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ORIGINAL ARTICLE

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Study of laminated object manufacturing with separately applied heating and pressing

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Abstract To improve the hot-pressing process currently employed in laminated object manufacturing (LOM), an innovative heating-and-pressing separation system is proposed, and heat transfer problems of this system are investigated. A thermal model is first established. It is solved numerically by the finite element method (FEM) software ANSYS, and verified by experiments. Based on the numerical solution under various operating conditions, it is found that the operating temperature of an adhesive can be reached quickly when the heater is maintained at a higher temperature, corresponding to a deeper heat-affected zone. This shortcoming can be effectively reduced if the speed of the heater is increased. Hence, a higher heater temperature together with a higher moving speed is suggested to shorten processing time and promote manufacturing efficiency. Through analysis, the appropriate distance between the roller and the heater, so as to obtain finished parts of high quality, is determined.

Keywords Heat affected layer · Laminated object manufacturing · Rapid prototyping · Thermal model

1 Introduction

Rapid prototyping (RP) manufacturing technology has been highly valued and explored by manufacturing industries and scientific institutes worldwide in recent years. Laminated object manufacturing (LOM) is one of the RP techniques that principally adopts the process of laminated forming [1, 2]. The bonding process is accomplished by applying heat and pressure by way of rolling a heated metal cylinder across a paper sheet, which has a thin layer of thermoplastic adhesive on the bottom side. The iterative process of bonding and laser cutting is repeated until the construction of the final layer is completed.

Pak and Nisnevich [3] proposed a formula for a thermal model of LOM to analyze the heat transmission while the hot roller, i.e., the heated metal cylinder, hot-presses on the workpiece. Sonmez and Hahn [4] later addressed some of the problems that occurred in the hot-pressing process by analyzing the effects caused by parameters like temperature and pressure upon the paper with the FEM. However, there are still several disadvantages and difficulties in the LOM process. For example, papers are easily to be peeled off at the adhesion layer, bubbles occur in the workpiece, and it is hard to control the parameters during the hot-pressing process. The workpiece can either be burnt due to overheating, or an integrating failure can occur due to insufficient temperature. Furthermore, improper pressure and speed are the major causes for poor quality of cohesion as well.

To effectively reduce the disadvantages of LOM caused by the hot-pressing process, a process of heating-and-pressing separation to is proposed for better workpiece results. This method is in contrast to the joint approach of the LOM machine, in which heating and pressing are applied simultaneously. This paper studies the heat transfer problems of the proposed system. The effects of the operating parameters on the hot-pressing process and on the arrangement of the heating and pressing are investigated.

2 Thermal model

2.1 Conceptions for heating-and-pressing separation

The heating-and-pressing separation process of this research involves isolating the operations of heating and pressing, as shown in Fig. 1, which gives a 2D demonstration of the hot-pressing process. The workpiece is 30 cm long and 1 cm thick, and the roller is made of brass, which has a 6 cm outer diameter and is 48 cm long. By utilizing the roller's weight of about 98 N, the pa-

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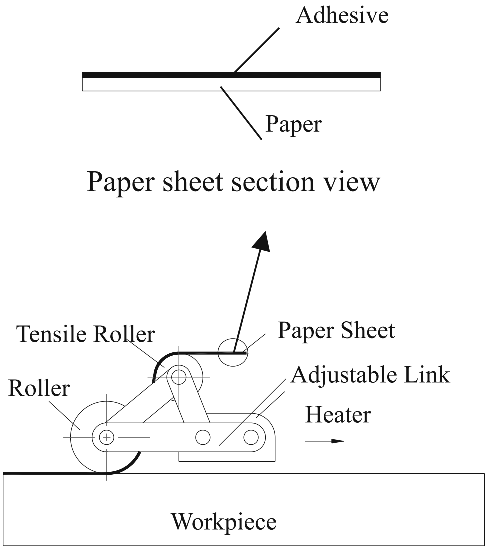

Fig. 1. Heating-and-pressing separation arrangement

per can be pressed smoothly and evenly onto the workpiece. The heating source is provided by an infrared radiant ceramic heater. The adhesive, ethylene-vinylacetate (EVA), is placed not as it is in traditional LOM, but on the top side of the paper. The paper, LPH 042 140-LOM manufactured by HELISYS, has a thickness of 0.01 cm, and its material properties are shown in Table 1. The surface of the workpiece is heated to a specific temperature. This is followed by the application of a new layer of paper and pressing by the roller.

