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A Numerical Study on the Thermal Transient Model with Moving Laser Heat Source of AISI 304 stainless steel plate

Patiparn Ninpetch[a], Pruet Kowitwarangkul[a,*]

[a]*The Sirindhorn International Thai-German Graduate School of Engineering (TGGS),*
King Mongkut's University of Technology North Bangkok (KMUTNB)
1518 Pracharat 1 Road, Wongsawang, Bangsue Bangkok, 10800, Thailand

*Corresponding Author's E-mail: pruet.k@tggs.kmutnb.ac.th

Abstract

Laser beam is commonly used as a moving heat source in various metal processing such as cutting, heat treatment, welding, and recently in additive manufacturing or metal 3D-printing. Understanding of thermal behavior resulting from a moving laser beam are essential to control the product quality in those processes. This research aims to study the 3D thermal transient model of moving laser heat source with changeable direction of motion in order to investigate the effect of process parameters, e.g., power intensity, scanning speed and hatch spacing on the temperature distribution of the AISI 304 stainless steel plate. The numerical study is carried out using the commercial software ANSYS 18.1 and considering the simulation of the low intensity laser heat flux with Gaussian intensity distribution. The results of temperature profile at the probe point from numerical simulation are in agreement with the experiment results.

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Keywords: Moving laser heat source; Numerical simulation; Thermal transient model; Gaussian distribution

1. Introduction

Moving laser heat source is commonly used in various metal processing such as cutting, surface treatment, welding, and metal additive manufacturing (AM) or metal 3D-printing [1]. AM process using metals is still considered a relatively new technology. It is the joining process from metal powder to create objects from 3D model data, usually layer upon layer [2]. Compared to other metal processing that use laser heat source, one obvious difference for AM process is that the laser heat source has repeatedly changeable moving direction which results in the thermal cycle

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effect in the work piece. Since the properties of the metal AM-product are related to the thermal stress, microstructure and phase transformation that influenced by thermal cycle during the process, the understanding of thermal behavior effect of moving laser heat source is necessary for further prediction of thermo-mechanical properties and for controlling the product quality.

In the numerical simulation of transient thermal behavior of the laser moving heat source, the Gaussian laser beam distribution, which utilizes the symmetrical distribution of laser irradiance across the beam, is widely used to describe the laser characteristic [3]. The main data required in the thermal analysis of the moving heat source problem are such as: (1) power, spot diameter and intensity distribution of the heat source, (2) the convection of surrounding atmosphere, (3) the thermal properties of the work material, and (4) the moving speed of the heat source [1]. Monem *et al*. [4] studied the effect of laser welding parameters on the fusion zone shape of austenitic stainless steels and found that the laser power and moving speed of heat source have effects on the thermal field and shape of fusion zone. Bianco *et al*. [5] studied heat transient conduction in solids irradiated by a moving heat source using COMSOL Multiphysics code for solving the problem. They found that surface heat transfer strongly affected the temperature distributions in the considered solid specimen. Ming *et al*. [6] used simulation software ANSYS with heat source model for laser welding to investigate temperature field on a stainless steel 304 sheet and concluded that the temperature distribution of workpiece changes quickly with the variety of time and space. Shanmugam [7] used software ANSYS to investigate behavior of temperature field and molten pool shape during the welding process of AISI 304 stainless steel using a Gaussian laser distribution heat source model and found that the increase of welding speed reduces the peak temperature value.

The current research aims to study the 3D numerical simulation of thermal transient model of moving laser heat source with changeable direction in order to investigate the effect of moving heat source parameters, e.g., laser power intensity, scanning speed and hatch spacing, on the temperature field of the simple shape work piece of AISI 304 stainless steel plate. The simulations were done with the laser which has low power intensity in the range of 200-500 W/mm^2. The numerical results were validated with the experimental results in this study as well.

2. Theoretical background

2.1 Heat transfer equations

Fourier heat conduction equation is used to simulate a heat transfer process in the work piece. The governing equation for heat conduction is described in equation (1). Equations (2) and (3) are the initial and boundary conditions with surface convection and radiation respectively.

