

6º CONGRESSO BRASILEIRO DE PESQUISA E DESENVOLVIMENTO EM PETRÓLEO E GÁS



TÍTULO DO TRABALHO:

Transient temperature distribution analysis using Goldak's double ellipsoidal moving heat source

AUTORES:

Guangming Fu, Marcelo Igor Lourenço de Souza, Segen F. Estefen

INSTITUIÇÃO:

Subsea Technology Laboratory, COPPE/UFRJ-Ocean Engineering Department,

P.O.Box 68508, 21945/970 Rio de Janeiro, Brazil

Este Trabalho foi preparado para apresentação no 6º Congresso Brasileiro de Pesquisa e Desenvolvimento em Petróleo e Gás- 6º PDPETRO, realizado pela Associação Brasileira de P&D em Petróleo e Gás-ABPG, no período de 09 a 13 de outubro de 2011, em Florianópolis-SC. Esse Trabalho foi selecionado pelo Comitê Científico do evento para apresentação, seguindo as informações contidas no documento submetido pelo(s) autor(es). O conteúdo do Trabalho, como apresentado, não foi revisado pela ABPG. Os organizadores não irão traduzir ou corrigir os textos recebidos. O material conforme, apresentado, não necessariamente reflete as opiniões da Associação Brasileira de P&D em Petróleo e Gás. O(s) autor(es) tem conhecimento e aprovação de que este Trabalho seja publicado nos Anais do 6ºPDPETRO.

Transient temperature distribution analysis using Goldak's double ellipsoidal moving heat source

Abstract

Welding technology is widely used in offshore structure construction because of the high productivity during the assemble process. The simulation accuracy of welding thermal transfer analysis is an important pre-requisite to ensure the reliability of thermal stress and deformation analysis. In this paper, a finite element code, ABAQUS, is used for the thermal transfer simulation. Temperature-dependent material properties, the convection and radiation boundary conditions are included in this model. "Element birth" technology is used to realize the multi-pass welding process. The heat source model is assumed to be Goldak's double ellipsoidal heat source model. A FORTRAN subroutine is employed to implement heat into the FE model and realize the heat source moving along the welding pass. The transient temperature distributions under different geometric parameters of Goldak's heat source model and welding speed are investigated.

1. Introduction

Classical solutions for the transient temperature field such as Rosenthal's solutions [1] can be used to predict the temperature at a distance far from the heat source but fail to predict the temperature in the vicinity of the heat source. Eagar and Tsai [2] modified the Rosenthal's theory and found an analytical solution for the temperature of a semi-infinite body subjected to 2D surface Gaussian distributed moving heat source. Goldak et al. [3] introduced 3-D semi and double ellipsoidal moving heat source and predicted the temperature of the welded plate with much deeper penetration. Nguyen [4, 5], M. Van Elsen, M. Baelmans [6] and Jerzy Winczek [7] used the analytical solution method to resolve the transient temperature of a semi-infinite body subjected to 3-D moving heat source. Gery. D [8] investigated the effects of welding speed, energy input and heat source distribution on temperature variations in butt joint welding with one welding pass.

In this paper, the transient thermal simulation of welding process using ABAQUS software and subroutines program has been developed. The influences of the welding speed and the geometric parameters of double ellipsoidal heat source model are discussed. Welding residual stress and distortion will be discussed in further research. The experiments are being prepared and the results will be reported in the near future.

2. Moving distributed heat source

2.1 Heat transfer analysis

The transient temperature distribution T is defined by the following equation [9]:

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where, q , ρ , C , and k are the internal heat source rate, density of the material, specific heat and thermal conductivities, respectively. Boundary and initial conditions are specified. Heat convection equation assumed as following [10]:

$$q = -h(T - T^0) \quad (2)$$

where, q is the heat flux across the surface, h is a reference film coefficient. The heat flux on a surface due to radiation to the surrounding medium, following the Stefan-Boltzmann law, is governed by [7]:

$$q = \varepsilon \sigma [T^4 - (T^0)^4] \quad (3)$$

where q is the heat flux across the surface, T is the temperature at this point on the surface, T^0 is an ambient temperature, ε is the emissivity of the surface. σ is the Stefan-Boltzmann constant. During the analysis, in ABAQUS software, $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ } ^\circ\text{C}$ is considered as the Stefan-Boltzmann constant [10], surrounding medium temperature is assumed as 20°C . Film coefficient and emissivity are defined to be 20 W m^{-2} and 0.85 , respectively.

