Influence of process parameters on the surface roughness in hotwire cutting of EPS foam sheet for VLM-S rapid prototyping process

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The rapid prototyping (RP) process involves adding raw material successively to rapidly create the three-dimensional parts in CAD/CAM environments [1–3]. The RP technologies have some disadvantages such as low building speed due to the thin layer(≅0.02–0.5 mm), additional post-processing and high building cost due to building device and materials [4]. In order to improve the building speed and stair-step of the side surface for RP parts, thick layered RP technologies using thicker layer (≥1 mm) and ruled edge with side slopes have been developed [5, 6]. In general, the thick layered RP technologies utilize laser, hotwire cutter and water-jet as cutting devices, and expandable polystyrene (EPS) foam as materials [5, 6]. The key technology of VLM-S, variable lamination manufacturing using EPS foam as a rapid prototyping process, is hotwire cutting of an EPS foam sheet using a four-axis synchronized automatic hotwire cutter, as shown in Fig. 1 [4, 5]. The VLM-S process is classified into the transfer type (VLM-ST) and the progressive type (VLM-SP) according to material supplying technique [6]. In VLM-ST, one layer is created by one USL(Unit Shape Layer). In VLM-SP, one layer is created by one or more USPs (Unit Shape Parts). The surface roughness of the cut part is dependent on the thermal field of the EPS foam induced by the combination of the process parameters such as effective heat input, cutting angle, material characteristics, etc. [6]. In addition, low heat input incurs the insufficient decomposition of EPS foam and bending of hotwire due to the cutting resistance induced by the melted residuals of EPS foam.

Bram *et al.* [7] has qualitatively studied the surface quality of EPS block in hot blade cutting. Ahn *et al.* [6] investigated the influence of the sloped cutting angle on kerfwidth and the melted area at the edge of the cut parts during hotwire cutting of EPS foam sheet. Although hotwire cutting is a well-known technology to generate arbitrary shapes from EPS foam, so far only a few research works have been performed on the physical phenomena of cutting and the influence of process parameters on the process in an attempt to improve the surface quality of the cut parts [8–11].

The objective of this research work is to investigate the influence of the process parameters, such as effective heat input and cutting angle, on the surface roughness in the hotwire cutting of EPS foam for the case of single–sloped cutting to estimate the surface roughness of the VLM-S parts for each cutting condition. In addition, decomposition characteristics of EPS foam and the critical value of effective heat input are estimated to obtain optimal cutting conditions and to analyze the surface microstructure of the cut parts.

The hotwire cutting process in VLM-S consists of melting of EPS foam and subsequent decomposition of the melted foam. Hence, in order to examine the formation of microstructure of the cut surface, the characteristics of decomposition for EPS foam should be investigated. The decomposition temperature (T_d) and the relationship between weight loss and temperature are measured by Thermal Gravimetric Analysis (TGA). The density of the EPS foam and the sample size are 6.25 kg/m^3 [8] and 30 × 30 × 3.9 mm, respectively. The experiment is carried out in a nitrogen environment and the scanning rate of 10°C/min.

The results of the experiment show that the weight loss expressed in percentage begins to rapidly increase at 370°C, as shown in Fig. 2. In addition, it is seen that the percentage of weight loss is maintained at 96% from 470°C. From the results, the temperature of decomposition for EPS foam is determined to be 470°C.

The critical value of effective heat input without losing the stiffness of hotwire due to insufficient decomposition of EPS foam is estimated by normal hotwire cutting tests and numerical analyses. The effective heat input (Q_{eff}) is calculated using Equation 1 [6].