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

$$T(x,y,z) = T_0 \qquad (2)$$

$$-\lambda\frac{\partial T}{\partial z} = \varepsilon_\theta\sigma(T^4-T_e^4)+h(T-T_e) \qquad (3)$$

where T is the temperature, λ is the conductivity coefficient, ρ is the density (7,800 Kg/m^3), c is the specific heat capacity, q is the internal heat, T_o is the initial temperature, T_e is the environment temperature, ε_θ is the thermal radiation coefficient, σ is the Stefan-Boltzmann constant (5.67e-8 W/m^{2}K^4), and h is the convection heat transfer coefficient which is assumed to be 3 W/m^{2}K. Fig. 1 shows the conductivity coefficient λ and the specific heat capacity c

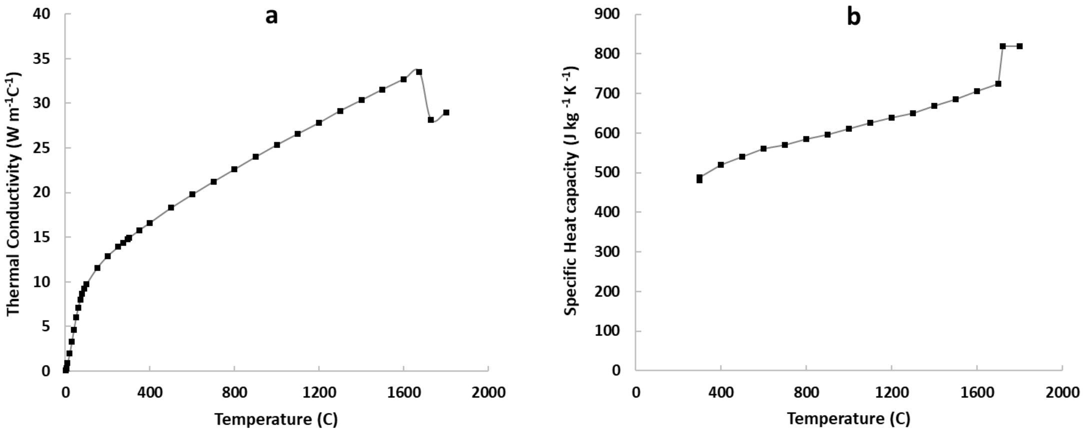

Fig.1 (a) The Thermal conductivity coefficient of AISI 304, (b) The specific heat capacity of AISI 304, [8]

2.2 Moving laser heat source model

The Gaussian heat flux source model used in this study is described [9] as in equation (4)

$$q = \frac{2P}{\pi\omega^2} e^{-\frac{[(x-x_0)^2+(y-y_0)^2+(z-z_0)^2]}{\omega^2}} \tag{4}$$

where q is heat flux on the surface, ω is radius of beam, I_o is power intensity, (x_o, y_o, z_o) is instantaneous position of the center of the heat flux which is on the moving path at distance of x, y, z from start point, v is velocity of moving heat source, t is time.

The Gaussian heat energy source model is described [9] as in equation (5)

$$E = I_o e^{-\frac{[(x-x_0)^2+(y-y_0)^2+(z-z_0)^2]}{\omega^2}} . e^{-AC(z-z_0)} \tag{5}$$

where E is heat energy, AC is absorption coefficient. The value of parameters in the equations (4) and (5) are shown in next section.

3. Methodology

3.1 Numerical simulation setup

Numerical simulation was performed by commercial simulation software ANSYS 18.1. The material used in this study is AISI 304 stainless steel plate with a dimension of 50x70x2 mm^3. The geometry and moving path of laser heat source are shown in Fig.2(a). An computational mesh of around 70,000 cells is used for the simulation. The mesh is shown in Fig.2(b). The parameters of moving laser heat source are listed in Table 1. The temperature history during the process is measured by the probes at six points as shown in Fig.1(a). The distance between each point is 1 mm.

