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Numeric Calculation for Transient Thermal Stress Field in Wall-Shape Metal Part During Laser Direct Forming

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Abstract In order to investigate the transient thermal stress field in wall-shape metal part during laser direct forming, a FEM model basing on ANSYS is established, and its algorithm is also dealt with. Calculation results show that while the wall-shape metal part is being deposited, in X direction, the thermal stress in the top layer of the wall-shape metal part is tensile stress and in the inner of the wall-shape metal part is compressive stress. The reason causing above-mentioned thermal stress status in the wall-shape metal part is illustrated, and the influence of the time and the processing parameters on the thermal stress field in wall-shape metal part is also studied. The calculation results are consistent with experimental results in tendency.

Key words: Finite element method, Laser direct forming, Thermal stress field, 316L stainless steel

INTRODUCTION

Laser direct forming refers to a process that laser fuses gas delivered metal powders to fabricate metal parts layer by layer from computer-aided design (CAD) model. Los Alamos and Sandia National Laboratories have developed Directed Light Fabrication (DLF)[1-2]process and Laser Engineered Net Shaping (LENS)™[3-5] process, respectively. Aeromet Corp has developed Lasform™[6] technique, which is similar to DLF and LENS™ process, to form titanium alloy component. During laser direct forming, the adoption of improper processing parameters will easily induce the generation of the un-uniform thermal stress field in metal part because of the un-uniform temperature field in metal part. The excessive un-uniform thermal stress field in metal part, which is being formed, can offer more chances for the occurrence of crack or directly cause the distortion of the metal part. At present, it has great difficulties for experimental means to study the transient thermal stress field in metal part during laser direct forming. In this paper, a FEM model basing on ANSYS is established to calculate the transient thermal stress field in the wall-shape metal part. The technique of 'birth and death' element defined by ANSYS is used to simulate material addition process, which is identical with laser direct forming.

DESIGN OF ALGORITHM

As we know, the un-uniform temperature distribution in metal part directly leads to the generation of the un-uniform thermal stress distribution in metal part. In order to solve the transient thermal stress field in metal part as it is being formed, two FEM model must be established, one divided by heat transfer element is used to solve the transient temperature field[7] in metal part being formed by laser direct forming, the other divided by structural element is used to solve the transient thermal stress field in metal part being formed by laser direct forming. Both FEM models have the same the shape, the dimension and the number of meshes and nodes. During calculation, both FEM models keep the same time step size. The process of solving the transient thermal stress field in metal part is composed of many solution steps. As shown in Fig. 1, the temperature field in metal part at time T1 is loaded as temperature load on the FEM model which is used to solve the transient thermal stress field in metal part to solve the thermal stress filed in metal part at time T1, this is the first solution step. Under the thermal stress field in metal part at time T1 acts as initial condition and the temperature field in metal part at time T2 acts as temperature load conditions, the thermal stress field in metal part at time T2 can be solved out, this is the second solution step.