$$Q_{\text{eff}} = \frac{Q_L}{V_{tr}} \tag{1}$$

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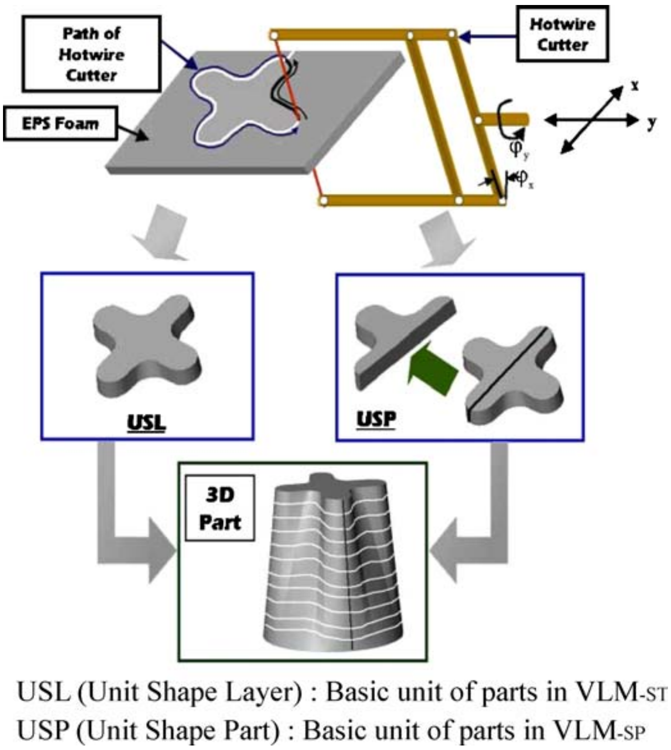

Figure 1 Concept of hotwire cutting of EPS foam in the VLM-s rapid prototyping process.

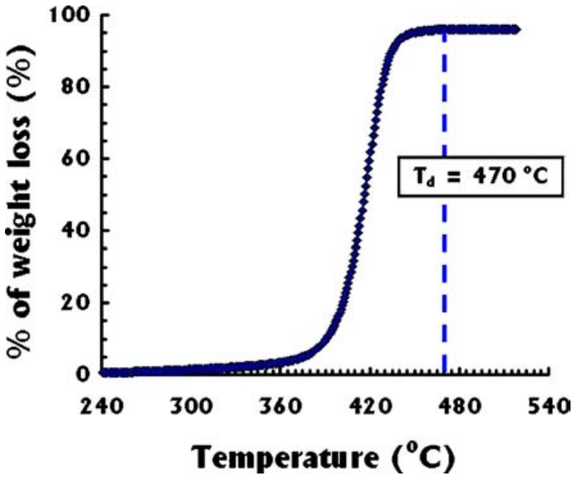

Figure 2 Relationship between weight loss and temperature.

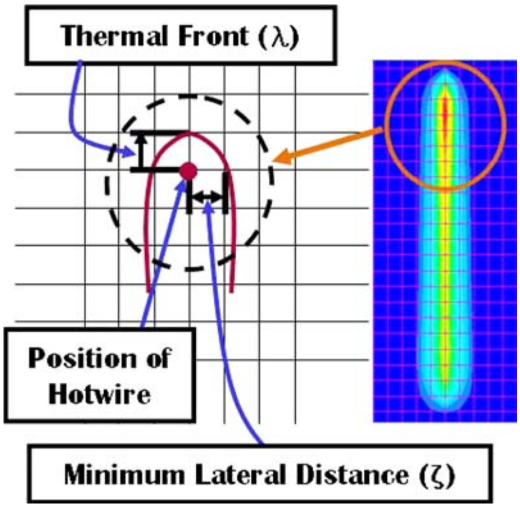

Figure 3 Definition of thermal front and minimum lateral distance.

where Q_L and V_{tr} are the heat input per length of hotwire and the cutting speed of hotwire cutter, respectively.

The normal cutting tests are carried out on the VLM-ST rapid prototyping apparatus. The VLM-ST apparatus consists of four-axes synchronized automatic hotwire cutter, automatic material feeding devices, manual stacking devices using pilot pins and holes, and control software [2]. Table I shows the experimental conditions of the normal cutting test. The specimen dimension is 250 × 180 × 3.9 mm. The specimen is cut in the width direction. The results of the normal cutting tests show that the hotwire is about to lose its stiffness when the effective heat input is 0.010 W·sec/mm^2.

TABLE I Experimental conditions of the normal cutting test

Diameter of hotwire (mm)	Q_L (Watt/mm)	V_{tr} (mm/sec)	Cutting length (mm)
0.36	0.49	44, 46, 47, 48, 49, 50	100
	0.58	52, 54, 55, 56, 57, 58	100

The numerical analyses are carried out using the commercial code SYSWELD + [12]. The size of the thermal front (λ) and the minimum lateral distance (ζ) when the hotwire begins to bend in the opposite direction of the cutting direction are predicted by the regression method using the analyzed data. Fig. 3 shows the definition of the thermal front and the minimum lateral distance and Fig. 4 shows the results of the numerical analyses.

