

Optimization of Thermal and Discretization Parameters in Laser Welding Simulation Nd:YAG Applied for Shin Plate Transparent Mode Of DP600

Chansopheak Seang, Afia David Kouadri, Eric Ragneau

Abstract—Three dimensional analysis of thermal model in laser full penetration welding, Nd:YAG, by transparent mode DP600 alloy steel 1.25mm of thickness and gap of 0.1mm. Three models studied the influence of thermal dependent temperature properties, thermal independent temperature and the effect of peak value of specific heat at phase transformation temperature, AC1, on the transient temperature. Another seven models studied the influence of discretization, meshes on the temperature distribution in weld plate. It is shown that for the effects of thermal properties, the errors less 4% of maximum temperature in FZ and HAZ have identified. The minimum value of discretization are at least one third increment per radius for temporal discretization and the spatial discretization requires two elements per radius and four elements through thickness of the assembled plate, which therefore represent the minimum requirements of modeling for the laser welding in order to get minimum errors less than 5% compared to the fine mesh.

Keywords—FEA, welding, discretization, ABAQUS user subroutine DFLUX

I. INTRODUCTION

ONE of the problems in numerical simulation is how to choose suitable parameters for accurate results and gain in time of preparation and resolution of those models. Facing some constraints in welding simulation laser Nd:YAG in which the laser seam is quite small, high speed welding many simulators used refined mesh at the seam and rather coarse meshes far away at the specimen edge [6], [2], [5], [3]. The mesh density has been study in the work of Schenk, it show that the mesh density plays a very important role in determining the accuracy of distortion amplitude, the buckling shape as well as the critical buckling load and the stress required in material in order to produce the expected buckling mode [6]. Relation between mesh dimensions and circular disc source model in the work of ZHANG [8] show a notable solution for surface treatment but not complete for full penetration welding model which used a tiny dimension. Minimum value in [8] imposes constraint on time consuming of full penetration welding simulation of transparent mode

because of high DOFs. Base on this idea the relation between mesh density and dimension of conical heat source model has been conducted. The quadratic interpolation function gives more accurate results close to the weld seam [6] and is used in this simulation.

The material properties functions of temperature are playing an important factor in the iteration of the numerical analysis. ZHU observed the influence of temperature dependent material properties on the welding simulation of 5052-H32 aluminum alloy. The thermal conductivity has some effect on the distribution of transient temperature field during welding; the material density and specific heat have negligible effect on the temperature field [9]. Regarding the material-dependent properties of steel that have a peak-point of specific heat at the phase transformation and lot of variations compared to aluminum. Another study for steel is necessary in order to understand those variations.

This paper concentrates on 2 studies, the influence of the material- dependent temperature properties and the material independent temperature and second is the hexagonal meshing parameter compared to the dimension of heat source model by using quadratic element, with fine mesh on weld pool and coarse meshes on the edge, for thermal simulation of full penetration welding of dual phase steel DP600 (1.25mm x 50mm x 110mm), within transparent mode include 0.1mm gap.

II. MODEL

A. Thermal Model

The heat transfer from the volumetric heat source and the metal by conducting mode which is expressed by the following equation:

$$\rho \frac{dH}{dt} - \text{div}(\lambda \text{grad}T) - Q = 0 \quad (1)$$

The convection limits condition on the surrounding surface is:

$$\lambda(T) \text{grad}T(x_i, t)_{\text{surface}} + H(T(x_i, t) - T_0) = 0 \quad (2)$$

The radiation limits condition on the weld pool surface is:

$$\lambda(T) \text{grad}T(x_i, t)_{\text{surface}} + \varepsilon \sigma (T(x_i, t)^4 - T_\infty^4) = 0 \quad (3)$$

An initial condition is defined by the temperature of metal, T equal to the surrounding temperature 25°C and no boundary condition, such as prescribed heat fluxes or prescribed temperatures, was applied for thermal model.

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TABLE I
UNITS FOR THERMAL PROPERTIES

Symbol	Quantity	SI ^a
ρ	density	kg/m ³
H	enthalpy	J/(kg.°C)
λ	Thermal conductivity	W/(m.°C)
Q	Internal heat	W/m ³
ϵ	emissivity	0.25
σ	Stefan Boltzmann	5.6704 10 ⁻⁸ W/(m.K ⁴)
-	absolute zero	-273.15°C
t	time	s
x_i	spatial coordinate	m

^a m = meter, J = joule, kg = kilogram, W = Watt, C = Degree Celsius, K = Kelvin, s = second.

