COMPUTATIONAL MECHANICS
WCCM VI in conjunction with APCOM'04, *Sept. 5-10, 2004, Beijing, China*

Investigation on the Interaction of Laser Beam and Metal Powders Conveyed by Coaxial Powder Feeder

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Abstract To study the temperature and the phase state of metal powders during the interaction of laser beam and metal powders, a FEM model basing on ANSYS is established to calculate the temperature of metal powder. The calculated results show that all 316L SS powders are melted after they have passed through the laser beam with power of larger than 1000W. The amount of the absorption of laser beam energy by 316L SS powders is calculated simultaneously. After 316L SS powders have entered laser molten pool, the energy exchange between laser molten pool and 316L SS powders is also calculated. Results show that during laser direct forming, approximately 5% of laser energy is used to heat and melt metal powders and 95% of laser energy is used to form laser molten pool.

Key words: Laser direct forming 316L SS powder Finite element method Interaction

INTRODUCTION

Laser direct forming is a computer-aided manufacturing process, which is similar to Laser Engineered Net Shaping (LENS)™ [1-2]process and Directed Laser Fabrication (DLF)[3-4] process that uses a laser beam to melt delivered powder to form a metal part layer by layer. The AeroMet Corporation has developed a process for the laser additive manufacture of near net shape titanium alloy structures for advanced aircraft use.[5] During laser direct forming, metal powders are delivered through a nozzle which is coaxial with laser beam into laser molten pool. While metal powders passé through laser beam, they absorb laser energy from laser beam and are heated simultaneously. When metal powders get to the surface of laser molten pool, the temperature of metal powder is calculated using a FEM model basing on ANSYS. The amount of laser beam energy absorbed by metal powders is also calculated. After metal powders enter laser molten pool, the energy exchange between laser molten pool and metal powders is also investigated.

INTERACTION TIME OF LASER BEAM AND 316L SS POWDERS

Fig. 1 shows that 316L SS powders conveyed by Ar gas through a nozzle which is coaxial with CO_2 laser beam into laser molten pool. The atomized 316L SS powders are spherical in shape and theirs average size are about 60μm. Due to powder size being very tiny, it is appropriate to assume that the outlet velocity of 316L SS powders is equal to that of Ar gas. For powder delivery rate =4.5g/min, the outlet velocity (V_0) of 316L SS powders can be calculated from

$$V_0=\eta/S=111111/139=799 \text{ (mm/s)} \quad (1)$$

Where η and S represent Ar gas flux (mm3/s) and the area of the annulus outlet (mm2), respectively.
V_0 is at an angle of 650 with respect to the X axis. The horizontal velocity component V0h and the normal velocity component V0N of V0 can be calculated from

$$V_{0H}= V_0\times \cos 65^0 =337 \text{ (mm/s)} \quad (2)$$

$$V_{0N}= V_0\times \sin 65^0 = 724 \text{ (mm/s)} \quad (3)$$

The distance (H) from outlet to base plate is 25mm at laser beam with a diameter of 3mm. Without considering the influence of gravity force on powders, the flight trace of 316L SS powders is expressed with the imaginal lines in Fig. 1. As shown in Fig. 1, according to the physical dimension of the nozzle, 316L SS powders fly over a short horizontal distance (R=8.25mm) before they enter laser beam, the flight time (T_{flight}) is given by