The results of the analyses show that the size of the thermal front at 0.011 W·sec/mm^2 of the effective heat input is 0.30 mm and the size is 1.6 times the radius of the hotwire, as shown in Fig. 4a. In addition, the size of the lateral minimum distance (ζ) at 0.011 W·sec/mm^2

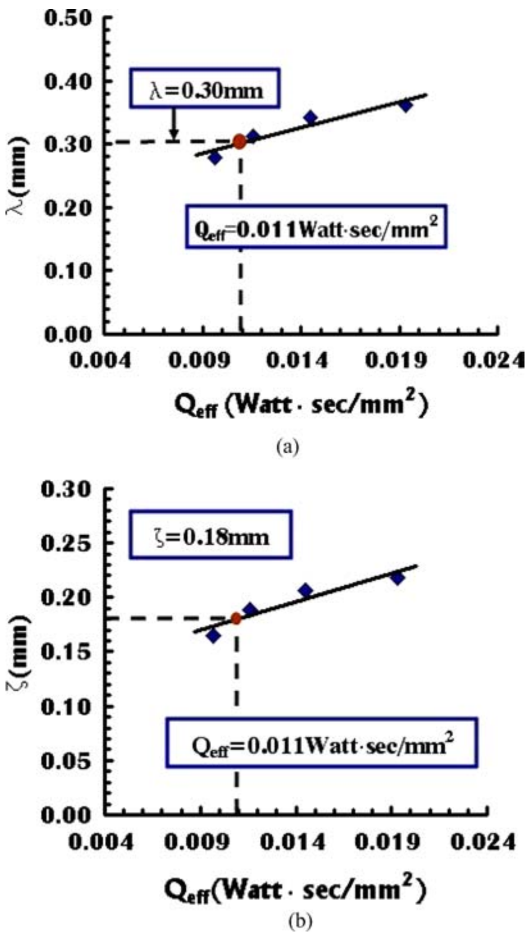

Figure 4 Influence of effective heat input on the size of thermal front and minimum lateral distance: (a) The size of thermal front (λ) (b) The size of minimum lateral distance (ζ).

of the effective heat input is 0.18 mm, as shown in Fig. 4b and the size is the same as the radius of the hotwire. From the results of the analyses, it has been known that the insufficient minimum lateral distance due to low effective heat input induces a loss in the stiffness of the hotwire. Comparing the results of the experiments with those of the analysis, the effective heat input, in which unstable cutting is started, of the experiments is lower than that of the analysis. This may be ascribed to the fact that the numerical model does not simulate the increase of cutting speed induced by the initial tension of hotwire. As the results of the experiments and the analysis, the critical value of the effective heat input ($Q_{\mathrm{cr.eff}}$) without losing the stiffness of the hotwire, is estimated as 0.011 W·sec/mm^2.

In order to investigate the influence of the effective heat input and cutting angle (Φ_y) for the case of single-sloped cutting on the surface roughness, the single-sloped cutting experiments, in which the rotation axis remains in the moving direction of the hotwire cutter, are carried out on the VLM-ST apparatus. The specimen dimension is 250 × 180 × 3.9 mm. The dimension of the cut specimen is 60 × 22.8 × 3.9 mm. The effective heat input is set at three levels; 0.0081, 0.011, and 0.016 W·sec/mm^2. The cutting angle about the x-axis (Φ_y) is set to be 0–50°. Table II shows the experimental conditions of the single-sloped cutting test. The surface roughness and the microstructure of the cut surface are

TABLE II Experimental conditions of the single-sloped cutting test

Diameter of hotwire (mm)	Q_L (W/mm)	V_{tr} (mm/s)	Q_{eff} (W·sec/mm^2)	θ (deg)
	0.324	20.0	0.016	0, 10, 20,
		30.0	0.011	30, 40, 50
0.36		40.0	0.008	
	0.465	28.7	0.016	
		43.1	0.011	
		57.4	0.008	

measured by a roughness tester (Surftest SJ-401) with stylus instrument and Scanning Electron Microscope (SEM), respectively. The measured roughness is the maximum roughness (R_{max}) and the average absolute value of the profile deviations from the mean line (R_{a}). In order to verify the fact that the microstructure is not changed by the measurement with the stylus, the status of the measured surface, such as existence of scratches and dents and changes of microstructures, is verified by the optical microscope. The results of the verification show that the state of the measured surface does not change after the measurement using the stylus.