Heat transfer in weld pool simulation, Metal Inert Gas (MIG) model, is transferred quickly first in the thickness direction and then in the width direction to reach uniform distributions. The heat conduction plays an important role in heat flow but surface convection and radiation have little effect on FZ and HAZ boundaries [4]. Applied to Nd:YAG the convection and radiation have less influence in the simulation because of the fast speed welding and tiny heat source model.

B. Parameter of Heat Source

The conical heat source with Gaussian distribution [7] is used in modeling represented by the following equation:

$$Q(r, z) = \frac{9\eta P e^3}{\pi(e^3 - 1)} \cdot \frac{e^{-\left[\frac{3r^2}{r_e^2}\right]}}{(z_e - z_e)(r_e^2 + r_e r_i + r_i^2)} \quad (4)$$

With

$$r_c = r_i + \frac{(r_e - r_i)(z - z_i)}{z_e - z_i} \quad (5)$$

The dimension of heat source model is recommended to be 10% less than the real weld pool dimension [11]. But because of the high speed welding process and small weld pool, 10% less than the real value lead to a small value of efficiency in order to maintain the maximum temperature in weld pool. The number of element in this section must be increase too in order to suite with the dimension of the model. So the real dimension from transversal section of weld pool is used in this work.

[7] used the efficiency 37% for laser Nd:YAG simulation of aluminum AA 6056-T4 of the plate joint. SCHENK simulated with 64% for gas metal arc welding of 1mm overlap joint of DP600 steel [6]. The same value of efficiency 64.3% for Gas Metal Arc (GMA) welding simulation of 5052-H32 aluminum alloy [9]. In the Nd: YAG simulation of ZE41A magnesium alloy show that the increasing of welding speed from 4 to 7m.min⁻¹, the coupling efficiency increased from 25% to 42% [1].

According to the [1, 7], the efficiency of 34% has been adopted for laser Nd:YAG with success as show in Fig.1. This value is also varies base on the dimension of the heat source model predefine by the measurement of the transverse section of the weld part.

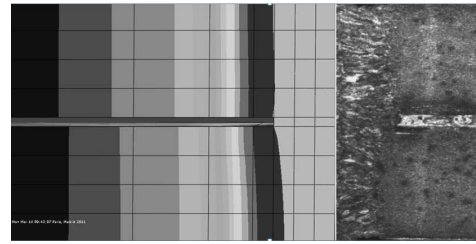


Fig. 1 cross section FEA & experimental

The welding speed, MIG, energy input and heat source distributions have important effects on the shape and boundaries of FZ and HAZ; they also influence peak temperature in FZ, which consequently affect the transient temperature distributions in the welded plate. FZ and HAZ boundaries are sensitive to the variation of heat source parameters [4].

TABLE II
PARAMETER OF HEAT SOURCE MODEL

Symbol	Quantity	Value
r_e	radius superior	0.65m ⁻⁶
r_i	radius inferior	0.5 m ⁻⁶
r_c	distribution parameter	m ⁻⁶
z_e	position in Z axis of r_e	2 m ⁻⁶
z_i	position in Z axis of r_i	0 m ⁻⁶
P	laser power	4000 W
η	efficiency	34%
V	welding speed	0.05m/s

C. Material Data

The influence of temperature dependent material properties on the welding simulation of 5052-H32 aluminum alloy observed in the work of ZHU and assumed that the thermal conductivity has some effects on the distribution of transient temperature field during welding; the material density and specific heat have negligible effect on the temperature field [9]. This is maybe the small change of density and specific heat in function of temperature. Regarding the thermal properties of DP600 steel [6], the density is less change with the variation of temperature, the density assumes to 7594 Kg/m³ at room temperature. The convection coefficient 73.5 W/m².K and emissivity of 0.25 is constant base on the result of [4]. On the other hand, the specific heat reached the peak value at the phase change temperature, 750°C. So the specific heat dependent of temperature is reconsidered in this work.

