STUDY OF THE HEATING-AND-PRESSING SEPARATION PROCESS OF LAMINATED OBJECT MANUFACTURING (LOM)

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ABSTRACT

To improve hot-pressing process currently employed by the laminated object manufacturing (LOM), an innovated heating-and-pressing separation system is proposed, and heat transfer problems of this system is investigated. A thermal model is first established. It is solved numerically by the finite element method (FEM) software ANSYS, and verified by experiments. According to the numerical solution under various operating conditions, it is suggested that if the temperature and the moving speed of the heater are both increased, the depth of the heat affected laminates will be reduced. The processing time will be shortened and the manufacture efficiency will be promoted. Through analysis, it is concluded that, to obtain finished parts of high quality, the appropriate distance between the roller and the heater can be determined.

Keyword: laminated object manufacturing, thermal model, heat affected layer

1. INTRODUCTION

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

Pak and Nisnevich[1] proposed a formula of thermal model in 1994 for the LOM to analyze the heat transmission while the hot roller, i.e. the heated metal cylinder, hot-presses on the workpiece. Concerning all kinds of problems that occurred in the hot-pressing process, Sonmez and Hahn[2], furthermore, analyzed the effects caused by parameters like temperature and pressure upon the paper by the FEM in 1998. However, there are still several disadvantages and difficulties in LOM process. For example, papers are easily to be peeled off at the cohering layer; bubbles occur in the workpiece, and it is hard to control the parameters during the hot-pressing process. Workpiece is either burnt out for over heating, or integrating failure due to insufficient temperature. Furthermore, improper pressure and speed are the major causes for poor quality of cohering as well.

To effectively improve the disadvantages of LOM caused by the hot-pressing process, a process of heating-and-pressing separation to alter the joint approach of LOM machine, in which heating and pressing are applied simultaneously, for better results of workpiece is proposed. This paper studies the heat transfer problems of the proposed system. Effects of operating parameters on 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 is to isolate operations of heating and pressing as shown in Fig. 1, the 2D demonstration of hot-pressing process. Specifically, 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 efficiently cohere with the paper below, the adhesive must maintain good adhesion force at the point that the roller touches. Proper thermal analysis of hot-pressing process is carried out for understanding the temperature distribution on surface of the workpiece.

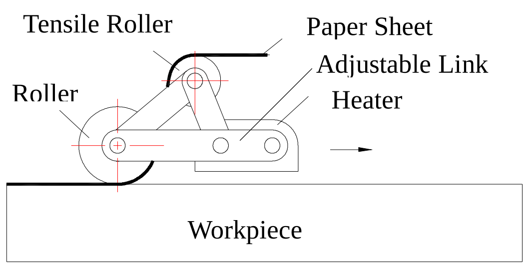


Figure 1. Heating-and-pressing separation arrangement.

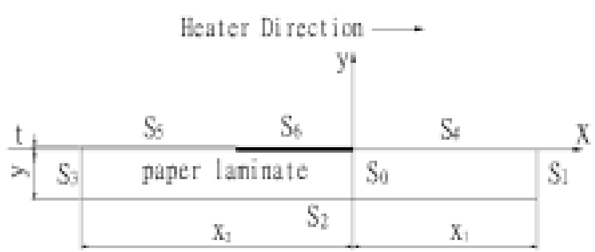


Figure 2. Control volume model.

2.2 Thermal Model

The workpiece can be taken as a 2D non-homogeneous material in 2D heat transfer analysis. Fig. 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 S_6 boundary. The following analysis excludes the heat transfer between the newly-added layer and the roller.

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.

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 [3] is expressed as (1):

$$K_x(T)\frac{\partial^2 T}{\partial x^2} + K_y(T)\frac{\partial^2 T}{\partial y^2} = \rho C_p\left[\frac{\partial T}{\partial t} + V_X\frac{\partial T}{\partial x}\right] \tag{1}$$

In the equation, K_x and K_y are the thermal conductivity (W/m°C) of the paper workpiece, which are changeable with the variation of temperature along directions X and Y, respectively; ρ(kg/m^3) is its density; C_p(J/kg°C) 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 movements 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 of being surrounded by the air, the paper sheet (S_0) maintains 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 are

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

Where T_0 is room temperature and it is 28 ^{o}C in our analysis.

Beyond 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 expose 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°C) 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 being heated.