$$T_{flight}=R/V0h=8.25/337=0.0245(s) \quad (4)$$

The vertical distance ($H_{falling}$) of powders falling in air is given by

$$H_{falling}=V_{0N*Tflight}=724\times0.0245=17.74(mm) \quad (5)$$

The vertical distance (H_{heated}) of powders falling in laser beam is given by

$$H_{heated}=H-H_{falling}=25-17.74=7.26\ (mm) \quad (6)$$

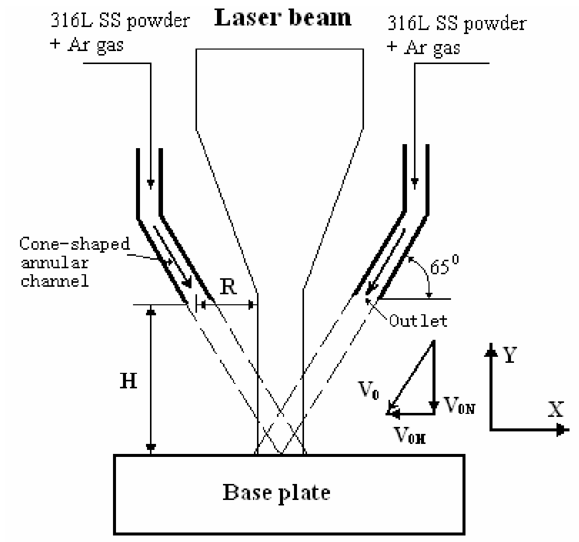

Fig.1 Schematic for interaction of laser beam and metal powder

So, the interaction time (T_{heated}) of laser beam and 316L SS powders can be calculated from

$$T_{heated} =H_{heated}/ V_{0N}=7.26/724=0.01(s) \quad (7)$$

CALCULATION FOR THE TEMPERATURE OF 316L SS POWDERS OF DIFFERENT SIZE

The interaction time of 316L SS powders and laser beam is 0.01s. In calculation, the powder is spherical in shape. Since the energy density of laser beam is less than 105W/cm2, the influence of plasma cloud on laser energy can be ignored. At the same time, the heat transfer among metal powders is not to be considered.

Fig. 2 shows that the FEM model for calculating the temperature of 316L SS powder is divided freely by Solid 70 thermal element, which is hexahedron with 8 nodes.

During the interaction of laser beam and 316L SS powder, the hemisphere of 316L SS powder facing the laser is heated by laser beam, so the heat flux density HFLUX, which is calculated from Eq.8, should be loaded as thermal load on the hemisphere heated by laser beam.

$$HFLUX = \eta\frac{4Q}{\pi\phi^2} \quad (8)$$

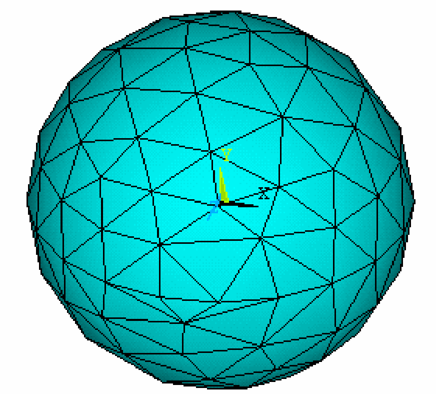

Fig.2 The FEM model for calculating the temperature of 316L SS powder

where η is the absorptivity of laser energy (η=0.35[6]), Q is the laser beam power (W), andφ is the diameter of the laser beam (mm).

Due to the existence of the natural-convection heat transfer between 316L SS power and air, so the natural-convection heat transfer between 316L SS powder and air is calculated using surface element SURF152. Ambient temperature is 20℃, and the natural-convection heat transfer coefficient of air is 10 ($W\cdot m^{-2}\cdot ℃^{-1}$). The size distribution of 316L SS powders with average particle size of 60μm is listed in table 1.

Table 1 The size distribution of 316L SS powders

Powder size (μm)	35	55	75	85
Percentage (%)	9	40	30	21

The thermophysical properties of 316L SS are listed in table 2 and table 3[7-8].

Table 2 Thermophysical properties of 316L SS

Density(kg/m^3)	Latent heat of fusion (J/m^3)	Temperature interval of phase change(℃)	Temperature of liquid phase line(℃)
8000	2.94×109	1399～1434	1434

Table 3 Conductivity factor and specific heat of 316L SS at different temperatures

Temperature(℃)	20	200	400	800	1200
Specific heat J/(kg·k)	494	536	569	644	669
Conductivity factor w/(m·k)	14.7	18	20.8	26.3	31.9

As shown in Fig. 3, under the same laser power conditions, the calculated temperature of 316L SS powder decreases with powder size increasing. The melting point temperature of 316L SS is 1434℃. The calculated results show that all 316L SS powders are melted after they have passed through the laser beam with power of larger than 1000W. while the power of laser beam is less than and equal to 800W, those finer 316L SS powders (≤55μm) are melted, but those coarser powders (≥75μm) are not be melted.