2.2 Heat source model

2.2.1 Gaussian heat source

Gaussian heat source model is more realistic than point heat source as shown in Fig. 1. The geometric features of Gaussian distribution can be expressed by the following equation [11]:

$$q(r) = q_{\max} \exp(-cr^2) \quad (4)$$

where $q(r)$ is the surface heat flux at radius r , $q_{\max}$ is the maximum flux at the center of the heat source. C and r is the concentration coefficient and radial distance from the center of the heat source, respectively. Gaussian model can be used for the low penetration arc welding processes like GTAW, SAW, etc. However it does not reflect the action of arc pressure on the molten pool surface and hence it is not suitable for the welding process which produces deeper penetration.

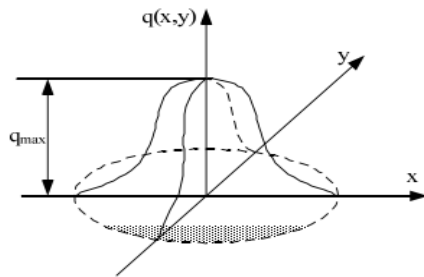


Fig. 1. Gaussian heat source

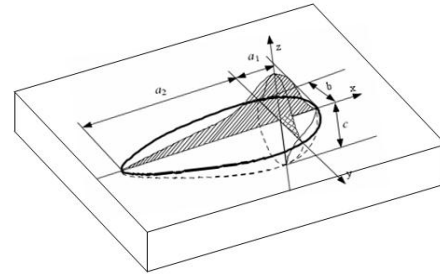


Fig. 2. Double ellipsoidal heat source

2.2.2 Semi and Double ellipsoidal heat source

Goldak's semi ellipsoidal heat source model has the capability of analyzing the thermal fields of deep penetration welds. The expression of the semi ellipsoidal heat resource is expressed as following [3]:

$$Q(x, y, z) = \frac{6\sqrt{3}Q}{abc\sqrt{\pi}} \exp\left(-\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right) \quad (5)$$

where x , y and z are the local coordinates of the double ellipsoid model. Q is the power. a , b and c is related to the characteristics of the welding heat source.

Some results with the semi ellipsoid heat source shown that the temperature gradient in front of the arc are less steeper the experimentally observed ones, and the gradients in the rear of the arc are steeper than those measured. To overcome this shortcoming, two semi ellipsoidal heat sources are combined and proposed a new heat source called double ellipsoidal heat source model as shown in

Fig. 2. In this model, the fractions f_f and f_r of the heat deposited in the front and rear quadrants are needed, where $f_f + f_r = 2$. In this work, $f_f = \frac{2a_f}{a_f + a_r}$ and $f_r = \frac{2a_r}{a_f + a_r}$ are used [12]. The power density distribution inside the front quadrant becomes [3]:

$$Q(x, y, z) = \frac{6\sqrt{3}f_f Q}{a_f b c \sqrt{\pi}} \exp\left(-\frac{3x^2}{a_f^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right) \quad (6)$$

Similarly, for the rear quadrant of the source the power density distribution inside the ellipsoid becomes:

$$Q(x, y, z) = \frac{6\sqrt{3}f_r Q}{a_r b c \sqrt{\pi}} \exp\left(-\frac{3x^2}{a_r^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right) \quad (7)$$

where Q is the power. a_f, a_r, b and c are related to the geometric characteristics of the welding heat source, respectively.

In Eqs. (6) and (7), the parameters a, b, c can have different values in the front and rear quadrants since they are independent. Indeed, in welding dissimilar metals, it may be necessary to use four octants, each with independent values of a, b , and c .

3. Transient temperature distribution simulation

The FE model used in this paper is Q235 steel plate with the size of 90 mm×60 mm×3 mm as following shown in Fig. 3. 13446 elements of DC3D20 are created and 24 PATHs are introduced into FE model in order to observe the transient temperature distribution in various locations. For example, the PATH L-i-tran-j is the j^{th} PATH along the transverse direction in the i^{th} surface and the PATH L-i-LONG-j is the j^{th} PATH along the welding pass direction in the i^{th} surface. In Fig. 3, seven PATHs in different location and detail profiles of three welding passes are plotted.