To make the new layer of paper underneath the roller adhere firmly onto the workpiece, the adhesive must maintain a good adhesion force at the point where the roller touches the workpiece. Proper thermal analysis of the hot-pressing process is carried out in order to understand the temperature distribution on surface of the workpiece.

2.2 Thermal model

The workpiece can be taken as a 2D non-homogeneous material in 2D heat transfer analysis. Figure 2 displays the control volume model, which includes the boundary conditions, S_0 to S_6, and the coordinate system used in the following analysis. The heater moves in the x-direction and transfers heat to the control volume through the S_6 boundary. The following analysis excludes the heat transfer between the newly-added layer and the roller.

Table 1. Material property data for LOM paper LPH042 [5–7]

LPH042 LOM Paper	
Density	0.900 grams/m^3
Thermal conductivity (in-plane)	0.117 W/m °C
Thermal conductivity (transverse)	0.31 W/m °C
Thermal expansion coefficient (in-plane)	178×10^{-6} /°C
Thermal expansion coefficient (transverse-plane)	3.8×10^{-6} /°C
Specific heat	1455 J/kg °C
Deflection temperature	77 °C
Glass transition temperature	30 °C

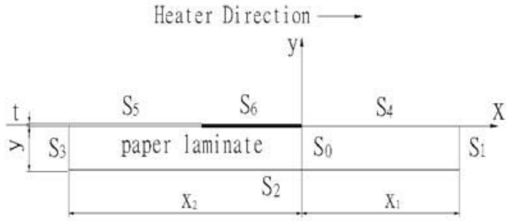

Fig. 2. Control volume model

Basic assumptions

a. The heating process is treated as a transient state.
b. The compactly integrated paper layers and adhesive are treated as a single object.
c. It is taken as a two-dimensional problem because of the uniform heat source along the paper width direction.
d. The paper laminate is taken as a moving object.
e. Before the new layer is paved on the previously-added layer, the workpiece has reached ambient temperature.

Governing equation:

Although various materials may be used in LOM, which means the thermal characteristics of the paper and the adhesive may be different in different cases, LOM is still simplified as an anisotropic but homogeneous continuum and a two-dimensional problem. The governing equation [8] is expressed as Eq. 1:

$$K_x(T)\,\frac{\partial^2 T}{\partial x^2} + K_y(T)\,\frac{\partial^2 T}{\partial y^2} = \rho\, C_p V_x \frac{\partial T}{\partial x} \tag{1}$$

In the equation, K_x and K_y are the thermal conductivity $(\mathrm{W/m \cdot K})$ of the paper workpiece, which are changeable with the variation of temperature along directions x and y, respectively; $\rho\,(\mathrm{kg/m^3})$ is its density; $C_p\,(\mathrm{J/kg \cdot K})$ is its heat capacity, which is also varied with the change of temperature; and V_x (m/sec) is the velocity of the moving heater source.

Boundary conditions:

Disregarding the movement of the newly-added paper layers, the boundary conditions, S_0, S_1, S_2, S_3, S_4, S_5, and S_6 are set as follows.

Because it is surrounded by air, the paper sheet (S_0) maintains a stable temperature. Also, since heat flux has not yet reach the end area S_1 in Fig. 2, the temperature on S_1 should be equal to the initial temperature. Hence, the boundary condition for S_0 and S_1 is

$$T = T_0 \tag{2}$$

where $T_0 = 28\,°\mathrm{C}$ is room temperature in our analysis.

Beyond a certain workpiece depth, the heat transfer of the material is quite small along the y direction, so it can be taken as adiabatic, and for S_2

$$\frac{\partial T}{\partial y} = 0 \tag{3}$$

In the thermal control volume model, most heat transfer is due to conduction; other heat transfer modes become relatively negligible. Hence, the thermal gradient along S_3 in the x direction approaches zero; i.e., for S_3

$$\frac{\partial T}{\partial x} = 0 \tag{4}$$

The boundaries, except the area in contact with the heater, are exposed to the surrounding air. Hence, the boundary conditions for S_4 and S_5 are described. by Eqs. 5 and 6, respectively, as follows

$$K_T \frac{\partial T}{\partial y} = h(T - T_0) \tag{5}$$

$$K'_T \frac{\partial T}{\partial y} = h'(T' - T_0) \tag{6}$$

where in Eq. 5, K_T is the thermal conductivity (W/m · K) of the paper workpiece, and h is the convection heat-transfer coefficient. In Eq. 6, K'_T and h' are the thermal conductivity of the paper workpiece and convection heat-transfer coefficient, respectively, at a particular temperature of the workpiece after heating.