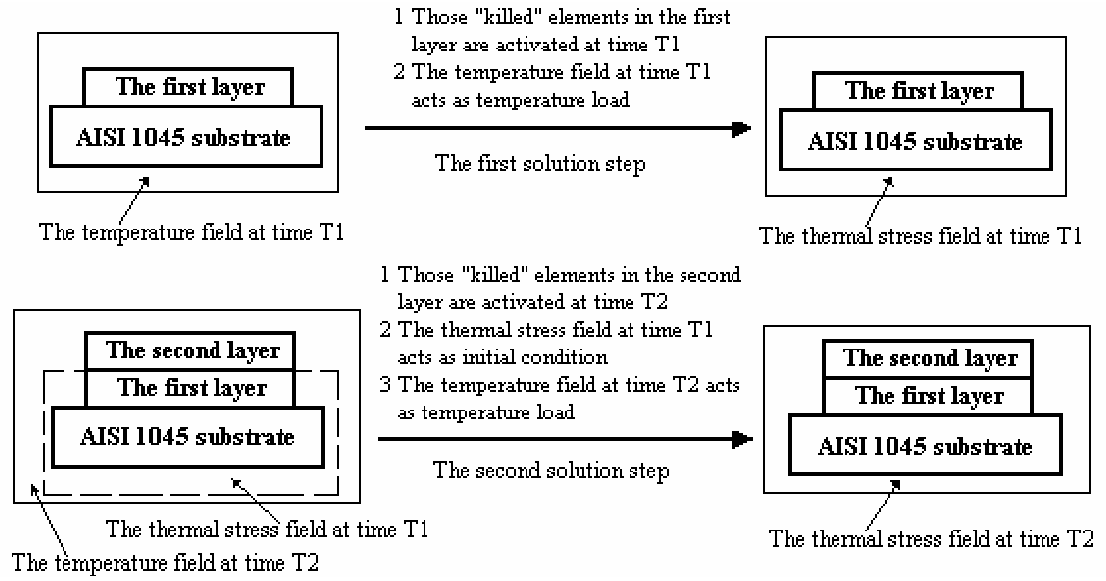

Fig. 1 Schematic of illustrating algorithm

During laser direct forming, the material is continues added to form a metal part. How to simulate such a material addition process in the FEM model? The technique of ‘birth and death’ element can be used to solve the above-mentioned problem. Firstly, the FEM model to solve the transient thermal stress field in metal part is established. Secondly, all elements in wall-shape metal part are killed at start time; the ‘killed’ elements are not being removed from the FEM model. Instead, they are just deactivated and become ‘nonexistent’. Those elements in substrate are kept to be alive throughout the process of deposition. Thirdly, at time T1, the first layer is deposited on the substrate. This means that new material is added, so the ‘killed’ elements in the first layer are activated and become ‘existent’. Fourthly, after the second layer has been deposited on the first layer, those ‘killed’ elements in the second layer are activated and become ‘existent’ at the time T2.

ESTABLISHMENT OF THE FEM MODEL TO SOLVE THE TRANSIENT THERMAL STRESS FIELD IN WALL-SHAPE METAL PART

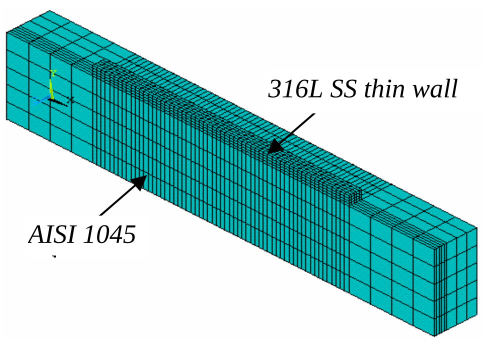

Fig.2 The FEM model for calculating the transient thermal stress in wall-shape part

Fig. 2 shows the FEM model to calculate the transient thermal stress field in wall-shape 316L SS part during laser direct forming. The FEM model consists of two parts, one is the substrate made of AISI 1045, and the other is the wall-shape part made of 316L SS. The size of the substrate and the wall-shape part is 50mm×10mm×5mm and 30mm×3mm×1.2mm, respectively. The elements with small size are applied to divide the portion of the wall-shape 316L SS part for acquiring high calculation precision. The element is SOLID 45 structure element, which is hexahedron with 8 nodes, defined by ANSYS software. Due to the FEM model having symmetrical characteristics, the size of the FEM model established in this paper is a half as big as that of both the substrate and the wall-shape metal part. Nodal displacement at interface between the substrate and the wall-shape metal part is restricted to zero.

MECHANICAL PROPERTIES OF AISI 1045 AND 316L SS AT DIFFERENT TEMPERATURE

Mechanical properties of AISI 1045 and 316L SS at different temperature were listed in from Table 1 to Table 5.[9-10] The Poisson's ratio of AISI 1045 and 316L SS was 0.3.

Table 1 Young's Modulus of 316 L SS at Different Temperature

Temperature(℃)	93	149	204	316	482	538	593	704	816
Young's modulus(GPa)	194	190	186	177	162	157	153	143	132

Table 2 Yield Strength and Heat Expansion Coefficient of 316L SS at Different Temperature

Temperature(℃)	24	93	149	204	316	427	538	593	649
Coefficient of thermal expansion μm/(m·℃)	17.5								
Yield strength(MPa)	232	197	176	163	142	128	116	109	98

Table 3 Heat Expansion Coefficient of AISI 1045 at Different Temperature

Temperature(℃)	100	300	500	700	900	1000
Coefficient of thermal expansion μm/(m·℃)	11.59	13.09	14.18	15.08	13.56	14.45

Table 4 Young's Modulus of AISI 1045 at Different Temperature

Temperature(℃)	20	200	300	400	600	800
Young's modulus(GPa)	200	193	190	172	140	121

Table 5 Yield Strength of AISI 1045 at Different Temperature

Temperature(℃)	20	100	200	300	400	500	600
Yield strength(MPa)	353	339	328	264	210	175	81