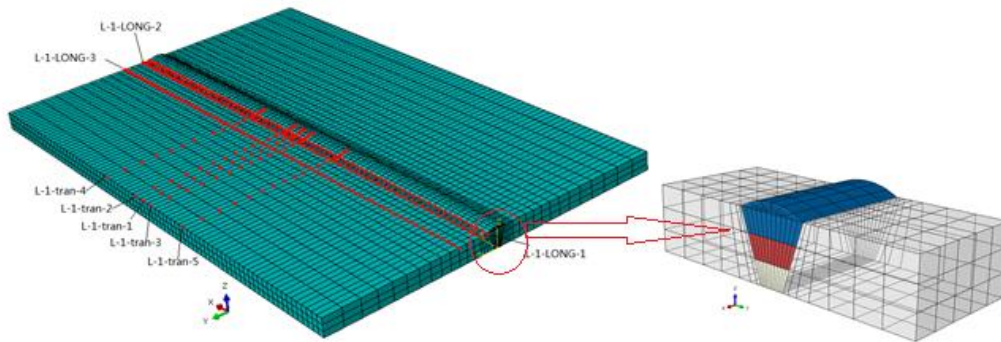


Fig. 3. Element-DC3D20 quadratic heat transfer solid elements and welding line.

The “element birth” technology is used in the FE model to deactivate or reactivate selected elements and achieve the “element death” and “element birth” effect [10]. The subroutines FORTRAN program is developed in order to realize the heat source inputting and moving. In this paper, three welding pass are created and controlled by the “element birth” technology and subroutines program. Three welding speed of 1.64mm/s, 1.8mm/s and 2.25mm/s are investigated. Three groups of Goldak’s double ellipsoidal parameters, P1, P2 and P3, are used as listed in table 1.

Table 1 Geometric parameters of Goldak's double ellipsoidal model

	Geometric Parameters	Bottom welding pass(mm)	Middle welding pass(mm)	Top surface welding pass (mm)
Parameters of double ellipsoidal model---P1	a_f	0.0017	0.0017	0.0017
	a_r	0.0068	0.0068	0.0068
	b	0.0032	0.003	0.004
	c	0.002	0.003	0.004
Parameters of double ellipsoidal model---P2	a_f	0.0017	0.0017	0.003
	a_r	0.0068	0.0068	0.012
	b	0.0032	0.003	0.004
	c	0.002	0.003	0.004
Parameters of double ellipsoidal model---P3	a_f	0.0017	0.0017	0.004
	a_r	0.0068	0.0068	0.016
	b	0.0032	0.003	0.004
	c	0.002	0.003	0.004

4 Results and discussion

The transient temperature distributions are completed by ABAQUS software for different welding speed and heat source parameters. A sample of transient temperature distribution for welding speed of 1.8mm/s and heat source parameters of P1 at different welding time are plotted in Fig. 4. From this figure, it can be seen that the temperature around the arc is rising rapidly. It is also noticed that the thermal field is stationary and only coordinate with the heat source moving. The temperature distributions at the reference cross section from welding time of 23s to 40s are plotted in Fig. 5. Heat transfer quickly in the vertical direction of welding pool and then reaches uniform distribution at the cross section.

As shown in Fig. 6, temperature distributions along the welding direction at different thickness direction location are plotted when the arc locate in the middle of the plate at 25s. From Fig. 6(a), it can be seen that temperature decreases rapidly as the distance to welding line increases. As shown in Fig.6 (b), temperature decreases are non-linear along the thickness direction.

Fig. 7 shows detailed temperature distributions at different reference cross sections and different thickness direction locations at welding time of 25s. From Fig. 7(a), the temperature in the L-1-tran-1 which locates in the middle of welding line (see in Fig.3) is up to maxima and the L-1-tran-3 is following. Temperature in L-1-tran-5 which locates rear of the heat source decreases significantly. In L-1-tran 4, the temperature is more uniform along the transverse direction.

