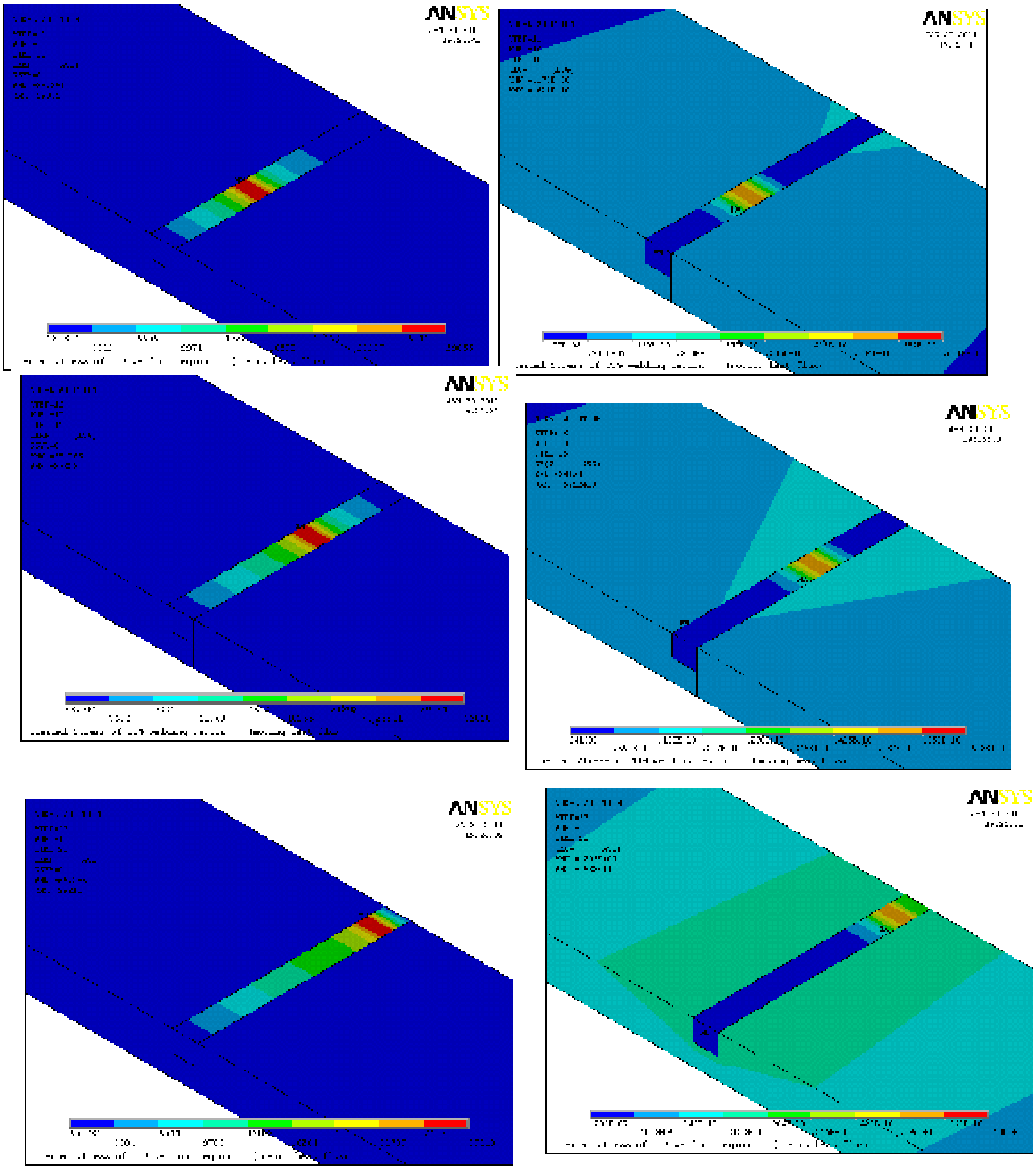


Temperature distribution Thermal stresses distribution

Figure (5) Moving heat source on the specimen group – C –







Temperature distribution Thermal stresses distribution

Figure (6) Moving heat source on the specimen group – D –