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

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

Where

- q_0: total heat flux through the boundary
- h: convection heat-transfer coefficient
- ε: material film emission rate
- σ: Steven-Boltzman's constant and $\sigma = 5.67 \times 10^{-8} W/m^2 \cdot K^4$
- T_e: surface temperature of the heater
- T_{sur}: 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 workpiece by direct measurements, a commercially available FEM software ANSYS is adopted to solve the temperature distributions under various operating conditions in this paper. The numerical results are compared with the experimented data to verify the effectiveness of the FEM. One case of numerical solution and experimental results are plotted and given in Fig. 4. 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.

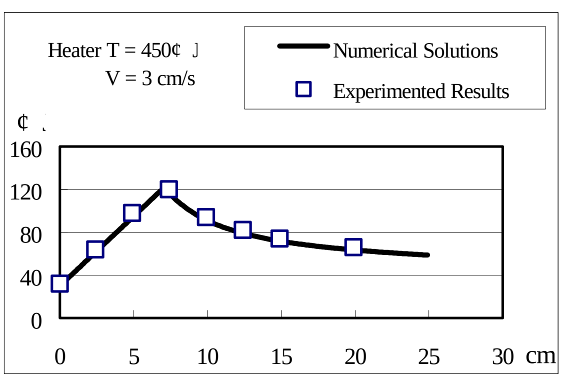


Figure 4. Numerical solutions and experimental results of the surface temperature of the workpiece.

4. ANALYSES AND DISCUSSION

4.1 Effects of Operating Parameters on Hot-Pressing Process

4.1.1 Effects of Operating Parameter on Layer Surface Temperature

Figure 5 show the estimated temperature of the workpiece with the heat source of 300 ^{o}C but 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. Temperature of adhesive can be efficiently increased by lowering heater speed. But on the other hand, this would lead to the rapid temperature descending in exothermic. For the paper sheet as 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 same moving speed, the higher the paper surface temperature. The temperatures of the heater and the paper surface are almost linearly positively dependent.

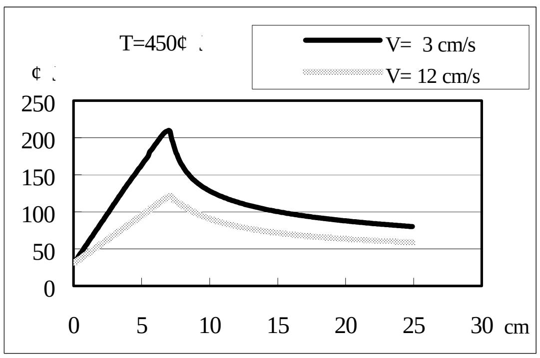


Figure 5. Estimated surface temperature of the workpiece with the heat source of 450 ^{o}C but different moving speeds of the heat source.

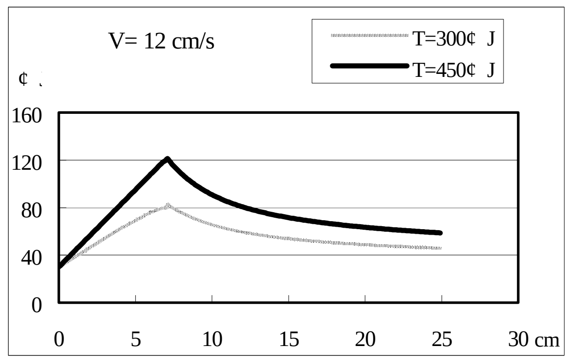


Figure 6. Estimated surface temperature of the workpiece with two different heat sources moving at a speed of 12 cm/s.

4.1.2 Relation between Operating Parameters and Hot-Pressing Process

Adhesive on the paper obtains sufficient adhesion force at 80^{o}C and above, and the paper can stand up to a temperature as high as 200^{o}C. Beyond this temperature, coking of the paper would occur and adhesive becomes ineffective as well. Hence the layer surface should be remained between 80^{o}C and 200^{o}C to ensure the workpiece quality.

Figure 7 shows the configuration of 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 wide. Within this range the layer plays the role of heat absorption. At the position of 7cm, it is the rear edge of the heater and also the position that the layer obtains the highest temperature. The area from position 7 cm to 18 cm retains effective adhesion because of proper temperature of 80 ^{o}C ~200^{o}C. The real pressing action starts from the location of 7 cm plus the roller radius since the roller diameter should be brought into consideration. Assuming the roller radius is 3cm, then the roller can be arranged to a position between 10 cm and 18 cm. This range is suitable for pressing and adhesion processes, and it is indicated by the solid line triangles in Fig. 7.

