Springer

KSME

Journal of Mechanical Science and Technology 30 (5) (2016) 2163~2169
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-016-0423-z

Effects of forming parameters on temperature in frictional stir incremental sheet forming †

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(Manuscript Received June 4, 2015; Revised December 18, 2015; Accepted January 2, 2016)

Abstract

Frictional stir Incremental sheet forming (ISF) is a new technology used to fabricate parts of hard-to-form materials without using heating equipment. Thus far, limited information is known about the effects of main forming parameters, except spindle speed of the tool, on the temperature of formed sheet in friction-stir ISF. The effects of six forming parameters, namely, sheet thickness, tool vertical step, tool diameter, spindle speed, feed rate, and wall angle of the formed part, were identified using the design of experiment of orthogonal array, analysis of response tables and graphs, and analysis of variance. Results show that spindle speed, feed rate, sheet thickness, and tool vertical step significantly affect the temperature of the sheet. In addition, the temperature of the sheet is significantly increased by increasing sheet thickness, tool vertical step, and spindle speed but significantly decreased with increasing tool feed rate.

Keywords: Frictional stir incremental sheet forming; Forming parameters; Temperature variation; Design of experiment; Analysis of variance

1. Introduction

Incremental sheet forming (ISF) is a new process of forming sheet metals; this technique does not require dedicated dies and is suitable for small-batch production of metal sheets. The process is used in many industries, such as automotive, aerospace, and biomedicine [1-4]. The formation of ISF has become challenging because of increased demand for hard-to-form lightweight materials, such as magnesium, titanium, and aluminum alloys [5]. Several heating approaches are used to increase the formability of hard-to-form materials; these approaches include laser heating [6], halogen lamp heating [7], heater band heating [8], electric heating [5, 9], and frictional stir heating [10-12]. Of these techniques, frictional stir ISF shows superior advantages because it does not require additional heating equipment.

In 2005, Jeswite et al. [1] explained the temperature rising phenomenon in ISF; in this study, friction is a significant heat source, and the high spindle speed of the tool generates high amounts of heat, resulting in excessive heating of sheet metals. Thus, the study focused on decreasing frictional heating speed. However, subsequent studies revealed that temperature rising in sheet metals is useful. In 2008, Park et al. [13] first evaluated the feasibility of forming AZ31B magnesium alloy sheet at room temperature by ISF with a rotational tool, called Rotational incremental sheet forming (RISF). The effects of tool vertical step and spindle speed on the temperature rising of the formed sheet. Box-shaped parts with wall angles of 45° and 60° were fabricated using AZ31 magnesium alloy at room temperature by the same process [12]. Otsu et al. [14] introduced "frictional stir" into ISF and named the process as frictional stir incremental forming; in this process, the tool rotates with high spindle speed and a large amount of heat is generated on the contact area between the forming tool and the metal sheet. Otsu et al. [14] reported that A5052 aluminum alloy can be formed by frictional stir ISF at room temperature. Furthermore, the formability of AZ31, AZ61 and AZ80 magnesium alloys, which are hard-to-form materials, significantly increased after frictional stir ISF [15]. Similarly, Buffa et al. [11] indicated that the formability of AA1050-O, AA1050-H24, and AA6082-T6 aluminum alloys significantly increased by elevating the spindle speed of the tool. Xu et al. [10] studied the effects of spindle speed of the forming tool on formability, forming force, and microstructure changes in AA5053-H32 aluminum alloy within 0-7000 r/min. Wang et al. [16] performed numerical simulation to determine the contribution of three heat sources to temperature rising of sheet metal in ISF at high spindle speeds. The heat sources investigated included friction generated by relative movement, relative rotation between the tool and the sheet, and plastic deformation of the sheet. The results showed that contribution of

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friction of relative rotation accounts for about 96.5% of the total increase in temperature. Researchers [17] also studied the temperature distribution and changes in sheet metals by using a commercial finite element code of MSC.Marc. The profile of temperature was analyzed at contact and non-contact areas. In addition, the effects of process parameters on formability of AZ31B magnesium alloy in frictional stir ISF were investigated [18]; the optimal combination of process parameters for forming AZ31B magnesium alloy at room temperature was established.

Frictional stir ISF is a potential die-less sheet forming process, which is suitable for hard-to-form lightweight materials. The formability of the materials may significantly enhance frictional stir ISF because of elevated temperatures caused by frictional heat. Previous research mainly focused on the formability of sheet metals and the influence of spindle speed of the forming tool. Although spindle speed remarkably affects friction heat, other forming parameters can also influence the amount of friction heat generated. Thus far, limited information is known about the influence of forming parameters, except spindle speed, on the temperature of sheets in frictional stir ISF. Therefore, this paper mainly focused on the temperature of sheet under the influence of six main forming parameters, namely, sheet thickness, tool vertical step, tool diameter, spindle speed, feed rate, and wall angle of the formed part. Our results provide a basis to employ frictional stir ISF to fabricate hard-to-form materials.