TABLE III
PARAMETER OF MESH DIMENSION (MM)

Model	FZ		HAZ		NHAZ ^a
	DX	DY	DZ	DY	BIASE
M4	1.25	0.6	0.625	1.88	10:12
M2	1	0.6	0.625	0.94	10:25
M7	0.5	0.6	0.625	0.94	10:25
M6	0.5	0.6	0.625	0.47	20:25
M8	0.5	0.3	0.3125	0.313	20:25
M9	0.25	0.3	0.3125	0.313	20:25
M10	0.125	0.3	0.3125	0.313	20:25

^a10:12 means 12 elements with biases factor of 10 from the small and the bigger one.

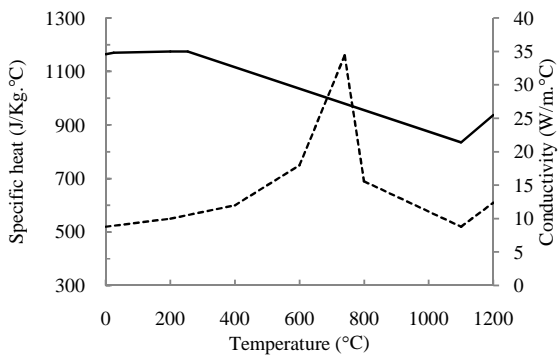


Fig. 2 Thermal properties DP600

The thermal simulation by using Gaussian distribution conical heat source model in solid phase leads to higher maximum temperature, more than 3000°C, in the center of the fusion pool. That is much more difference from reality.

The effect of fluid flow and solidification of material has significant effects on the temperature distribution and on the shape of weld pool. Deng proposed an artificially increased thermal conductivity to be approximately twice of the value at room temperature when the temperature is higher than the melting point [2]. The thermal effects due to solidification of the weld pool by the influence of latent heat for fusion is suppose to be less influence for the results of the simulation [10], and it is not counted in these simulations.

D. Preparation

Three models base on the properties of material was selected for studying the influence of materials properties.

- Model 1: density at room temperature, conductivity and specific heat are function of temperature.
- Model 2: density at room temperature, conductivity and specific heat are function of temperature but the specific heat of phase transformation ($T=600^{\circ}\text{C}-800^{\circ}\text{C}$) is overlooked.
- Model 3: density, conductivity and specific heat are at room temperature.

The dimensions of those models are the same as model 2 describe in Table III.

Another 7 models are simulated for studying the influence of meshing dimension. Three zones of model are considered, Fusion Zone (FZ), Heat Affect Zone (HAZ) and Non Heat Affect Zone (NHAZ) located at 10mm from welded centerline in transversal direction. The meshes dimensions are different in each zone for better understanding the influence of discretization indicated in Table III.

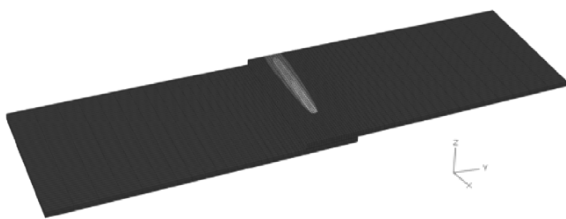


Fig. 3 meshing model

The computation time, on the Intel i7 3GHz 4-Cores 8GB-RAM, is presented in the Fig. 4 is in function of number of elements.

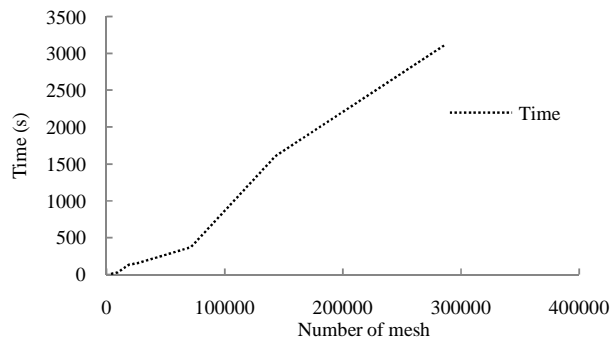


Fig. 4 Computation time & number of elements

III. RESULTS

A. Effects of Materials Properties

Three points situated at the transversal line counted from center of the weld pool point A (25, 0, 1.25), B (25, 0.6, 1.25) at the interface of solid and liquid phase and finally point C (25, 5.3, 1.25) at NHAZ are chosen to evaluate the evolution of temperature transient.