The influence of the cutting angle on the surface roughness is shown in Fig. 5a and b. In Fig. 5a and b, it is seen that the values of R_{a} and R_{max} lie in two difference ranges. One group shows 40 μm of R_{a} and 5–8 μm of R_{max} and the other groups show 60–70 μm of R_{a} and 10–15 μm of R_{max}. In addition, it is seen that the cutting angle does not appreciably affect the

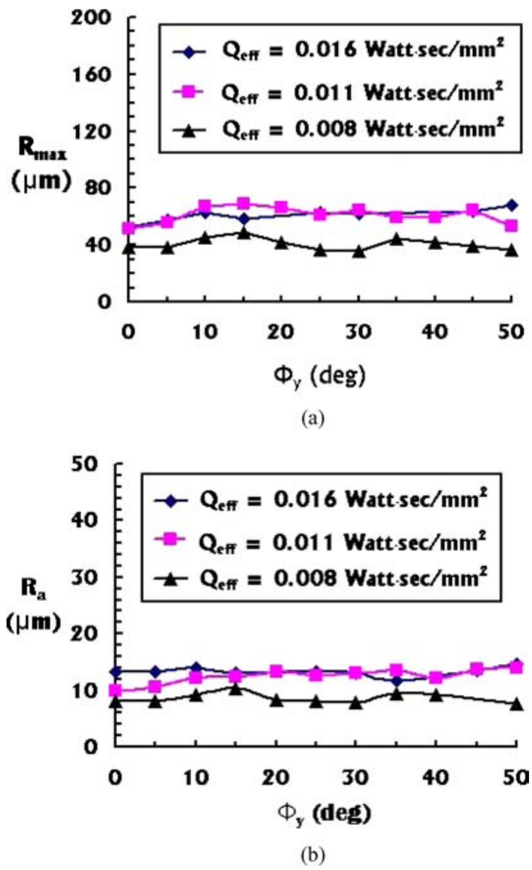

Figure 5 Influence of cutting angles (ϕ_y) and effective heat input on the surface roughness: (a) The maximum roughness (R_{max}), (b) The average absolute value of the profile deviations from the mean line (R_{a}).