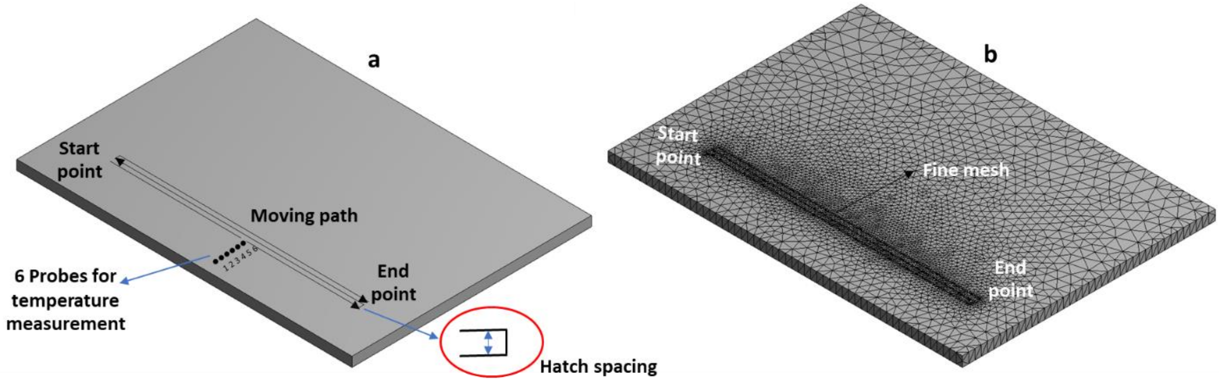

Fig.2 (a) The geometry and moving path of laser heat source, (b) mesh elements of the work piece model

Table 1. Parameters for the numerical simulation of moving laser heat source

Moving laser heat source parameter	Value
Power intensity (I_o)	200 - 480 W/mm^2
Scanning speed (v)	0.68 and 1.32 mm/s
Hatch spacing (s)	0.5 and 1 mm
Absorption coefficient (AC)	0.30
Initial temperature (T_o)	27-28 ^{o}C
Time (t)	120, 180 sec

Five scenarios of the numerical simulation with different parameters of moving laser heat source, as shown in Table 2, are conducted in this study.

Table 2. Five scenarios of the numerical simulation with different parameters of moving laser heat source

Scenario	Power intensity (W/mm^2)	Scanning speed (mm/s)	Hatch spacing (mm)
1	200	1.32	0.5
2	200	1.32	1
3	200	0.68	0.5
4	200	0.68	1
5	480	0.68	0.5

3.2 Experimental setup

The AISI 304 stainless steel plate with a dimension of 50x70x2 mm^3 were used as specimens in this experiment. Fig.3(a) shows the laser source device, JenLas® fiber ns 50, at Center Innovation of Design and Engineering for Manufacturing (Col-DEM), KMUTNB which has maximum power of 50 W. The laser focus position, the diameter of laser spot, and the power intensity used in this experiment are 18 cm, 0.35 mm, and 200 W/mm^2 respectively. The specimen and experimental setup are shown in Fig.3(b). The thermocouple probe is attached with the specimen at the same position as the probe point no.1 of the numerical model as shown in Fig.1(a). The experiment tests are conducted in order to validate the results from numerical simulation. The parameters of the moving laser heat source used in the experiment were as same as those used in numerical simulations (see Table 1). The experiments are done with the conditions as same as of scenario 1 and scenario 2 from the numerical simulation conditions shown in Table 2.

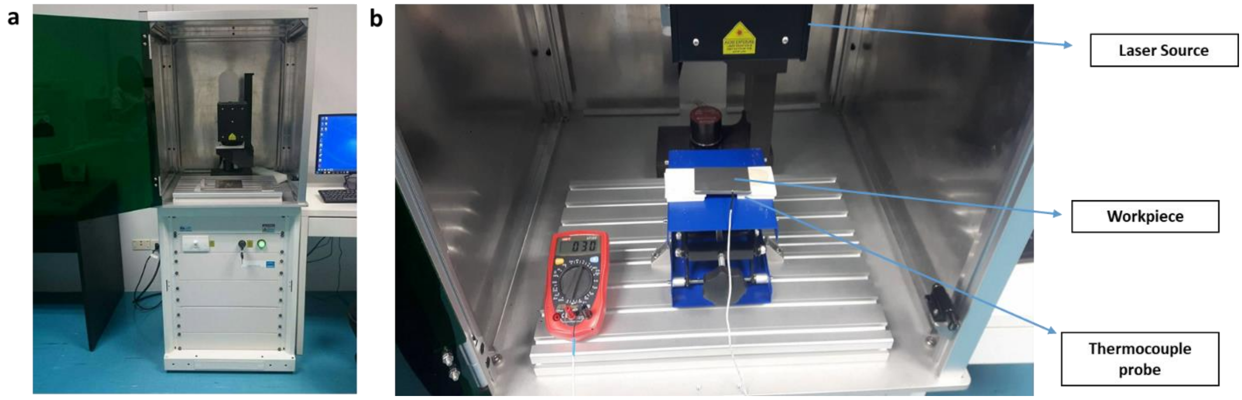

Fig.3. (a) Laser source device at Center Innovation of Design and Engineering for Manufacturing (Col-DEM), KMUTNB, (b) Specimen and experimental setup