Fig. 5 indicate that the simulation A2Q with simplified material properties give a high value of maximum temperature at the central of the weld pool compared to A1 and A2 from simulation1 and 2 seem to give the same value. The percentage of different is about 5.5% from model 1 and 3 and drop to 1.2% between model 1 and 2. In the cooling phase, the temperature drop on the same curve until 1500°C, below this temperature the difference between the curve A2Q and A1 or A2 appear clearly with 150°C of the gap between them. So the material dependent temperature properties with or without peak-point at the phase change has no influence on the evolution of temperature in the weld pool, but the simplified parameter have signification influence on the temperature include the maximal value and cooling speed even the thermal properties at the fusion zone are set to the same values for all simulations.

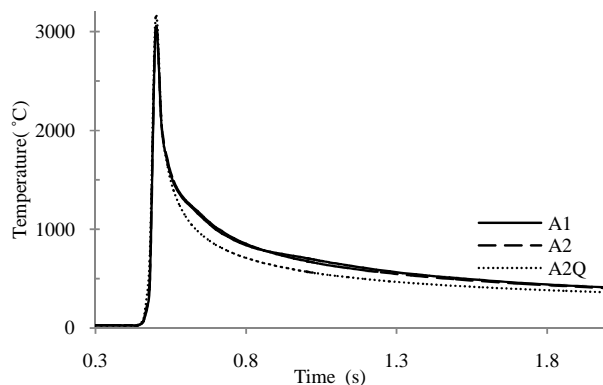


Fig. 5 Temperature at point A

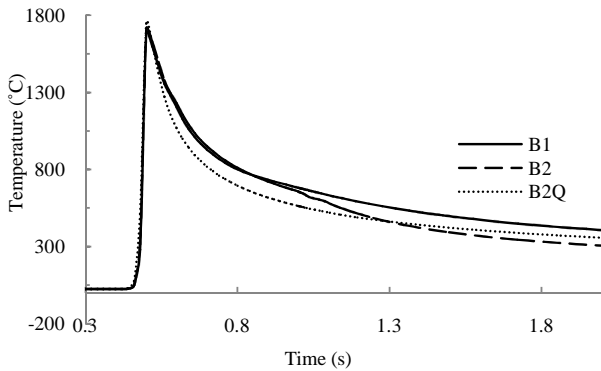


Fig. 6 Temperature at point B

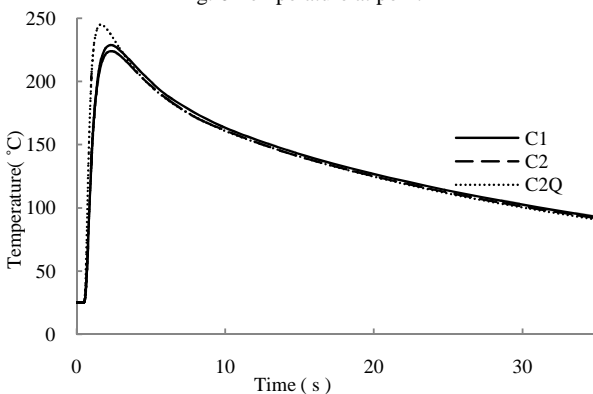


Fig. 7 Temperature at point C

The maximum temperature at the interface of solid and liquid of the weld pool, Fig. 5, is not quite different from the center of the welded pool, point A, and the percentage of B2 compared to B1 is 1.5% and 3.75% for simulation 3. Otherwise the cooling curve translate, around 800°C-500°C, an in-depth different between the curve B1 and B2, this is because of influence of the peak-point value of specific heat at AC1. The curve A2Q still indicates the difference from the curve B1 from the 1500°C as in the weld pool.

This gap indicates clearly the zone where maximum temperature reach 1800°C, don't have influence from the maximum value of the weld pool. The value of specific heat at the phase change, AC1, plays an important role in cooling phase between 800°C and 500°C. The accurate temperature about 600°C to 800°C is the most important for distortion and residual stress [11]. Without this value the process seems to have great value of cooling speed that is an important parameter in the metallurgical transformation.

The point C represent the position far from the heat source so the values indicate is Fig. 7 seem to be acceptable for all simulation include the value of maximum temperature and also cooling speed after welding. This is because of the parameters of thermal simulation in this interval of temperature are less change compared to the value at room temperature.

So the phase change dependent material properties have influence on the zone between FZ and HAZ. Beside this zone no influence has been identified.