2. Experimental procedure

AZ31B magnesium alloy, a hard-to-form lightweight alloy, was selected for experiments. This material mainly contains (mass percent, %) Al (3.05), Zn (1.1), Mn (0.44), Si (0.02), Fe (0.001), Cu (0.003), Ni (0.001), and Mg balance. The AZ31B sheets with 1 and 1.5 mm thicknesses were cut into 140 mm × 140 mm size of blanks. The roughness of the sheet described by the arithmetical mean value, Ra, was 1.8 µm. High-speed steel (HSS4341, with a hardness of HRC60-62) was used as forming tool. This tool has hemispherical end. The friction coefficient for AZ31B and HSS4341, which is not easy to obtain, was found to be less than 0.3 on the basis of previous friction tests using a tribometer. The influence of tool diameter was investigated using different diameters of 8, 10 and 12 mm. The geometries of truncated pyramid with three different wall angles of 30°, 40° and 50° (Fig. 1) were selected to analyze the influence of the wall angle of the formed part. The truncated pyramid parts with different wall angles have the same length of open and bottom edges (112 and 61.6 mm, respectively). Lithium-based grease was used for the blank at high temperatures to eliminate the milling effect caused by the high spindle speed of the forming tool. A specialized incremental sheet forming CNC machine (NHJ-1A, designed and manufactured by Nanjing University of Aeronautics and Astronautics, China) was employed to carry out the frictional stir ISF process. A data acquisition system (MX100, YOKOGAWA Corp.), with a frequency of 10 Hz, equipped with K-type thermocouple was used to measure the temperature of the sheet.

Table 1. Range of forming parameters.

Symbol	Parameter	Level 1	Level 2	Level 3
A	Sheet thickness	1	1.5	
B	Tool vertical step (mm)	0.2	0.4	0.6
C	Tool diameter (mm)	8	10	12
D	Spindle speed (rpm)	3000	4000	5000
E	Feed rate (mm/min)	200	400	600
F	Wall angle (degree)	30	40	50

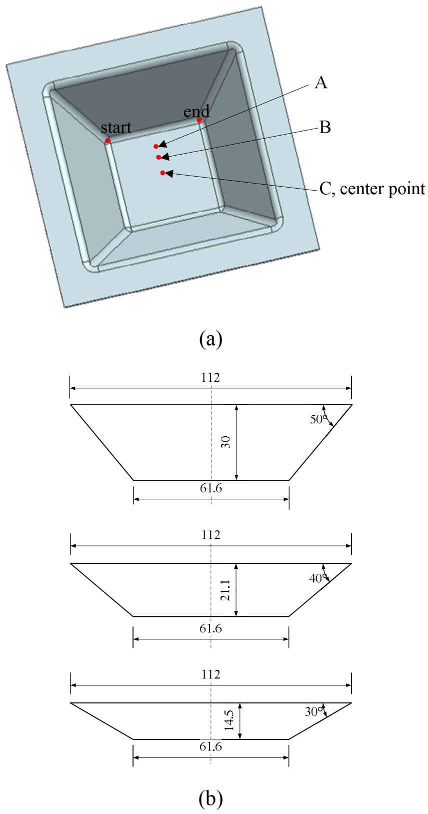
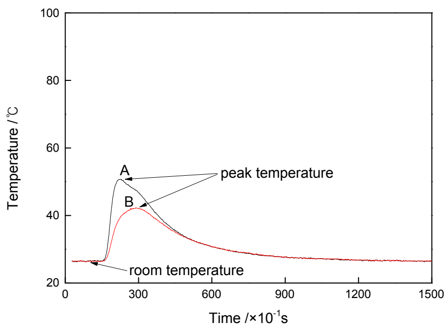


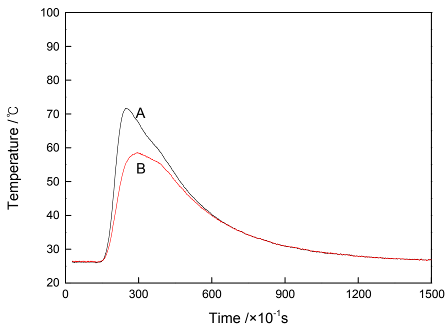
Fig. 1. (a) 3D model of geometry of part; (b) sections of geometries.

The influence of forming parameters was investigated based on Design of experiment (DOE) method. The six parameters evaluated included sheet thickness, tool vertical step, tool diameter, spindle speed, feed rate, and wall angle of the formed part. The forming parameters and their corresponding levels are listed in Table 1. These settings were selected after several preliminary experiments.