The boundary S_6 is just beneath the heater. There are heat convection and radiation in this area, and hence

$$q_0 = h(T - T_o) + \varepsilon\sigma\,(T_e^4 - T_{sur}^4) \tag{7}$$

where q_0 is the total heat flux through the boundary, h is the convection heat-transfer coefficient, ε is the material film emission rate, σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m$^2 \cdot$ K^4), T_e is the surface temperature of the heater, and T_{sur} is the surface temperature of the laminates.

3 Numerical solutions and experimental results

Because it is very time-consuming and tedious to obtain the temperature distribution on a workpiece by direct measurements, a commercially available FEM software, ANSYS, is adopted to solve the temperature distributions under various operating conditions in this paper. In the experiments, a the K-type thermocouple, which is embedded in the laminated workpiece as shown in Fig. 3, is used to measure the adhesive temperature. The voltage signal is transformed and passed to the PC with an A/D card.

The numerical results are compared with the experimental data to verify the effectiveness of the FEM. One case of the numerical solution and the corresponding experimental results are plotted in Fig. 4.

The numerical solution is obtained with the assumption of a fixed heat source and a moving workpiece. But for implementing the real measurement, the temperature variation of one fixed point is recorded with reference to different heating source positions. These two sets of temperature data are therefore matched in one graph with the same abscissa. It can be seen that the errors between numerical solutions and experimental results are quite small. The errors for all tested cases are within 10%. This suggests that the FEM approach is acceptable.

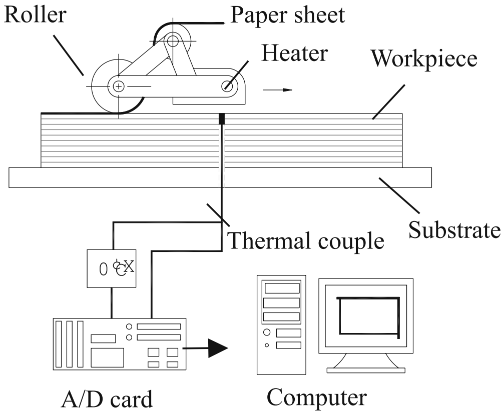

Fig. 3. Schematic diagram of the measurement devices

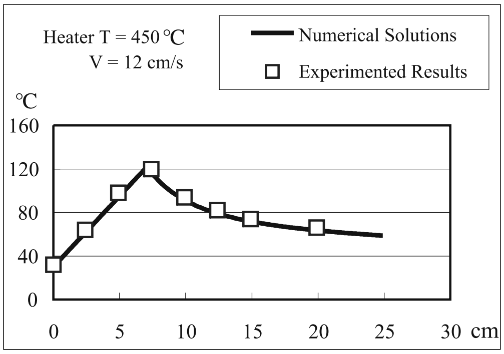

Fig. 4. Numerical solutions and experimental results of the surface temperature of the workpiece along the moving assembly of the heater and roller

4 Effects of operating parameters on hot-pressing process

4.1 Effects of operating parameters on layer surface temperature

Figure 5 shows the estimated temperature of the workpiece with a heat source of 450 °C, but with different moving speeds of the heat source. In the figure, the abscissa and ordinate represent the horizontal position and surface temperature of the laminates, respectively. The descending rate of temperature becomes greater under lower moving speeds of the heater than that under higher ones. The temperature of the adhesive can be efficiently increased by lowering heater speed. However, on the other hand, this would lead to the rapid temperature decline. For the paper sheet as a working material, this produces higher thermal stress and is not good for the prototype's quality. This also increases the time cost and reduces manufacturing efficiency. It is shown in Fig. 6 that the higher the heater temperature under the

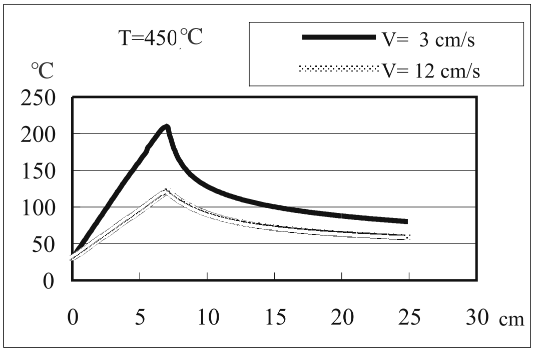

Fig. 5. Estimated surface temperature of the workpiece along the moving assembly of the heater and roller with a heat source of 450 °C but different moving speeds of the heat source