The material constant properties at constant temperature include the double values of conductivity at the fusion temperature give a signification different of maximum temperature, 3.75% to 5%, in HAZ and the FZ.

The material dependent temperature with and without peak point at phase change transformation have less effects on the results, on 1.2% to 1.5% of maximum temperature in HAZ and FZ. So the peak value can be overlooked without influence on the results.

The results have compromised with [9] which proved that the error percentage is less than 10% compared to the results getting from experimental for aluminum alloys.

B. Effects of Meshing Dimensions

Six points ES(25,0,1.25), EI(25,0,-1.26), FS(25,0.6,1.25), FI(25,0.6,-1.26), GS(25,10,1.25) and GI(25,10,-1.26), three situated on top surface ES, FS, GS and another three points on the bottom surface EI, FI, GI are used for examine the different values of temperature distributed on top and bottom surface. Seven simulations with different values of meshes dimension of hexagonal element shape DX, DZ and DZ.

The temperature on the longitudinal line through the weld line on the top and bottom surface at instance 0.5s are also considered in these studies, Fig. 15-16.

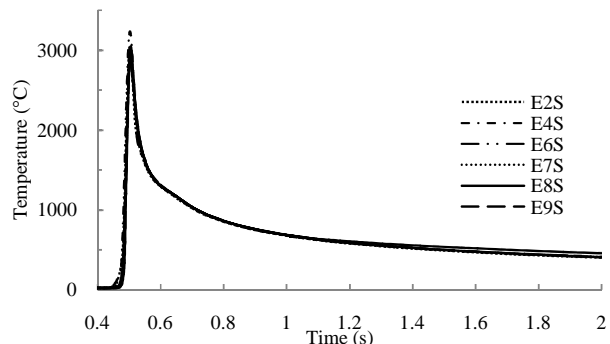


Fig. 8 Temperature at the center of weld pool on top surface

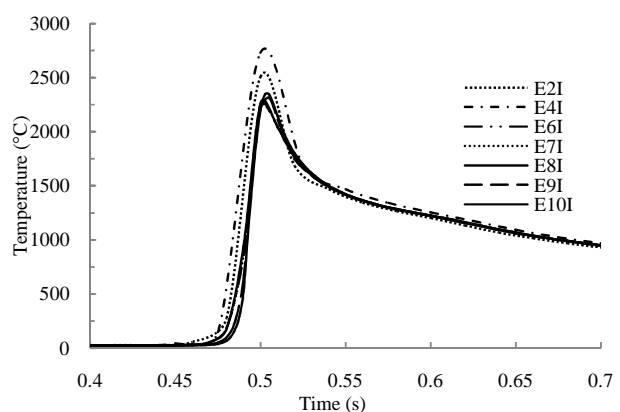


Fig. 9 Temperature at the center of weld pool on bottom surface

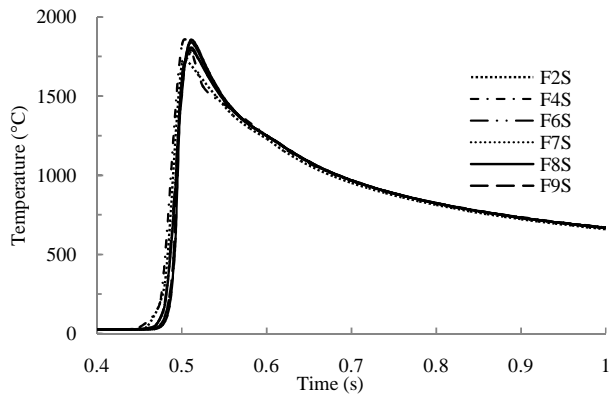


Fig. 10 Temperature at point F on top surface

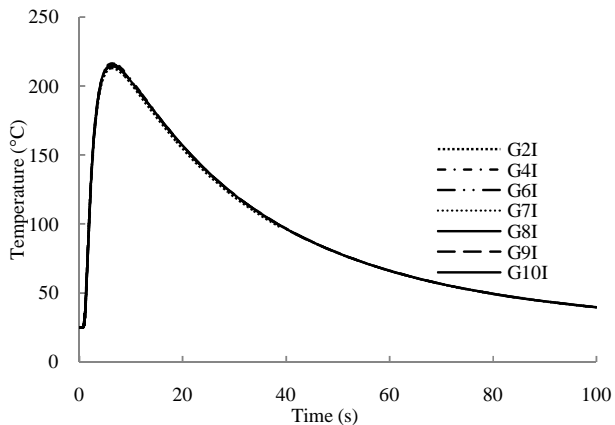


Fig. 13 Temperature at point G on bottom surface

The temperatures at different points of these simulations follow the same evolution from heating to cooling as showing in Fig. 7-12. The difference can be seen only at the maximum temperature. So the different values of meshing are not important in determination of cooling speed but in finding the maximum value of temperature in welding pool. The Fig. 13 represented the different values of maximum temperature in each simulation.