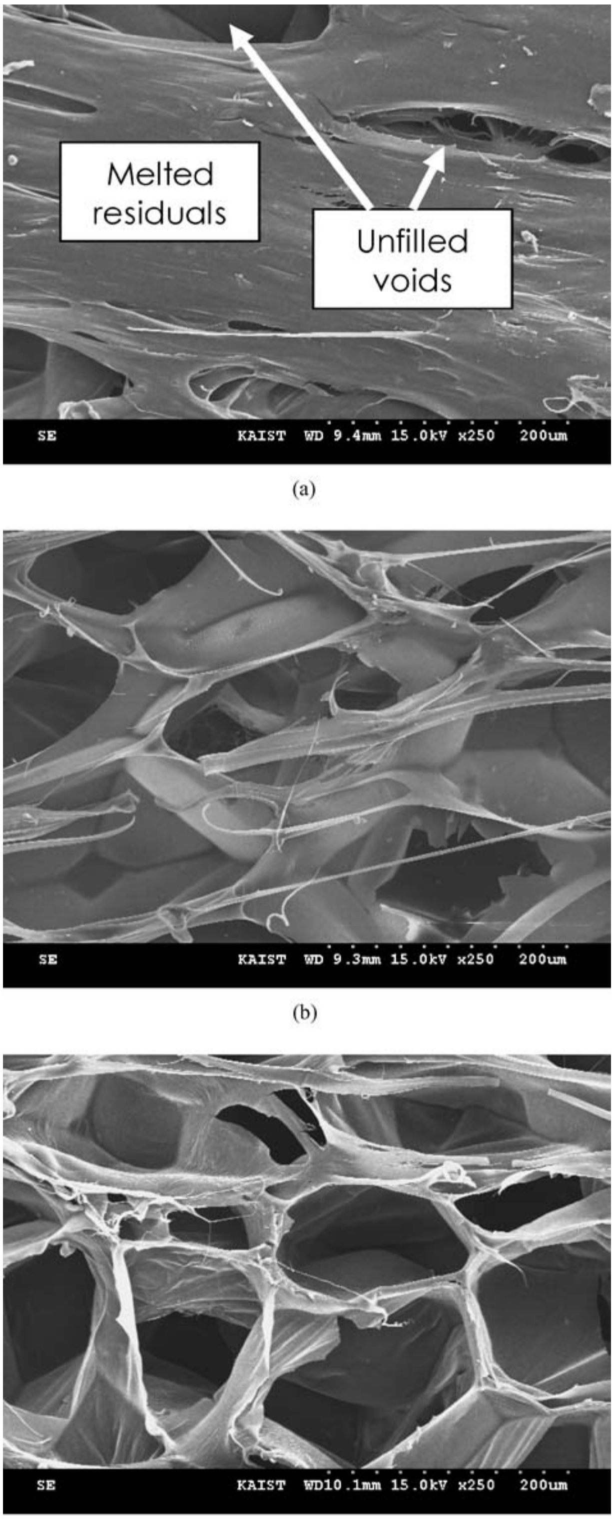

Figure 6 Microstructure in the vicinity of the cut: (a) $Q_{\mathrm{eff}} = 0.008$ W·sec/mm^2, (b) $Q_{\mathrm{eff}} = 0.011$ W·sec/mm^2, (c) $Q_{\mathrm{eff}} = 0.016$ W·sec/mm^2.

surface roughness of the cut part. From the results, it has been shown that the influence of the cutting angle on the surface roughness is negligible in comparison with that of the effective heat input.

In the case of 40 μm of $R_{\max}$, the effective heat input is lower than the critical value of the effective heat input, so that the applied heat input decomposes the remaining melted material incompletely. Subsequently, the void of the EPS foam is filled with remaining melted material as shown in Fig. 6a and the filled material forms a smooth surface. Hence, the surface roughness is reduced in the case of applying rather insufficient effective heat input to cut material. In the case of 60–70 μm of $R_{\max}$, the applied effective heat input is sufficient to decompose the melted material completely, so that the surface of the cut part is formed by only solid material of EPS foam without filling of the remaining melted material as shown in Fig. 6b and c. Hence, the surface roughness of the cut part indicates approximately the half of the grain size for the EPS foam.

In conclusion, the influence of process parameters, such as the effective heat input and cutting angle (Φ_y), on the surface roughness could be investigated by the desired experiments and numerical analyses. Through the investigation, it has been shown that the effect of cutting angle (Φ_y) on the surface roughness of the cut section in hotwire cutting of EPS foam sheet is negligible in comparison with that of the effective heat input. In addition, it could be confirmed that the surface roughness of the cut part in hotwire cutting of EPS foam is approximately the same as the half of the grain size for the EPS foam when the effective heat input is greater than the critical value of effective heat input. Based on the results, the minimum cutting condition of the effective heat input for optimal hotwire cutting of EPS foam has been limited to 0.011 W·sec/mm^2.

References

1. P. F. JACOBS, in "Stereolithography and other RP&M Technologies form Rapid Prototyping to Rapid Tooling" (ASME Press, 1996).
2. D. Y. YANG and H. K. SOHN, *J. Kor. Soc. Prec. Engng.* **17** (2000) 5.
3. P. KULKARNI, A. MARSAN and D. DUTTA, *Rap. Prototyp. J.* **6** (2000) 18.
4. D. G. AHN, S. H. LEE and D. Y. YANG, *Proc. Inst. Mech. Engrs.* **216** (2002) 1239.
5. S. H. LEE, D. G. AHN and D. Y. YANG, *Int. J. Adv. Mech. Manuf. Tech.* **22** (2003) 175.
6. D. G. AHN, S. H. LEE and D. Y. YANG, *ibid.* **43** (2003) 1447.
7. B. DE SMIT and H. J. BROEK, in Proceedings of Solid Freeform Fabrication Symposium 2004, edited by D. L. Bourell, R. H. Crawford, J. J. Beaman, K. L. Wood, and H. L. Marcus, August (2004) p. 591.
8. D. G. AHN, S. H. LEE and D. Y. YANG, *J. Mater. Sci.* **21** (2002) 747.
9. H. C. KIM, D. G. AHN, S. H. LEE and D. Y. YANG, *Int. J. Mech. Tools Manuf.* **45** (2005) 345.
10. A. VISWANATHAN, M. JOUANEH, P. DATSERIS and W. J. PALM, *IEEE Robot. Autom. Maga.* **32** (1996) 39.
11. M. JOUANEH, A. HAMMAD, P. DATSERIS, *Int. J. Mech. Tools Manuf.* **37** (1997) 437.
12. ESI Group, in "SYSWELD+2.0 Reference Manual" (SYSTUS International, New York, 1972).

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