Numerical Simulation of Laser Beam Cutting of Carbon Fiber Reinforced Plastics

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Abstract

Numerical Simulation of laser beam cutting of carbon fiber reinforced plastic (CFRP) is performed. It is important to understand the mechanism about generation of heat-affected zone (HAZ) in order to improve quality of CFRP cutting by laser. However, only a little theoretical or numerical studies about HAZ formation were performed. Especially, there is no research considering heat generation of oxidization of materials in the air condition. To develop the new calculation model to consider the effect of combustion and decomposition of each element of CFRP, thermo gravidy analysis (TGA) and differential thermal analysis (DTA) was performed about CFRP in the air condition. Finally, comparing with the results of experiments and our simulation, our calculation model is verified and what occurs inside CFRP after laser irradiation is explained.

1. Introduction

A carbon fiber reinforced plastic (CFRP) consists of carbon fiber and binding polymer. Carbon fiber makes contribution to its tensile strength. Because CFRP has higher specific strength compared with metal materials and chemical resistance and dimensional stability, it is expected as suitable material for automobile and airplane and any...

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case whenever higher strength-to weight ratio is necessary [1]. Although laser cutting method is applied to many materials to process these materials, CFRP are generally cut by mechanical machining, water jet machining and electro-spark machining. These methods have problems such as separation and nap of the target and wastage of processing tools [2-6], however the laser cutting method generates heat affected zone (HAZ) because of differences in thermal properties of carbon fiber and binding polymer [7].

Although many experiments were performed to apply laser cutting technique to CFRP, not enough theoretical or numerical studies are performed about HAZ generation. One dimensional analysis [8] and two dimensional analyses [9, 10] and three dimensional analysis [11] has been performed. However, there is no research considering heat generation of oxidization of materials in the air condition.

In this study, heat of combustion was included into calculation model to simulate laser processing of CFRP and validate this model qualitatively.

2. Simulation model

2.1. Thermo gravidity analysis (TGA) and differential thermal analysis (DTA)

To include the effect of combustion heat, TG-DTA was performed about CFRP itself. To realize this analysis, DTG-60 made by Shimadzu Corporation was used. A sample was heated from 40 degree Celsius to 1000 degree Celsius in the air and speed of temperature increasing was 20 K/min.

Figure 1 shows the result of TG-DTA of the CFRP that is mass and produced heat dependence on temperature. The epoxy resin in CFRP plate was decomposed about 460 degree Celsius and the carbon fiber also combust about 850 degree Celsius as following chemical equation.

\[ C + O_2 \rightarrow CO_2 + 394 \text{kJ/mol} \]

Fig. 1. Result of TG-DTA of CFRP plate. Resin decomposed about 460 degree Celsius and carbon fiber combus about 850 degree Celsius. More combustion heat is generated by carbon fiber than resin.

2.2. Theoretical model

In this study, we consider thermal conduction and heat generation of decomposition and combustion of each material. Therefore governing equation becomes time-dependent heat conduction equation as follows,

\[ \rho_i C_i \frac{\partial T}{\partial t} = \nabla(\lambda_i \nabla T) + Q \quad (i = c, r) \]

(1)
where $\rho$, $C$, $\lambda$, are density, specific heat and thermal conductivity respectively and indices $c$, $r$ refer to carbon fiber and resin. $Q$ is generated heat which includes laser absorption and decomposition or combustion heat at each position. Finite differential method is applied to solve this equation.

Generated heat is calculated from the result of Fig. 1 at each cell depends on the material ID and temperature. The material ID has three types of value, removed area, carbon fiber and resin. If material ID of a cell is resin, $Q$ is calculated from Fig. 2 when its temperature is about 460 degree Celsius and turns its material ID to removed area. If material ID of cell is carbon fiber, about 850 degree is used by the same way.