The peak temperature change with different number of meshing in the FZ only, nonlinear of curve ES & EI, and less influence on the HAZ, curve FS & FI, but no influence on the zone outside represented by curve GS & GI as reported in Fig. 14.

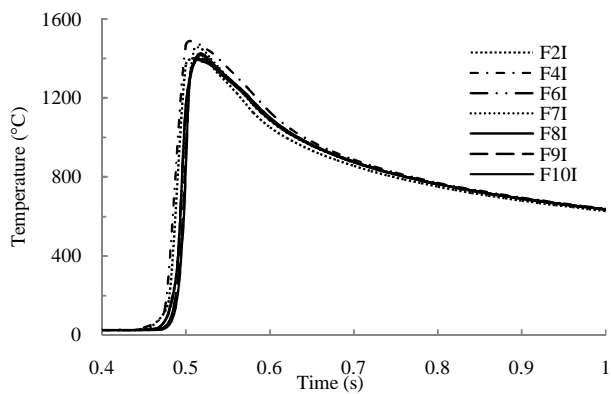


Fig. 11 Temperature at point F on bottom surface

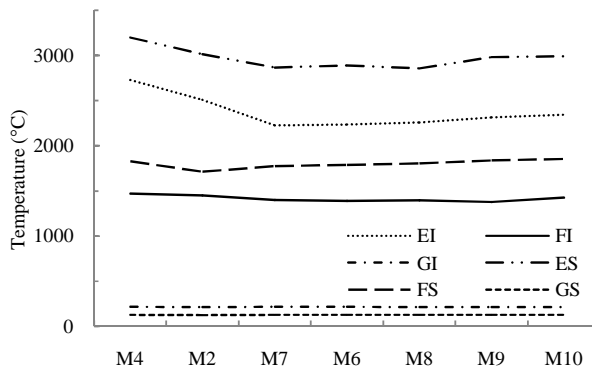


Fig. 14 Maximum temperature at point E, F and G

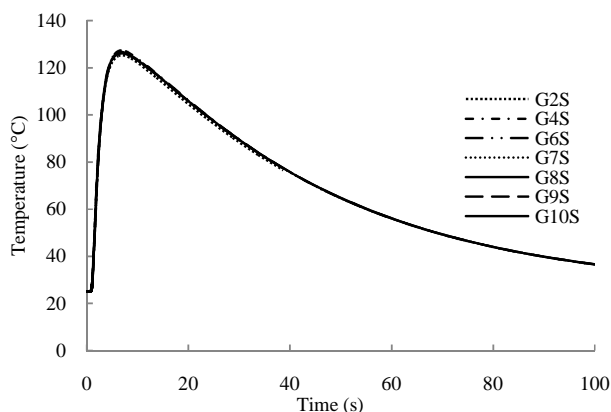


Fig. 12 Temperature at point G on top surface

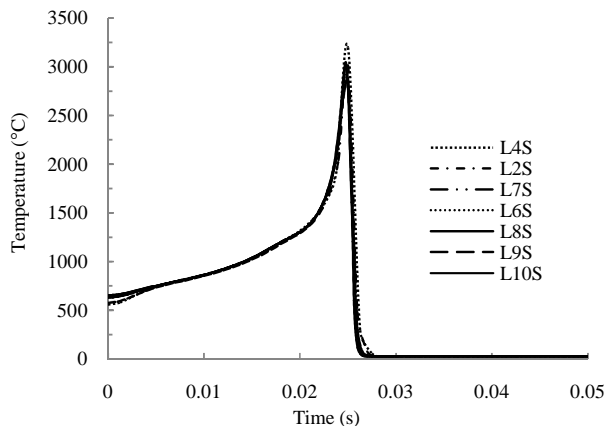


Fig. 15 Temperature along welding line on top surface at instant 0.5s

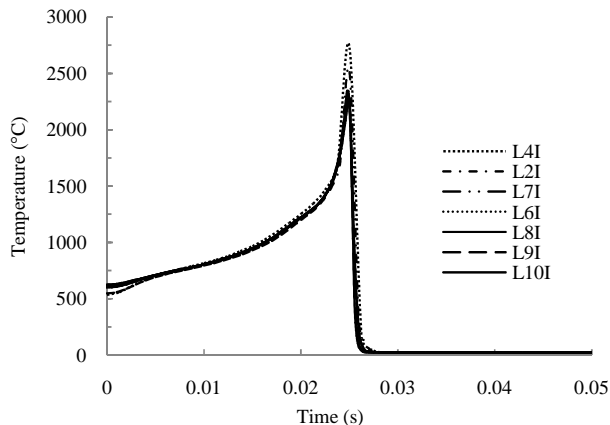


Fig. 16 Temperature along welding line on bottom surface at instant 0.5s

Maximum temperature, Fig. 14, on top surface of the fusion zone (FZ) decreases to a stabilized value in model M7, M6 and M8. Same phenomena for peak temperature in FZ on the bottom surface represent by curve EI in Fig. 14. This is because of the same value of DX is used but difference value of DY and DZ. So the variations of DY and DZ in those analyses, double elements in Y and Z direction for M8 compared to M6, have less influence on the maximum temperature, less than 1.5%, in weld pool.

The curves FS and FI of the models M7, M6, M8 indicate the same meaning as the curve ES and EI. So the difference of DX, DY and DZ has less influence on temperature at ZAT and furthermore no effects on the non heat affect zone, GS and GI.

The model M4 over evaluate the results, 19%, compared to M8, for EI and 11% for ES, because of the biggest mesh dimension in ZAT and FZ and also the ratio of DX/R is not the same for upper and bottom of the model that should be the cause of difference in percent of EI and ES. Passing from M4 to M2 by increasing element in DX, the error has been reduced twice. For M6 or M7 the error drops to 1.5%. So it is clear that the element along the welding direction is very important in precision of thermal analysis.

The model M9, 1608s of analysis, with small mesh give higher value of temperature on the upper surface and slice difference on the bottom surface. This is because of the very small dimension mesh especially DX that let to overlap of heat flux in the same position on top surface than on bottom in the simulation.