RESULTS AND DISCUSSION

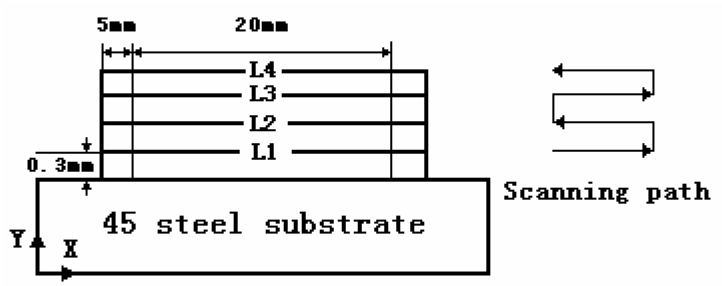

Fig.3 Schematic of illustrating the distribution of the thermal stress on the longitudinal section of 316L SS thin wall

Fig. 3 shows schematic to illustrate the distribution of the thermal stress field on the longitudinal section of the wall-shape 316L SS part. The wall-shape 316L SS part, whose size is 30mm×3mm×1.2mm, is composed of four deposited layers, and each deposited layer has the thickness of 0.3mm. Four straight lines on the longitudinal section of the wall-shape 316L SS part are marked by L1~L4. Each line has the length of 20mm, and the distance from the left end of lines (L1~L4) to the left end of the wall-shape 316L SS part is 5mm. Four lines (L1~L4) are used to stand for the location of four deposited layers, in the following paragraph, the influence of time and processing parameters on the distribution of the thermal stress along four lines (L1~L4) in both X direction and Y direction will be discussed. The total deposition time is 44 seconds on condition of laser beam scanning speed of 3mm/s.

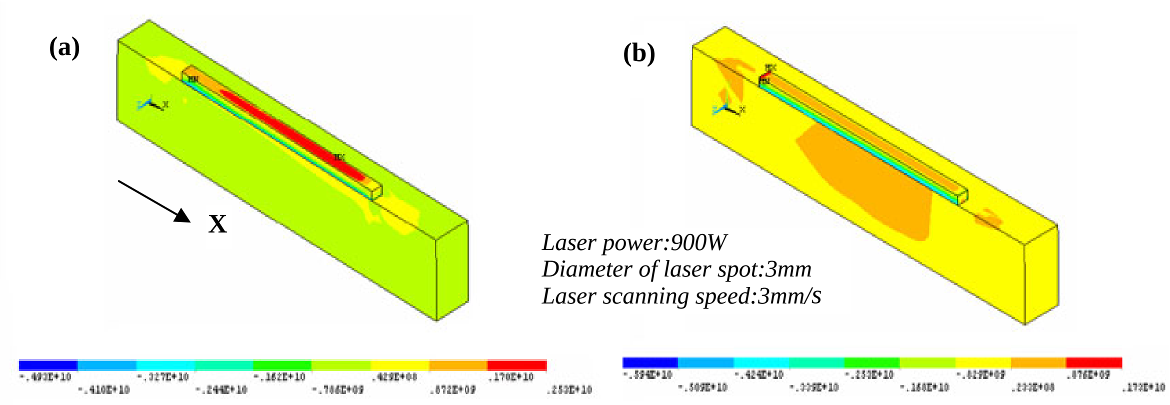

Fig.4 Nephogram of the distribution of the thermal stress in the wall-shape part

Fig. 4 shows the nephogram of the distribution of the calculated thermal stress in both the wall-shape part and the substrate. During deposition, the laser power is 900W, laser beam scanning speed is 3mm/s and laser spot is 3mm in diameter. As shown in Fig. 4 (a), after four layers have been built-up, it can be seen that in X direction, the thermal stress in the upper layers of the wall-shape part is tensile stress and the thermal stress in the lower layers of wall-shape part is compressive stress. (the value of tensile stress is positive and the unit of thermal stress is Pa). Fig. 4 (b) shows that in Y direction, the thermal stress in wall-shape metal part is compressive stress (the value of compress stress is negative).

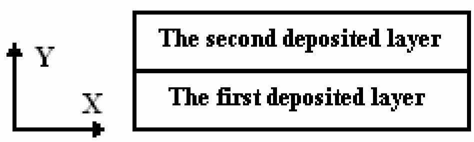

Fig.5 Schematic to explain the distribution of the thermal stress in the wall-shape part