The influences of welding speed are investigated in this paper. Several speeds ($V_0=1.64$ mm/s, $V_1=1.8$ mm/s and $V_2=2.25$ mm/s) are applied to the constants of double ellipsoidal geometric parameters.

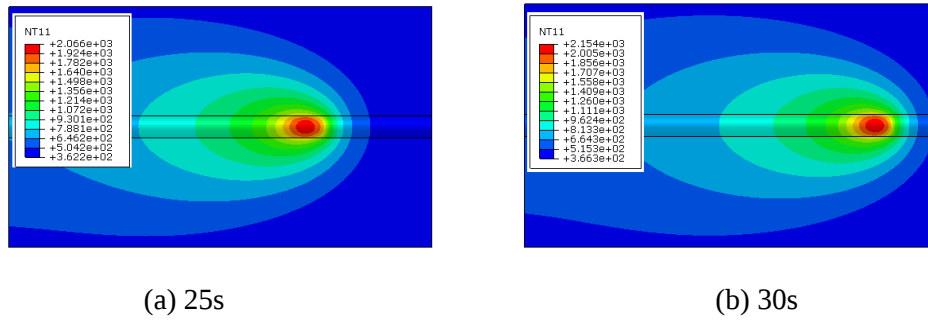


Fig. 4. Temperature distribution at various times.

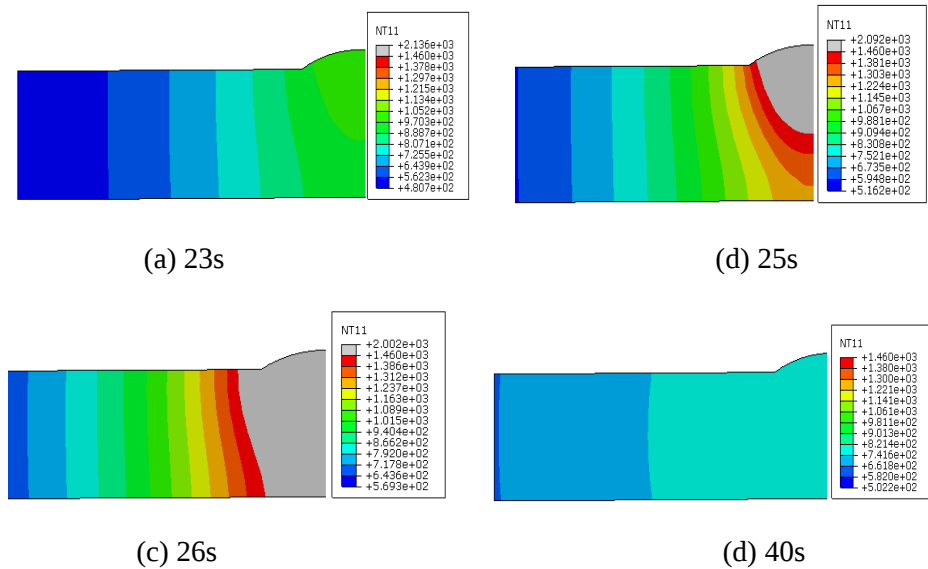


Fig. 5. Temperature distribution in reference cross section at different times.

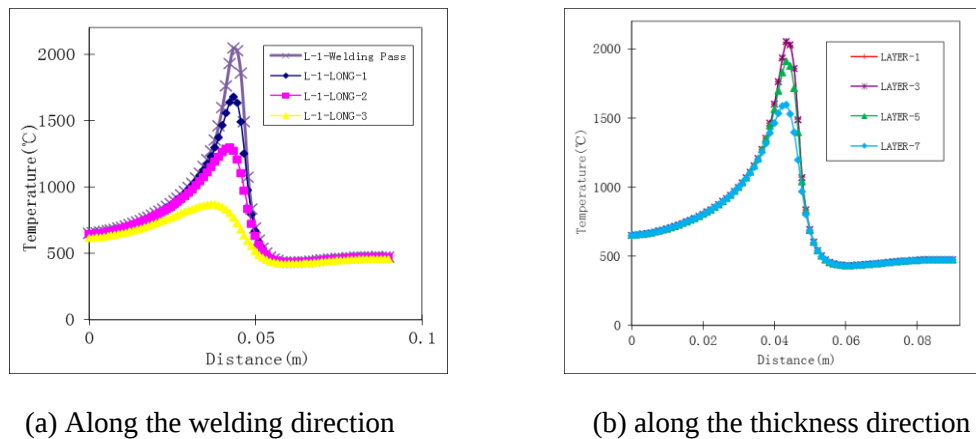
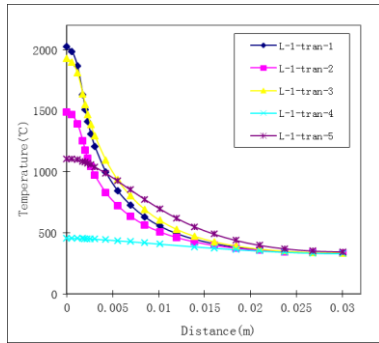


