Numerical Analysis on Stress Evolution During GTA-Additive Manufacturing of Thin-Walled Aluminum Alloys

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Abstract. GTA-Additive Manufacturing (GTA-AM) is one of the Wire Arc Additive Manufacturing (WAAM) technologies based on Gas Tungsten Arc Welding (GTAW). During the GTA-AM process, non-uniform heating, as well as rapid heating and cooling of deposited materials lead to inevitable temperature stress, while repeated remelting in subsequent deposition introduces complexity to the evolution of it. Finite element modeling was conducted in this work to investigate the stress evolution during the GTA-AM of thin-walled 5183-Al. Several thin-walled 5183-Al components with different bead widths are included to understand the influences brought about by geometry dimensions. Hole-drilling method is used to measure the residual stress of 5183-Al components manufactured by GTA-AM, which proves the reliability of this numerical model. Results of modeling show that the temperature stress is generated and released alternately and repeatedly as the deposition proceeds. The cycles of equivalent stress are in synchronization with the thermal cycles, in which equivalent stress reaches peak when temperature gets to its valley value. However, as the deposition layers pile up, the peak value of equivalent stress decreases gradually, and finally achieves stability after a certain layer. As for the influences of geometry dimensions, larger bead width results in higher level of stress due to much larger heat input as well as greater constraints.

1. Introduction
These GTA additive manufacturing is a kind of wire-based AM (Additive Manufacturing) techniques, which employs electric arc as heat source. It has shown advantages in large scale component manufacturing for its high deposition rate, remarkable flexibility, as well as reduced equipment costs [1, 2]. However, during GTA additive manufacturing, similar to the multi-layer welding process, components produced are influenced by complicated thermal cycles. Thermal cycle in the fabrication process is one of the key factors affect the microstructure formation. While it is difficult to investigate the thermal process by experimental approaches, numerical simulations provide an effective way. Thermal modeling of the additive manufacturing process has been an active research field recent years [3-6]. Although a lot of works have been done in the thermal process simulation of AM, few combine the numerical results with microstructure formation mechanism investigation. In this work, a FE model was used to simulate thermal process of GTA additive manufacturing of 5183-Al components.
2. Experimental Procedures and Modeling

A GTA-AM system was developed to produce 5183-Al components. The composition and detailed working procedure of this GTA-AM system has been explained in our previous research [1]. Employing ER5183 as feed wire, three thin wall components were produced using the parameters listed in Table 1 separately. Average layer heights of three samples were controlled at the same level i.e. 1 mm. Average thicknesses of thin wall are 3.9 mm, 7.3 mm, 9.6 mm separately, so the influences brought about by geometry dimensions can be investigated. All samples were sectioned, then polished by metallographic abrasive paper and velvet polish cloth. Thermal processes during 10-layer deposition of three samples were simulated, in which deactivate and reactivate element technique was adopted. The governing equation of heat transfer problem is the heat conduction differential equation expressed by Eq. (1). The heat loss of external boundaries was modeled as convection and radiation boundary conditions, which can be written as Eq. (2).

\[
\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + \frac{\partial}{\partial t} \lambda \frac{\partial T}{\partial t} + q
\]

(1)

\[-\lambda \frac{\partial T}{\partial n} = h(T - T_a) + \varepsilon \sigma (T^4 - T_a^4)
\]

(2)

Where \( \rho \) is density, \( c_p \) is heat capacity, \( T \) is temperature, \( q \) is input heat flux, while \( \lambda \) represents thermal conductivity, \( h \) represents heat convection coefficient, \( \varepsilon \) represents emissivity, \( \sigma \) represents Stefan-Boltzmann constant and \( T_a \) represents the room temperature. The arc power is modeled as a heat flux boundary condition in the simulation. The distribution of arc power is assumed to conform to the double ellipsoid heat source model [6], i.e.

\[
q(x,y,z) = \frac{6\sqrt{3} f_1 \eta U I}{\pi a_f bc \sqrt{\pi}} \exp\left(-3 \frac{x^2}{a_f^2}\right)\exp\left(-3 \frac{y^2}{b_f^2}\right)\exp\left(-3 \frac{z^2}{c_f^2}\right)
\]

(3)

\[
q(x,y,z) = \frac{6\sqrt{3} f_2 \eta U I}{\pi a_r bc \sqrt{\pi}} \exp\left(-3 \frac{x^2}{a_r^2}\right)\exp\left(-3 \frac{y^2}{b_r^2}\right)\exp\left(-3 \frac{z^2}{c_r^2}\right)
\]

(4)

Where \( f_1 \) and \( f_2 \) are energy fraction in front and rear hemisphere, \( \eta \) is the efficiency of arc, \( U \) is the welding voltage and \( I \) is the current, while \( a_f, a_r, b \) and \( c \) represent shape parameters of ellipsoid.