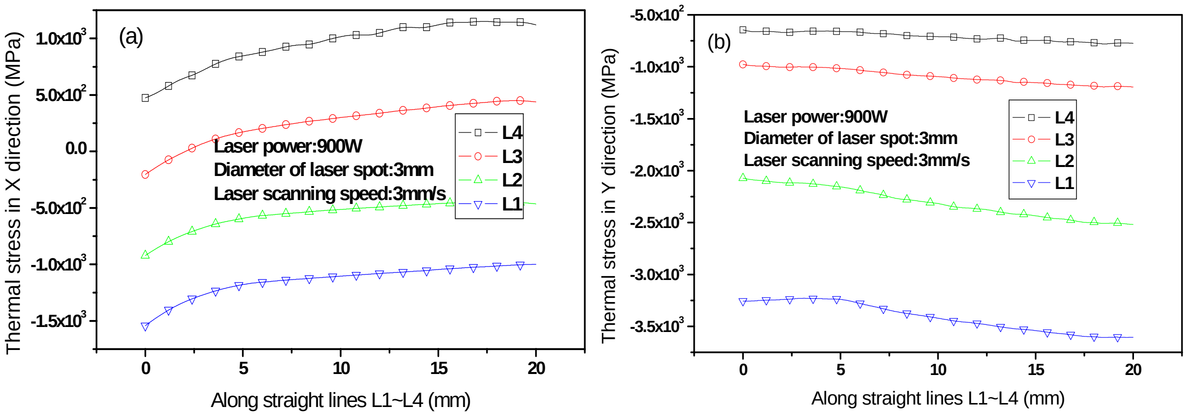

Fig.6 The distribution of thermal stress along straight lines L1~L4
(a) in X direction (b) in Y direction

Fig. 5 shows the schematic to explain the distribution of the thermal stress in wall-shape part. As shown in Fig. 6 (a), when deposition time is at 44s, the thermal stress along L3~L4 in X direction is tensile stress and the thermal stress along L1~L2 is compressive stress. Fig. 6 (b) shows that the thermal stress along L1~L4 in Y direction is compressive stress. What factors causes the above distribution of the thermal stress in wall-shape part? During laser direct forming, when laser beam acts on the surface of metal, a small molten pool will be created and metal powder is injected into the molten pool simultaneously. As soon as laser beam departs from the molten pool, the solidification of the molten pool occurs immediately, a new deposition segment is formed. The deposition process is just composed of a series of solidification processes of the molten pool. As shown in Fig. 5, the first layer is a former deposited layer and the second layer is a new deposited layer, so the temperature of the second layer is higher than that of the first layer. During cooling process, the cooling rates of the second layer is more than that of the first layer, therefore, in X direction, the shrinkage mass of the second layer is also more than that of the first layer. So the first layer will be compressed by the second layer, on the contrary, the second layer will be stretched by the first layer (in X direction). So the thermal stress along lines L3~L4 in X direction is tensile stress can be explained by the previous reason. In fact, during cooling process, the cooling rates of the two edges of wall-shape part is more than that of the middle portion of wall-shape part, base on the same reason, therefore thermal stress along lines L1~L4 in Y direction is compressive stress (as shown in Fig. 6 (b)), and the thermal stress along the two edges of wall-shape part in Y direction is tensile stress.

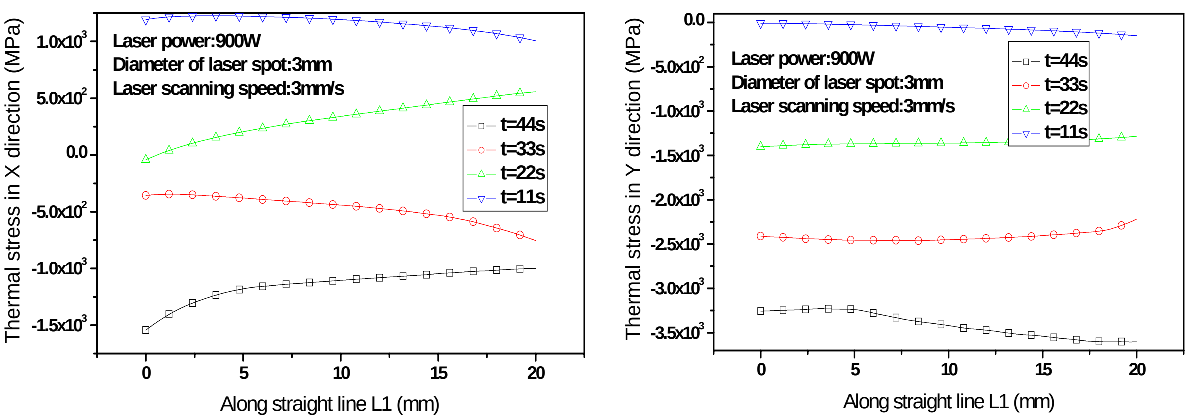

Fig.7 The variation of thermal stress along straight line L1 with time increasing
(a) in X direction (b) in Y direction