Figure 8 shows the surface temperature of the workpiece under three sets of operating parameters. The maximum temperature at the layer surface reaches 210 ^{o}C, a temperature higher than the paper coking temperature, under parameters of T=450^{o}C and V=3cm/s. This set of parameters can not be taken for the heating and pressing separation procedure. If the parameters are set to T=300 °C and V=12cm/s, the temperature of the effective pressing area (beyond position 10cm) is only 65 °C. No efficient pressing effects can be accomplished under such an insufficient temperature. If the parameters are set to T=450 °C and V=12cm/s, the maximum layer surface temperature is around 120 °C which is between the minimum agglutinating and coking temperatures of the paper. The temperature maintains 90 °C at the location nearest to the adhesion position and gradually descends to 80 °C at the position of 12cm. The stretched area of about 2cm width is apt for adhesive sticking. Hence this set of operating parameter is appropriate as far as the roller arrangement and hot-pressing are concerned.

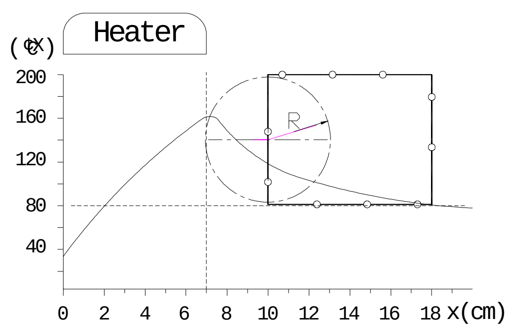


Fig. 7 Schematic diagram of pressing and sticking position.

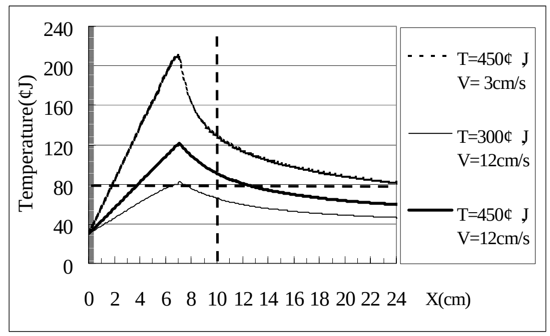
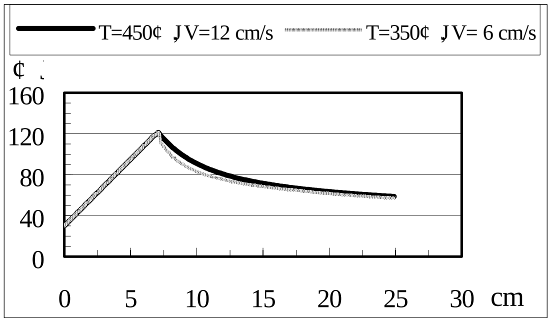


Fig. 8 Pressing and sticking areas under various operating parameters.

4.2 Effects of Operating Parameters on Temperature Distribution along Layer Thickness Direction

The temperature distributions under two sets of heater temperatures and moving speeds of T=350 °C, V=6cm/s and T=450 °C,V=12cm/s, are shown in Fig. 9. 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. But it is more significant at layer thickness direction as shown in Fig. 10. When the heater with higher temperature moves at 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 the fewer the heat affected layers area. The fact of fewer affected layers leads to better pressing and bonding effect and results in better manufacture quality. Therefore, even the layer surface temperatures are the same under two set heater temperatures and moving speeds of T=300 °C, V=6cm/s and T=400 °C,V=12cm/s, the later parameter set shows fewer heat affected layers. In respect to heat affected layer thickness, the higher heater temperature incorporated with higher moving speed ensure lower heat affected thickness and also working time, which proves manufacturing process efficiency.



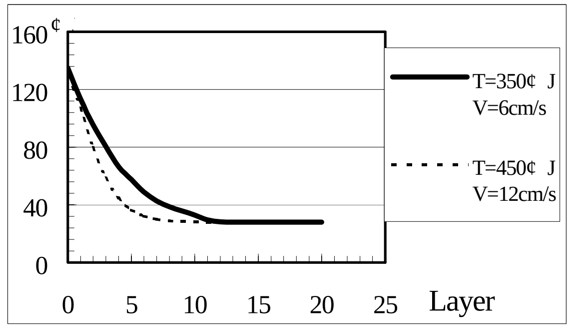


Figure 9. Estimated temperature of the workpiece under two sets of operating parameters.

Figure 10. Temperature variation at thickness direction under two sets of operating parameters.

5. CONCLUSION

To improve 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 steeper temperature gradient at heating process by elevating both the heater temperature and its moving speeds. By the same strategy, more mild temperature variation curve can similarly be obtained in the heat releasing process. This contributes to more 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 under higher heater temperature and higher moving speed. This also assures that surface paper layer could be maintained at a stable temperature much lower than the paper coking temperature, and will lead to lower manufacturing time cost and promote the 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 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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