4.Result and Discussion

4.1 Temperature field from the numerical simulation

Temperature distribution in the numerical specimen model from the scenario 1 at time 30 sec, 70 sec and 101 sec are shown in Fig.4. The contour shape of temperature distribution is influenced by the history and direction of moving laser heat source. At 30 sec, the temperature contour has a comet-shape with the tail opposite to the laser moving direction. The tail deviates toward the lower side since the upper zone has more volume for heat conductive transfer. The maximum temperature in the specimen model is 1361ºC in the region under direct irradiation. At 70 sec and 101 sec, the comet-shape area of temperature distribution are expand due to the heat accumulation during the back and forth moving of laser heat source on the specimen.

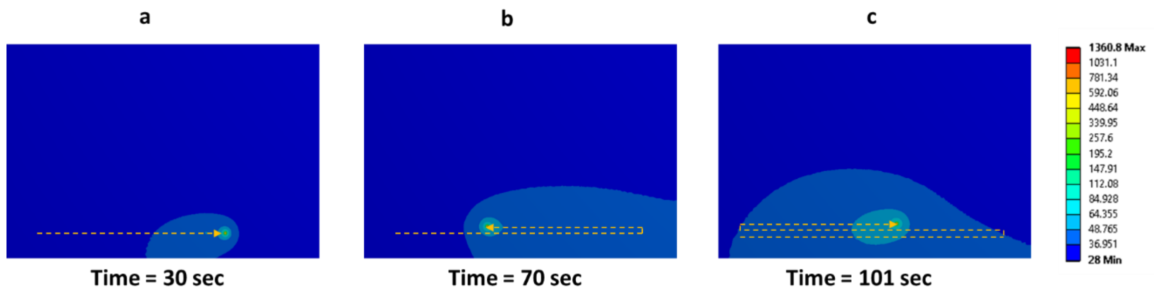

Fig.4. Temperature distribution in the numerical specimen model from the scenario 1 at time (a) 30 sec, (b) 70 sec and (c) 101 sec.

4.2 Effect of scanning speed and hatch spacing

The numerical simulation results from test scenario 1 and 2 were validated with the experimental results as shown in Fig.5. The graphs show the temperature history at the probe point no.1 (see Fig.2). The temperature peak took place after the moving of heat source passed that area. The temperature profile of scenario 1 (hatch spacing 0.5 mm) is slightly higher than that of scenario 2 (hatch spacing 1 mm), e.g., the second peak of scenario 1 and 2 are 184 ºC and

176 °C respectively. The comparison of the results from numerical simulations and experiments shows good agreement with minor difference. The peak of the results from experiment are slightly lower than that of the simulation. Fig. 6 shows the effect of moving laser heat source parameters, e.g., scanning speed and hatch spacing, on the temperature history at the probe point no.1 from the 4 scenarios of numerical simulation. When the scanning speed is decreased from 1.32 mm/s to 0.68 mm/s, the first temperature peak of the graph is increased from 128 °C to 194 °C. Different hatch spacing slightly affects the temperature history at probe point no.1 as can be seen from Fig.6. At the second temperature peaks in the graph, with the increasing of hatch spacing from 0.5 mm to 1.0 mm, the temperature peak is decreased for around 5-10 °C.

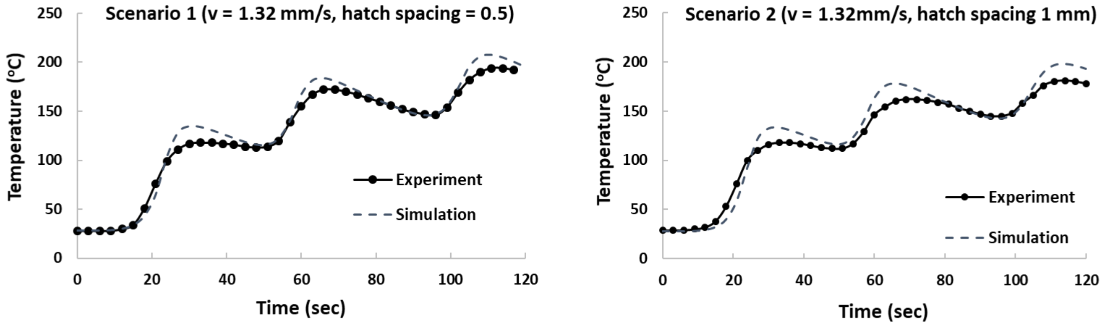

Fig.5. Temperature history at the probe point no.1 of specimen in (a) scenario 1 and (b) scenario 2