The model M10 with reducing DX from M9 by factor of 2, using minimum value defined in [8], show higher computing time compared to model and M9 around 3113s of analysis. maximum temperature in FZ increase less than 5% in FZ and less than 3% in HAZ compared to model M8 and less than 1% compared to M9.

In general, the maximum temperature increases when the time increments reduce. Model M6, M7, M8, M9, M10 give the difference on temperature less than 5% in FZ and less than 3% in HAZ.

The best value of DX must be less than 2R, model M4, and bigger than R, for a better results with suitable time consuming. DY and DZ have less influence and can be choose

to be bigger than R for reducing the number of element used. But DY and DZ must be less than R for better visualizes different values of results in this zone.

Two Fig.15&16 represent the distribution of maximum temperature along the welding line on upper and bottom surface at instant $t=0.5s$.

The maximum temperature distribute along the welding line at instance 0.5s also indicate the distinction by two curves for seven simulations with the gap of 100°C when the temperature at cooling stage less than 700°C this is because of the different mesh inside the FZ and HAZ. The over preheat in front of the heat source by larger value of DX has been notified, but this error is overlooked by rapid welding speed.

The ratio of DX/R must be less than two in order to get accurate precision of thermal simulation. This have been used in the work of [6], [7] with success and verified with experimental and can reduce numbers of discretization in the direction of welding. The others dimensions DY and DZ have less influence in the results but DY defined the different temperature in the weld pool. The value of DY, two elements per radius, and DZ, 4 elements per thickness, valid by the minimum value in [8].

IV. CONCLUSION

Two objectives of this observation have been reached.

The effects of material properties on the thermal result has been classified by percent of errors with the material dependent temperature properties from 1.5% to 5% in the model that overlooked the peak specific heat at phase transformation to the material independent of temperature. All those models can be used with error less than 10% compared to values gets from experimental as [9].

The meshes dimensions have been evaluated for laser Nd:YAG full penetration welding.

The further works should be specified on their effects on the residual stress, deformation and metallurgical transformation.

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