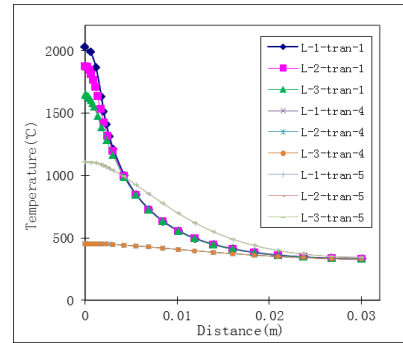
Fig.6. The temperature plotted: (a) along the weld direction, (b) along the z direction.

The temperature distribution for three different welding speeds at top surface along transverse direction and welding direction are plotted in Fig. 8. Two PATHs are discussed in this figure. One is the weld line($Y=0$), another is the PATH from welding line 6.88mm ($Y=6.88$ mm). As shown in Fig. 8(a), the peak temperatures decrease significantly as distance increase. Maximum temperature at $Y=0$ up to 2142.9 °C and drop to 891.87 °C at $Y=6.88$ mm. The temperatures along different PATH at top

surfaces are plotted in Fig. 8(b). Temperature distribution in tran-1 PATH which through the heat source center decreases non-linearly with the location changed. In PATH of tran-4 and tran-5, the influences can be ignored.

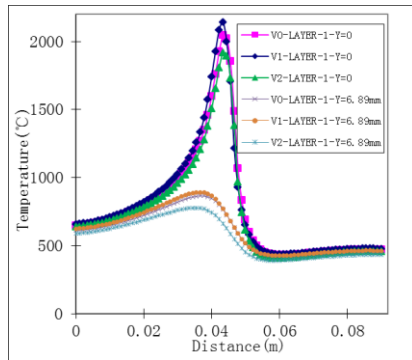


(a) PATHs at top surface

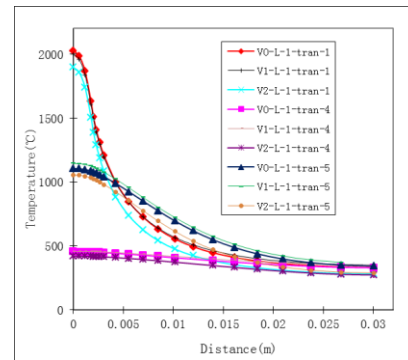


(b) Various PATHs at different surface

Fig. 7. Temperature distributions at different cross sections and layers

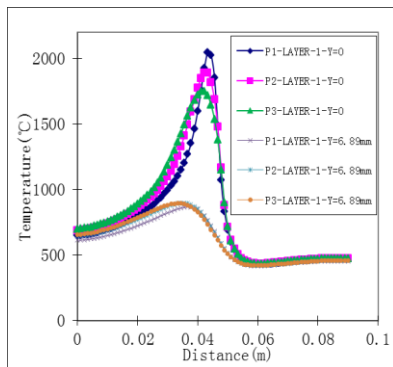


(a) Along longitudinal direction

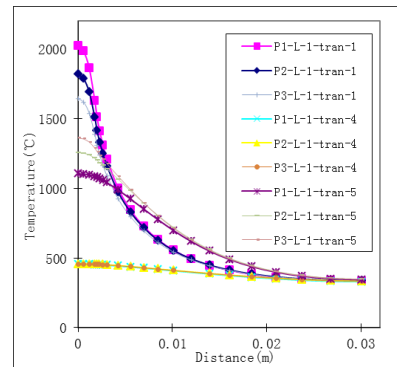


(b) Along transverse direction

Fig.8. Temperature plotted at three different welding speeds.