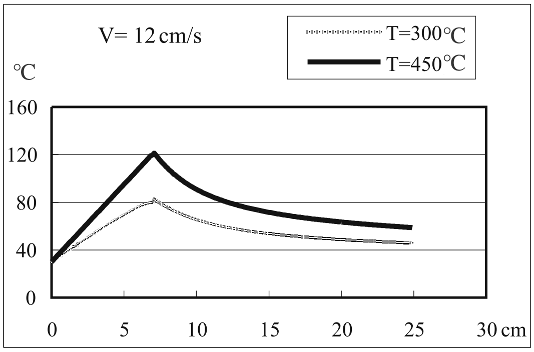

Fig. 6. Estimated surface temperature of the workpiece along the moving assembly of the heater and roller with two different heat sources moving at a speed of 12 cm/s

same moving speed, the higher the paper surface temperature. The temperatures of the heater and the paper surface are almost linearly positively dependent.

4.2 Effects of operating parameters on temperature distribution along the layer thickness direction

The temperature distributions under two sets of heater temperatures and moving speeds of $T = 350\,°\mathrm{C}$, $V = 6\,\mathrm{cm/s}$ and $T = 450\,°\mathrm{C}$, $V = 12\,\mathrm{cm/s}$, are shown in Fig. 7. The surface temperatures during the heat absorption process are the same, the temperature descending curves differ only a little bit for these two sets of parameters. However, it is more significant in the layer thickness direction, as shown in Fig. 8. When the heater with higher temperature moves at a higher speed, the temperature gradient at the layer surface is larger, which is revealed by the steeper slope of the curve in the figure. This implies that there are fewer heat-affected layers, leading to a better pressing and bonding effect and results in a better manufacture quality. Therefore, although the layer surface temperatures are the same under two set heater temperatures and moving speeds of $T = 350\,°\mathrm{C}$, $V = 6\,\mathrm{cm/s}$ and $T = 450\,°\mathrm{C}$, $V = 12\,\mathrm{cm/s}$, the latter parameter set shows fewer heat-affected layers. With respect to heat-affected layer thickness, the higher heater temperature together with higher moving speed ensure lower heat-affected thickness and a shorter working time, which proves manufacturing process efficiency.

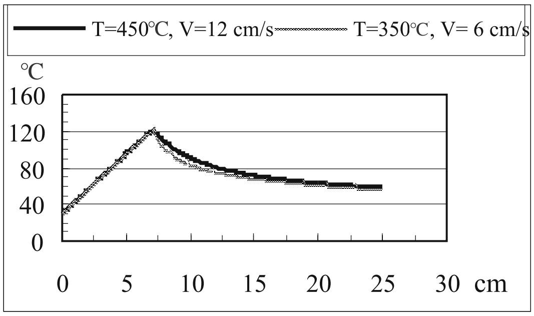

Fig. 7. Estimated temperature of the workpiece along the moving assembly of the heater and roller under two sets of operating parameters

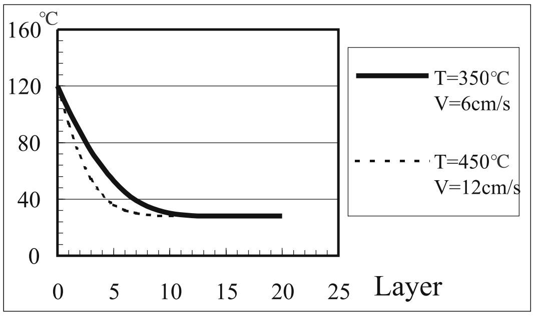

Fig. 8. Temperature variation in the direction of the thickness under two sets of operating parameters

4.3 Relation between operating parameters and the hot-pressing process

The adhesive on the paper obtains sufficient adhesion force at 80 °C and above, and the paper can stand up to a temperature as high as 200 °C. Beyond this temperature, coking of the paper occurs and adhesive becomes ineffective as well. Hence the layer surface should remain between 80 °C and 200 °C to ensure workpiece quality.

Figure 9 shows the configuration of the heater and roller superimposed on a typical surface temperature vs. position diagram of the workpiece. The heater is just above the layer material and it is 7 cm long. Within this range, the layer plays the role of heat absorber. At a position of 7 cm, which marks the rear edge of the heater, the layer reaches the highest temperature. The area from a position of 7 cm to 18 cm retains effective adhesion because of a proper temperature between 80 °C and 200 °C. The real pressing action starts from 7 cm plus the roller radius, since the roller diameter should be brought into consideration. Assuming the roller radius is 3 cm, the roller can be arranged to a position between 10 cm and 18 cm. This range is suitable for the pressing and adhesion processes, and it is indicated by the solid line rectangle in Fig. 9.