Table 1 Deposition Parameters and Dimensions of Thin Wall Components

| Sample | Current (A) | Deposition Speed (mm/min) | Wire Feed Speed (mm/min) | Resident Temperature (°C) | Average Thickness (mm) | Average Height (mm) |
|--------|-------------|---------------------------|--------------------------|---------------------------|------------------------|---------------------|
| 1      | 75          | 400                       | 1191                     | 80                        | 3.9                    | 1.12                |
| 2      | 107         | 210                       | 1301                     | 80                        | 7.3                    | 0.95                |
| 3      | 125         | 120                       | 879                      | 80                        | 9.6                    | 1.06                |

3. Results and Discussion

3.1. Numerical Simulation of the thermal cycles

Distributions of the temperature field during the Sample 1 manufacturing procedure was calculated and showed below in Figure 1. Where 1a shows the temperature field of the center point in the first deposition layer. Figure 1b shows the temperature field of the center point in the fifth deposition layer. Figure 1c shows the temperature field of the center point in the ninth deposition layer. The high temperature region could be defined as the region whose temperature is above 200°C. High temperature region behind the molten pool expands gradually with the follow-on deposition layer, which could represent that the heat dissipation of each deposition layer shows less relation to the base plate. Figure 2 and Figure 3 show the temperature field of Sample 2 and Sample 3 at the same point as Figure 1. As the forming dimension increases, the high temperature region expands. This would cause the difference of the distribution of the residual stress.
Figure 1 Temperature field evolution of Sample 1. (a) center point of the first layer; (b) center point of the fifth layer; (c) center point of the ninth layer.

Figure 2 Temperature field evolution of Sample 2. (a) center point of the first layer; (b) center point of the fifth layer; (c) center point of the ninth layer.

Figure 3 Temperature field evolution of Sample 3. (a) center point of the first layer; (b) center point of the fifth layer; (c) center point of the ninth layer.

Figure 4, Figure 5 and Figure 6 show the thermal cycles experienced by the center point in the first deposition layer of three samples. Peak temperatures of the first two cycles exceed the melting point of 5183-Al. The first one is defined as melting heat in this research. The second one is defined as remelting heat, while the rest are defined as post heat. As deposition procedure goes on, the center of the heat source moves away from the point inspected. So the peak temperatures show a downward trend. As the forming dimension increases, each peak temperature presents a tendency of increasing especially in Figure 3a where the value of the last peak is still above 400°C. It seems a poorer condition of heat dissipation as the forming dimension increases with deposition layer piled up. However, generally speaking, an increasing forming dimension would be beneficial to the condition of heat dissipation, without considering other factors. Chances are that wider forming dimension for each pile demands higher heat input and longer heating process. Increasing forming dimension means larger heat input on every single pile, which would cause an expansion of the liquid phase region and the high temperature solid phase region along the altitude direction starting with the current pile during the deposition process. Compared with the less forming dimension condition, both remelting times and thermal interaction increase at the point on the same position in the former piles, which would lead to an increment on the peak temperature and a decline on the difference between every adjacent peak value.
Figure 4 Thermal cycles at the center points on different layers of Sample 1. (a) thermal cycle on the first layer; (b) thermal cycle on the fifth layer; (c) thermal cycle on the tenth layer

Figure 5 Thermal cycles at the center points on different layers of Sample 2. (a) thermal cycle on the first layer; (b) thermal cycle on the fifth layer; (c) thermal cycle on the tenth layer

Figure 6 Thermal cycles at the center points on different layers of Sample 3. (a) thermal cycle on the first layer; (b) thermal cycle on the fifth layer; (c) thermal cycle on the tenth layer

For more intuitive observation, maximum temperature gradients at the center point of each layer on different samples were extracted in Figure 7. Temperature gradients in all three directions descend as layers pile up, indicating that the influence of heat dissipation caused by substrate diminishes gradually when components get higher. After the 8th layer, temperature gradients almost come to a steady state. During simulation, deposition is along the y axis and heat source moves along the z axis.