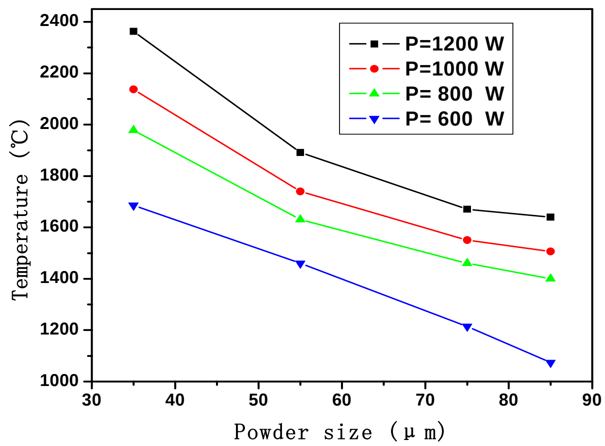

Fig.3 Under different laser power conditions, the calculated temperature of 316L SS powder of different size

CALCULATION FOR THE ABSORPTION OF LASER BEAM ENERGY BY POWDERS

During metal powders passing through laser beam, the amount of absorption of laser beam energy by single 316L SS particle can be calculated from

$$Q_{absorb}=\rho v\ c\ (T_1-T_0) \qquad (12)$$

Where ρis the density of 316L SS (kg/m^3), v is the volume of particle (m^3), c is the specific heat (J/(kg ℃)), T_0 is the temperature of the surroundings (20℃), and T_1 is the temperature of the particle which has passed through laser beam (℃).

After metal powders have passed the laser beam with power of 1000W, the temperature of 316L SS powders of different size is listed in table 4.

Table 4 The temperature of 316L SS powders of different size

Powder size (μm)	35	55	75	85
Temperature (℃)	2137	1790	1550	1506

The amount of absorption of laser beam energy by single 316L SS particle can be calculated from Eq.12 and table 4, as listed in table 5.

Table 5 The amount of absorption of laser beam energy by single 316L SS particle

Powder size (μm)	35	55	75	85
Absorbed energy (J)	2.3×10^{-4}	7.4×10^{-4}	1.7×10^{-3}	2.4×10^{-3}

During laser direct forming, experimental results show that the utilization ratio of metal powders is about 50%[12], namely, approximately 50% of metal powders delivered by powder feeder are used to build metal part, that is to say, only a half of metal powders have passed through laser beam. For powder delivery rate = 0.075g/sec, the weight of metal powders through laser beam per second is 0.0375g. According to the weight of 316L SS powders through laser beam per second, it can be calculated from the weight of single particle and the size distribution (table 1) that the number of 316L SS powders of different size pass through laser beam per second, as listed in table 6.

Table 6 The number of 316L SS powders of different size pass through laser beam per second

Powder size (μm)	35	55	75	85
Number	19509	22388	6470	3188

Thus, the absorption of laser beam energy (Q_{ab}) by 316L SS powders per second can be calculated from table 5 and table 6.

$$Q_{ab}=43\ (J)$$

For laser power =1000W, the laser output energy is 1000 (J) per second. So, during the interaction of laser beam and 316L SS powder, approximately 4.3% of laser output energy is absorbed by 316L SS powders.