Fig. 7 (a) shows the variation of the thermal stress along L1 in X direction with the deposition time. When the deposition time ranges from 0 to 11s, the first layer of metal is deposited on the substrate, so thermal stress along L1 in X direction is tensile stress. After the deposition time of 33s has elapsed, two layers of metal have been deposited on the first deposited layer, at time 33s, L1 is at the bottom layer of the wall-shape part, so the thermal stress along L1 in X direction has been turn from the tensile stress into the compressive stress. As shown in Fig. 7 (a), at time 44s, three layers have been deposited on the first layer. It can be seen that the longer the deposition time is, the larger compressive stress along L1 in X direction is. The calculated results also indicate that the thermal stress along L1 in X direction change with laser scanning path. Fig. 7 (b) shows the variation of the thermal stress along L1 in Y direction with the deposition time.

Fig.8 The wall-shape partmade of Rene'95 alloy

Fig. 8 shows the photograph of the wall-shape part made of Rene'95 refractory alloy. This part is formed at laser power being 1600W with laser beam scanning speed being 3mm/s, as well as the diameter of laser spot being 3mm. It can be seen that there is an obvious crack in wall-shape part.

During deposition, a short crack occurred firstly on the top surface of the wall-shape metal part, and then the crack extended to the length of around 20mm in high speed, the width of the crack on the top surface of wall-shape metal part was maximum. This indicates that the thermal stress in the top layer of wall-shape in X direction must be tensile stress in the process of deposition. Fig. 8 also shows the crack occurs when the wall-shape part has certain height. This phenomenon indicates that the tensile stress in the top layer of the wall-shape part increases with the deposition time increasing. From Fig. 6, 7 and 8, it can be found that the calculated results are consistent with the experimental results in tendency.

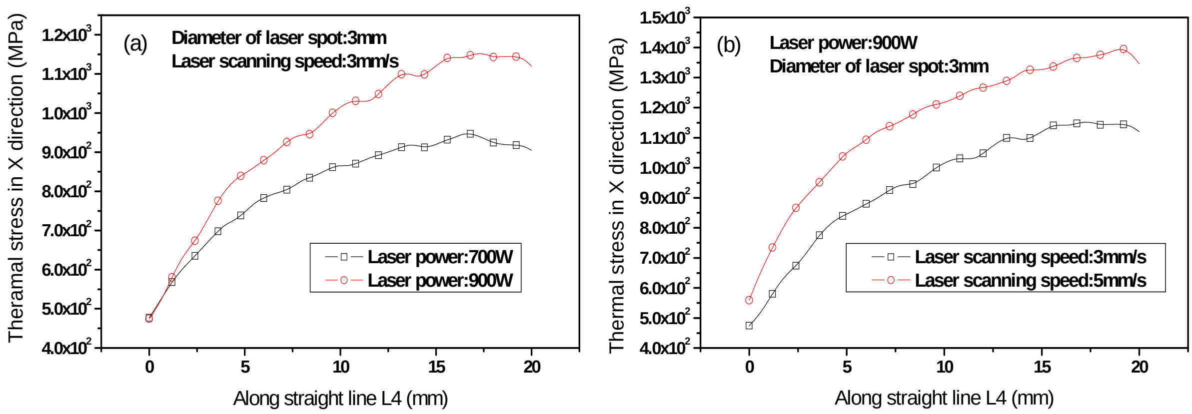

Fig.9 Influence of process parameters on thermal stress field along straight line L4
(a) Laser power (b) Laser scanning speed

Fig. 9 (a) shows the influence of laser power on tensile stress along L4 (refer to Fig. 3) in X direction. As shown in Fig. 9 (a), tensile stress along L4 in X direction increases with the laser power increasing. Fig. 9 (b) shows the influence of laser scanning speed on tensile stress along L4 (refer to Fig. 3) in X direction. As shown in Fig. 9 (a), tensile stress along L4 in X direction increases with laser scanning speed increasing. Since the size of the element used to divide the FEM model is not enough finer, this directly led to the occurrence of some little fluctuations on the curves in Fig. 9. When the intensive computation requirements are met, these fluctuations will be eliminated by applying much finer element to divide the FEM model.

CONCLUSIONS

A FEM model to calculate the distribution of the transient thermal stress in wall-shape metal part has been established in this paper. Calculation results show that in X direction, the thermal stress in the upper layers of the wall-shape part being formed by laser direct forming is tensile stress, and the thermal stress in the lower layers of the wall-shape part is compressive stress. Calculation results also indicate that the thermal stress in X direction in the top layer of the wall-shape part increases with laser power and laser beam scanning speed increasing. Experimental results show that the calculated results are correct in tendency.

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