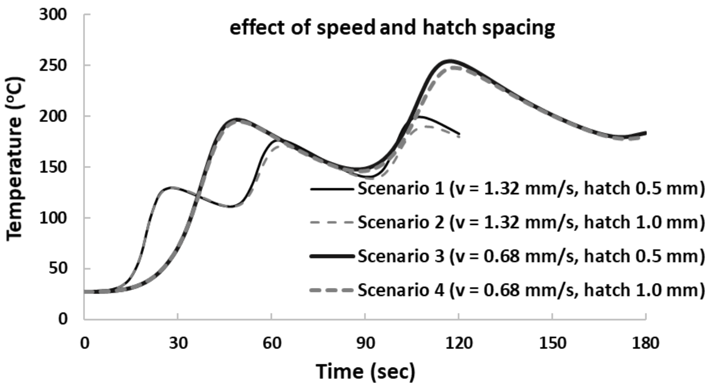

Fig.6. Comparison of temperature history at the probe point no.1 from the 4 scenarios of numerical simulation

4.3 Temperature history at six probe points

Fig.7 shows the temperature histories at six probe points (see Fig. 2) from the numerical simulations of scenario 3 and 5 which have power intensity of 200 W/mm2 and 480 W/mm2 respectively. At the probe point no.6 which is the position at the first forth path of laser beam, the first peak temperature was increased from around 1200 °C to 2500 °C after the power intensity was increased from 200 W/mm^2 to 480 W/mm^2. At the probe point no.1 to no.5, the temperature of both peaks are not so much different, while at the probe point no.6, the second temperature peak is much lower than the first peak since the laser source moved pass through that point only the first forth path (see Fig. 2).

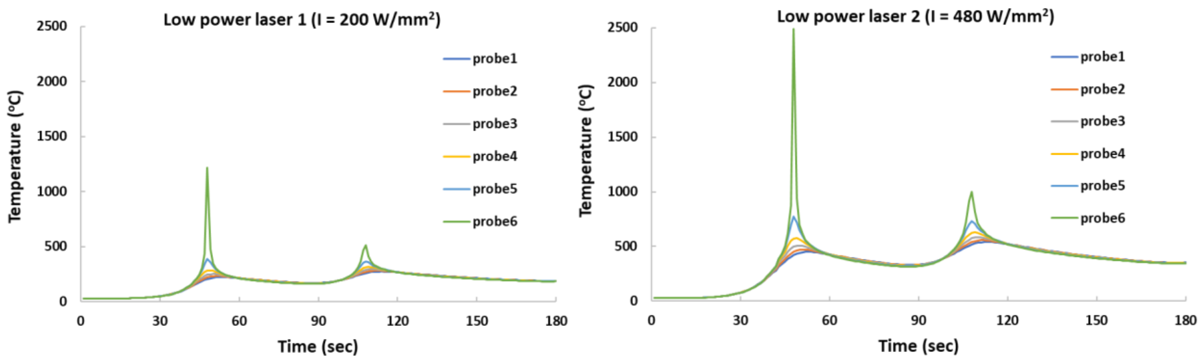

Fig.7. the temperature history profile at six probe points of (a) scenario 3 and (b) scenario 5

5.Conclusion

In this research, the effects of the moving laser heat source parameters such as speed, direction, hatch spacing and power intensity on the temperature distribution of the AISI 304 stainless steel plate were investigated through the numerical simulations and experiments. The effect of changeable direction moving laser heat source with low power intensity in the range of 200-480 W/mm^2 were studied through the numerical simulation. The comparison of the results from numerical simulations and experiments shows good agreement with minor difference. At some observed position in the specimen, the double speed of the moving heat source results in the decreasing of the temperature for around 30%. The increasing of power intensity from 200 W/mm^2 to 480 W/mm^2 results in the increasing of the temperature at the laser moving path for nearly double.

The future work of this research would be the numerical and experimental study of the laser powder bed fusion (L-PBF) additive manufacturing that use the moving laser beam as a heat source to selectively melt the powder metal which involves with fluid dynamics in molten pool, phase transformation, thermal-stress and distortion of the product specimen.

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