CALCULATION FOR ENERGY EXCHANGE BETWEEN LASER MOLTEN POOL AND POWDERS

After 316L SS powders had passed through the laser beam, without considering the flow of the laser molten pool, 316L SS powders always dropped onto the surface of the laser molten pool. Thus, the surface average temperature of laser molten pool will be thought as the temperature of the 316L SS powders being in the laser molten pool. So, the energy exchange between single 316L SS particle and laser molten pool can be calculated from

$$J_{exchange}=\rho v\ c\ (T_1-T_0) \qquad (13)$$

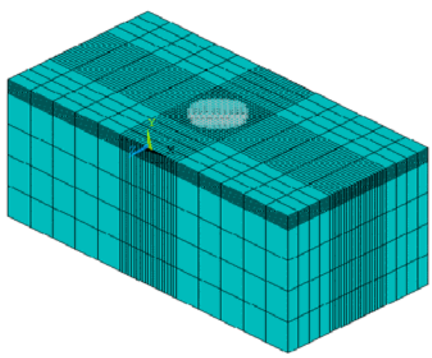

Fig. 4 The FEM model calculating the temperature field of laser molten pool

where ρ is the density of 316L SS (kg/m^3), v is the volume of particle (m^3), c is the specific heat of 316L SS (J/(kg ℃)), T_0 is the temperature of particle which just achieve the surface of laser molten pool (refers to table 4) (℃), and T_1 is the surface average temperature of the laser molten pool (℃).

A FEM model basing on ANSYS is established to calculated the temperature field of laser molten pool, the dimension of the FEM model is 20mm×10mm×10mm, as shown in Fig. 4. The base plate is made of AISI 1045. The calculation for the temperature field of laser molten pool can be acquired from Ref.[9].
The surface average temperature (T) of laser molten pool can be calculated from

$$T = \frac{\sum_{i}^{N} t_i}{N} \tag{14}$$

Where t_i is the temperature of node, and N is the number of nodes.

The calculation for the transient temperature field of laser molten pool is conducted at laser power being 1000W with the diameter of laser spot being 3mm, as well as calculation time being 1s. According to Eq.14, the surface average temperature of laser molten pool is 2036℃.
The energy exchange between laser molten pool and 316L SS powders of different size can be calculated from table 4, Eq.13 and Eq.14, as listed in table 7.

Table 7 The energy exchange between laser molten pool and 316L SS powders of different size

Powder size (μm)	35	55	75	85
Energy exchange(J)	-0.06	2.4	2.7	2.1

Table 7 shows that if the temperature of 316L SS powder is higher than the surface average temperature of laser molten pool, 316L SS powder will release heat to laser molten pool, inversely, 316L SS powder will absorb heat from laser molten pool. Table 7 also indicates that the total energy exchange (U) between laser molten pool and 316L SS powders is 7.14 (J). During metal powders through laser beam, the amount of the absorption of laser beam energy by 316L SS powders is 43 (J). Therefore, the laser energy used to heat and melt 316L SS powders is 50.14 (J) and 5% of laser output energy. (For laser power =1000W, laser output energy is 1000 (J) per second). From previous calculation, one can see that 5% of laser energy is used to heat and melt new material and approximately 95% of is used to make laser molten pool. The percentage of the laser energy used to heat and melt 316L SS powders in the laser output energy is also calculated at laser power being 800W and 1200W, respectively, with the diameter of laser beam being 3mm and calculation time being 1s, as listed in table 8.

Table 8 Under the different laser power conditions, the percentage of the laser energy used to heat and melt 316L SS powders in the laser output energy

Laser power (W)	*800*	*1000*	*1200*
Percent (%)	*5.6*	*5.0*	*4.6*

CONCLUSIONS

A FEM model, which considers the critical heat of the 316L SS powder and the natural-convection heat transfer between air and 316L SS powder, is established to calculate the temperature field of 316L SS powder through laser beam. The calculation results show that for the diameter of laser beam is 3mm, after 316L SS powders have passed through laser beam with power of larger than 1000W, all powders are melted. During laser direct forming, approximately 5% of laser energy is used to heat and melt 316L SS powder and 95% of laser energy is used to form laser molten pool.

Acknowledgements The support of labotory for laser intelligent fabrication in institue of mechnics, CAS is gratefully acknowledged.

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