(a) Along the welding direction



(b) Along the transverse direction

Fig. 9. Temperature distribution with different heat source parameters

The effects of the heat source parameters are predicted as shown in Fig. 9. In this figure, the results of temperature distribution at the top surface along welding direction and transverse direction are plotted. In Fig. 9(a), the temperature at two paths, $Y=0$ and $Y=6.88\text{mm}$, are plotted. It is seen that the peak temperature decreases rapidly as the distances increase. At welding line location ($Y=0$), peak temperature decrease as the double ellipsoidal geometric parameters increases as constant welding speed of 1.8 mm/s . Fig. 9(b) shows that temperature distribution in transverse direction when the

different geometric parameters are applied. At location L-1-tran-1 and L-1-tran-4, the peak temperatures decrease with the increase of the model parameters. At location L-1-tran-5, temperature change is very small. It also can be seen from the Fig. 9(a) and Fig. 9(b), in the far area, that the effects of model parameters can be ignored.

5 Conclusions

(1) A FORTRAN program based on the moving Goldak's double ellipsoidal heat source model is developed to realize heat inputs into FE thermal simulation and heat source moving along the welding line. Welding temperature distributions are predicted using this subroutine program.

(2) The effects of welding speed and geometric parameters of double ellipsoidal heat source model are investigated. The results demonstrate that they have important effects not only to the peak temperature but also to the distributions rounding the welding line. But, temperature distributions in the area which is far away from the welding line are uniform.

(3) The welding residual stress analysis should be done in the future. Further experiments are required in order to validate heat source model and to establish quantitative correlations between FE simulations and experiments.

Acknowledgement

This work is conducted with financial support from FINEP. The authors are also supported by ANP and CSC (China Scholarship Council). Thanks to the colleagues of LTS/COPPE/UFRJ for useful discussions about welding modeling.

References

1. Rosenthal D, Mathematical Theory of Heat Distribution during Welding and Cutting. Welding Journal 20(5) (1941) 220s to 234s.
2. Eagar, T.W. and Tsai, N.S, Temperature Fields Produced by Traveling Distributed Heat Sources. Welding Journal 62(12) (1983) 346-s to 355-s.
3. J. Goldak, A. Chakravarti, M. Bibby. A new finite element model for welding heat source, Metall. Trans. B 15B (1984) 299–305.
4. Nguyen, N.T., A. Ohta, K. Matsuoka, N. Suzuki and Y. Maeda. Analytical Solutions for Transient Temperature of Semi-Infinite Body Subjected to 3D Moving Heat Sources, Weld. Res. Suppl., Welding Journal, August, 1999.
5. N.T. Nguyen, Y.-W. Mai, S. Simpson, A. Ohta, Analytical approximate solution for double ellipsoidal heat source in finite thick plate, Weld. Res. (2004) 82–93.
6. M. Van Elsen, M. Baelmans, P. Mercelis, J.-P. Kruth, Solutions for modelling moving heat sources in a semi-infinite medium and applications to laser material processing, Int.J.Heat Mass Transfer 50 (2007) 4872–4882.
7. Jerzy Winczek, Analytical solution to transient temperature field in a half-infinite body caused by moving volumetric heat source, Int.J.Heat Mass Transfer 53 (2010) 5774–5781.
8. Gery D, Longb H, Maropoulos P. Effects of welding speed, energy input and heat source distribution on temperature variations in butt joint welding. J Mater Process Technol 2005;167:393 – 401.
9. F. Incropera, D. DeWitt, Introduction to Heat Transfer, fourth ed., Wiley, New York, 1996.
10. ABAQUS, Finite element software, User's Manual, Hibbit, Karlsson & Sorensen Inc.
11. Pavelic V, Tanbakuchi R, Auyehara O. Experimental and computed temperature histories in gas tungsten arc welding of thin plates [J]. Welding Journal Research Supplement, 1969, 48 (7): 295s-305s.
12. Andreas lundback, Finite element modeling and simulation of welding of aerospace components, Ph.D thesis, Lulea University of technology, 2003.