Figure 7 The maximum temperature gradient at the center point on different layers. (a) Sample 1; (b) Sample 2; (c) Sample 3
Figure 7 also shows that the deposition direction always has the optimum heat dissipation condition. As the forming dimension increases, the maximum temperature gradient goes lower and so does the value of difference between every two peaks. Although both the layers piling up and the forming dimension increasing can lead to a better heat dissipation, heat input and function time of the heat source practically increase to realize this process, which causes a decline in the difference between each maximum temperature gradient during the same deposition process.

Then, in a one-layer scale, as Figure 8 shows, temperature gradients decline significantly as solidification proceeds. Sample 3 also shows the least temperature gradients during solidification procedure. Chances are that Sample 3 would get a poorest residual stress distribution which could lead to a poorest property.

![Figure 8](image)

**Figure 8** The temperature gradient at liquid-solid interface. (a) Sample 1;(b) Sample 2;(c) Sample 3

3.2. Numerical Simulation of the stress evolution

Figure 9 shows the evolution of the stress field distributed on the whole Sample. No stress exists in molten pool during the heat source loading procedure. Yet material beside the molten pool could not be in liquid phase. With the solidification procedure, the tendency of its shrinkage would be declined by the material relatively cold around. Thus, equivalent stress region expands along the manufacturing direction behind the molten pool during the deposition procedure. Temperature decreasing, the value of residual stress would increase significantly. Finally, when the sample cools into the room temperature, residual stress occurs on the whole sample.
Figure 9 Distribution of equivalent stress with heat source moving during the deposition procedure. (a) heat source at the origin of the first layer; (b) heat source at the end of the first layer; (c) heat source at the origin of the fifth layer; (d) heat source at the end of the fifth layer; (e) heat source at the origin of the tenth layer; (f) heat source at the end of the tenth layer; (g) cooling to room temperature

With the deposition layer piling up, each layer can reheat the former layer. As the thermal cycles shown in 3.1, each former layer would be reheated up to the plastic state by the next layer, which could lead to some minor plastic deformation to decline the level of the equivalent stress. Hence, after certain piles, the equivalent stress tends to approach a stable value. As Figure 10 and Figure 11 show, extracted from the center point of each pile from Sample 1, the peak of the equivalent stress goes down as piles increase.

Figure 10 Equivalent stress cycle at the center point on the first layer  Figure 11 The maximum equivalent stress values at the center points on different layers

The equivalent stress could be released as described above and this effect could be observed more intuitive in Figure 12. The second valley shows the effect of remelting and the third shows the effect of post heat. As time goes by, the effect of the release goes weaker because of the peak temperature during post heat procedure going lower.
The stress cycles of the center point on the same layer among three samples were shown in Figure 13. As the forming dimension increases, the value of each peak increases and the time for reaching the stable value increases. As described above, wider forming dimension demands higher heat input and longer heating process. Meanwhile, wider forming dimension causes a stronger restraint on the solidified metal. Therefore, the level and the region of the residual stress would both be higher. These could be shown more directly in Figure 14.

**Figure 12** Temperature cycle and equivalent stress cycle at the center point on the first layer of Sample 1

**Figure 13** Equivalent stress cycles at the center points on the first layers among different samples. (a) Sample 1; (b) Sample 2; (c) Sample 3

**Figure 14** The maximum peak equivalent stress value at the center points on different layers

4. Conclusions
   (1) In the component scale, as the deposition proceeds, the influence of heat dissipation caused by substrate diminishes gradually, resulting in the stabilization of thermal process.
   (2) In the layer scale, temperature gradients at the solid liquid interface reduce as the solidification proceeds.
   (3) Deposition layers piled up, the peak value of equivalent stress decreases gradually and finally achieves stability after a certain layer.
   (4) Larger forming dimension results in higher level of equivalent stress due to much larger heat input as well as greater constraints.
   (5) Increasing piles result in a decrease in temperature gradients and their differences both in component scale and layer scale.
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