Figure 10 shows the surface temperature of the workpiece under three sets of operating parameters. The maximum tem-

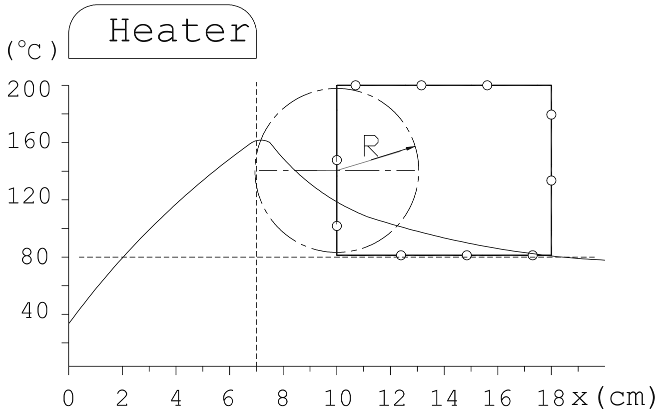

Fig. 9. Schematic diagram of the pressing and sticking positions

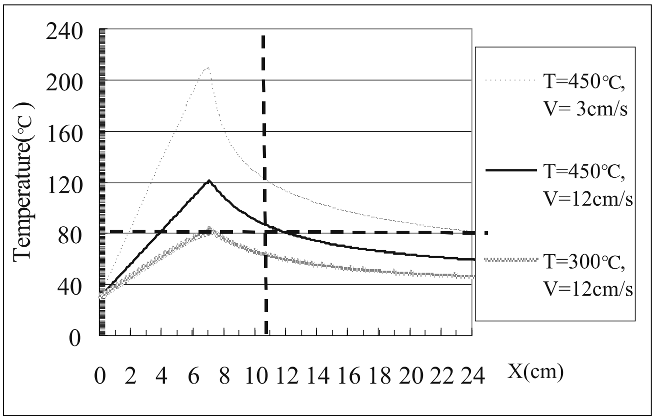

Fig. 10. Pressing and sticking areas under various operating parameters

perature at the layer surface reaches 210 °C, a temperature higher than the paper coking temperature, under parameters of $T = 450\,°\mathrm{C}$ and $V = 3\,\mathrm{cm/s}$. This set of parameters cannot be used for the heating-and-pressing separation procedure. If the parameters are set to $T = 300\,°\mathrm{C}$ and $V = 12\,\mathrm{cm/s}$, the temperature of the effective pressing area (beyond position 10 cm) is only 65 °C. No efficient pressing effects can be accomplished under such an insufficient temperature. If the parameters are set to $T = 450\,°\mathrm{C}$ and $V = 12\,\mathrm{cm/s}$, the maximum layer surface temperature is around 120 °C, which is between the minimum agglutinating temperature and the coking temperature of the paper. The temperature is maintained at 90 °C at the location nearest the adhesion position and gradually descends to 80 °C at a position of 12 cm. The stretched area of about 2 cm in width is apt for adhesive sticking. Hence, this set of operating parameters is appropriate as far as the roller arrangement and hot-pressing are concerned.

5 Conclusion

To rectify some problems of the current LOM apparatus with the combined heating and pressing operations, a heating-and-pressing separation mechanism is proposed. The FEM is carried out to solve heat transfer problems, and the numerical solution of the temperature field is used for inference. The conclusions are described as follows:

1. The heating-and-pressing separation apparatus in this research can obtain a steeper temperature gradient in the heating process by elevating both the heater temperature and its moving speed. By the same strategy, a milder temperature variation curve can similarly be obtained in the heat-releasing process. This contributes to a larger pressing and sticking area and better sticking effects.
2. For the proposed heating-and-pressing separation process, the heat-affected layer thickness can be reduced with a higher heater temperature and a higher moving speed. This also ensures that the surface paper layer can be maintained at a stable temperature much lower than the paper coking temperature, and will lead to lower manufacturing time and cost, and promote efficiency of the whole process.
3. The proper sticking temperature and the sustainable coking temperature limit of the adhesive on the paper layer are observed through FEM analysis and experiments. With these characteristics of the adhesive, if a proper roller diameter is given, a suitable pressing and sticking area can be arranged to obtain well-operated effects. In addition, the optimum pressing and sticking position can be obtained by adjusting the distance between the heater and the roller to generate good workpiece quality.

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