In particular, absorbed power of laser is calculated considering absorption coefficient of the material and laser intensity as follows,

$$Q_{laser} = \frac{l_{laser}(1 - \exp(\alpha dy))}{dx}$$

where $Q_{laser}$, $l_{laser}$, $\alpha$, $l$, $dx$, $dy$ are absorbed power density, power density of laser input, absorption coefficient of material, cell length of x and y direction respectively because two dimensional calculation is performed in this study as described below. The laser intensity inside the target is calculated by Lambert-Beer’s law as follows

$$\frac{dl_{laser}}{dy} = \alpha l_{laser}$$

### 2.3. Geometry of calculation and boundary condition

Two-dimensional model is adopted in this study. Schematic figure of geometry and boundary condition is shown in Fig. 1. Diameter of carbon fiber is expected as 8\(\mu\)m and diameter of input laser spot is 100\(\mu\)m and all boundaries have symmetric condition because the purpose of this study is clarify what occurs inside CFRP not at the surface. Therefore calculated area is rectangular of 7.5\(\mu\)m times 100\(\mu\)m.

![Fig. 2. Schematic figure of geometry and boundary condition. Diameter of carbon fiber is expected as 8\(\mu\)m and all boundaries are symmetric condition to simulate not surface but inside of CFRP. Single shot laser is irradiated vertically to the target from upper(y) direction.](image)

As described above section about TG-DTA, each material is removed generating heat. However, the reaction is able to occur only at the boundary of each material but not inside the material. Therefore combustion or decomposition is simulated at the boundary between removed area and resin or carbon fiber.

### 2.4. Material properties and input laser condition

One of the most difficult points to apply laser processing technique to CFRP is inhomogeneous thermo-physical properties of the target. Thermo-physical properties of CFRP are shown in Table 1[12, 13, 14]. Absorption coefficient of resin is measured by us.
Table 1. Thermo-physical properties of CFRP[12, 13, 14].

|                        | Resin | Carbon fiber | Removed area (air) |
|------------------------|-------|--------------|--------------------|
| Density [kg/m$^3$]     | 1250  | 1850         | 1.293              |
| Thermal conductivity [W/m.K] | 0.2   | 50 (parallel) 5 (perpendicular) | 0.0241 |
| Heat capacity [J/kg.K]  | 1200  | 710          | 1005               |
| Refractive index @ 1 $\mu$m | 2.05 + 0.7i (parallel) | 3.1 + 2.1i (perpendicular) |
| Absorption coefficient@1$\mu$m [cm] | 75.1  |              |                    |

It’s necessary for non-hydrodynamic simulation to create some model emulate removal of decomposed or combusted materials. In this study, decomposed or combusted resin and carbon fiber are considered having same properties of the air.

Input laser condition is shown in Table 2. Time step is varied in two parts because laser duration time is much smaller than speed of thermal conduction. When laser is irradiating to the target, the calculation is done by small time steps and large time step is applied after laser irradiation is finished. Former limit is determined by maximum temperature increasing in the time step and latter limit is determined by stability condition of explicit method of FDM.

Table 2. Input laser condition.

|                          | Value       |
|--------------------------|-------------|
| Pulse energy [J]         | 1.0         |
| Spot diameter [$\mu$m]   | 100.0       |
| Pulse duration [ns]      | 10.0        |
| Wave length [nm]         | 1064        |
| Beam profile             | Flat top    |

3. Results and discussion

Calculated results after laser irradiation are shown in Fig. 2. Figure 2 shows magnified figure around HAZ (x=40–60 $\mu$m). Although speed of thermal conduction is higher in carbon fiber than resin, decompose temperature of resin is lower than that of carbon fiber. Resin around carbon fiber is decomposed fast and then generated heat decompose surface of resin and resin around fiber is removed. Therefore resin around carbon fiber is removed and HAZ is generated.

Comparing this simulation results with experimental results of SEM image (Fig. 3), our calculation model succeeded in simulate removal of resin around carbon fiber in CFRP. Therefore we verified our simulation model qualitatively.
Fig. 3. Calculated result of numerical simulation about magnified area around HAZ(x=40~60μm). (a): Time development of material ID. Blue is removed area, red is resin and green is carbon fiber. (b): Time development of temperature distribution. Resin around carbon fiber is decomposed fast and generated heat decompose surface of resin and resin around fiber is removed.

Fig. 4. SEM images of CFRP after laser irradiation. Resin around carbon fiber is removed.
4. Conclusion

In this paper, FDM method and results of TG-DTA analysis are used to simulate the material removing during the laser ablation process. This model is based on the assumption that heat source is not only laser power but decomposition or combustion heat at boundary of removed area and resin or carbon fiber.

Simulation results are verified by comparison with SEM image of experimental result. Our new calculation model succeeded in simulating removal of resin around carbon fiber in CFRP.

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