As shown in Table 1, six forming parameters, of which one parameter has two levels and the remaining five parameters have three levels, were selected without considering the interaction effect. A mixed level L_{18} ($2^1 \times 3^7$) Orthogonal array (OA) was employed for analysis. The six forming parameters were assigned to the former six columns of the OA. The last



(a)



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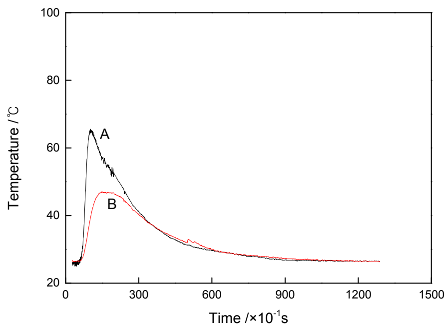

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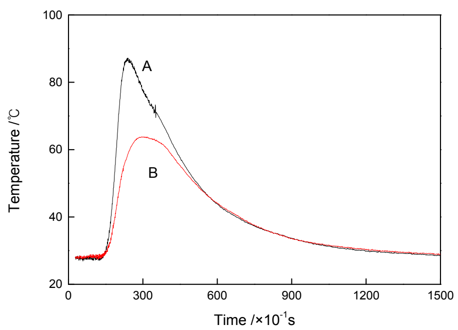

(d)

Fig. 2. Experimental temperature curves of sheet at points A and B in experiment of (a) No.4; (b) No.7; (c) No.8; (d) No.18 in Table 2.

column of the OA was set as null.

The experiments were performed as follows:

Step 1: A truncated pyramid was formed according to the order of OA at a spindle speed of 4500 rpm, which is similar to the feasible speed used to form AZ31B sheet in our previous works.

Step 2: Rotating ISF tool was placed in the "start" position, as shown in Fig. 1(a).

Step 3: Two thermocouples were placed on the forming surface of the part [Fig. 1(a)]. The first thermocouple was placed at the position of point A. The distance between points A and C, which is the center of the bottom square, is 23 mm. The second thermocouple was placed at point B. The distance between points B and C is 15 mm.

Step 4: After cooling of the preformed part to room temperature, a rotating forming tool was fabricated and used to penetrate a given vertical step and move on the straight path along the edge of the truncated pyramid part until it arrived at the "end" position. Temperature of points A and B was recorded during the process until the part cooled to room temperature again.

Each temperature measurement was performed in duplicate. Two directions of the orthogonal edges at the bottom of the part were selected.

Table 2. Results of Design of experiments (DOE).

Exp. No.	Forming parameter levels						Average of two repetitions of maximum temperature variation (°C)	
	A	B	C	D	E	F	Point A	Point B
1	1	1	1	1	1	1	23.45	15.25
2	1	1	2	2	2	2	26.15	16.15
3	1	1	3	3	3	3	21.75	17.30
4	1	2	1	1	2	2	22.65	16.30
5	1	2	2	2	3	3	21.10	17.60
6	1	2	3	3	1	1	42.10	27.35
7	1	3	1	2	1	3	46.25	35.30
8	1	3	2	3	2	1	37.65	24.15
9	1	3	3	1	3	2	21.30	15.65
10	2	1	1	3	3	2	24.05	21.10
11	2	1	2	1	1	3	45.50	28.20
12	2	1	3	2	2	1	24.35	18.30
13	2	2	1	2	3	1	30.75	25.05
14	2	2	2	3	1	2	69.40	52.60
15	2	2	3	1	2	3	33.10	25.90
16	2	3	1	3	2	3	62.80	43.65
17	2	3	2	1	3	1	20.55	15.90
18	2	3	3	2	1	2	52.65	39.90

3. Results

3.1 Experimental temperature curves

Fig. 2 shows the temperature curves recorded at points A and B in different experiments. In Fig. 2(a), the temperature increased from room temperature to 51°C at point A and to

Table 3. Average response table for point A.

Forming parameter	Average of maximum temperature variation of point A (°C)					Rank
	Level 1	Level 2	Level 3	Range	Modified range	
A	29.16	40.35		11.19	23.83	2
B	27.54	36.52	40.2	12.66	16.13	4
C	34.99	36.73	32.54	4.18	5.32	6
D	27.76	33.54	42.96	15.2	19.36	3
E	46.56	34.45	23.25	23.31	29.69	1
F	29.81	36.03	38.42	8.61	10.97	5

Table 4. Average response table for point B.

Forming parameter	Average of maximum temperature variation of point B (°C)					Rank
	Level 1	Level 2	Level 3	Range	Modified range	
A	20.56	30.07		9.51	20.26	1
B	19.38	27.47	29.09	9.71	12.37	4
C	26.11	25.77	24.07	2.04	2.60	6
D	19.53	25.38	31.03	11.49	14.63	3
E	33.1	24.08	18.77	14.33	18.25	2
F	21	26.95	27.99	6.99	8.90	5

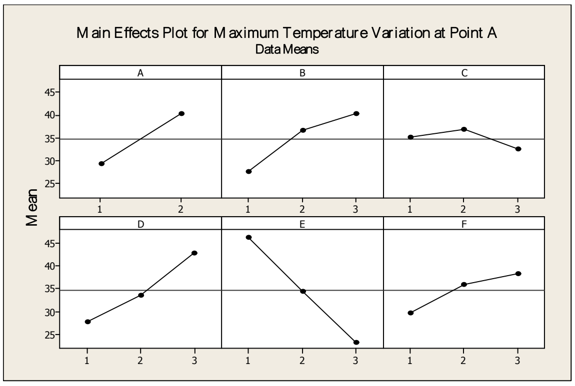

Fig. 3. Response graph of main effects of six forming parameters on temperature at point A.

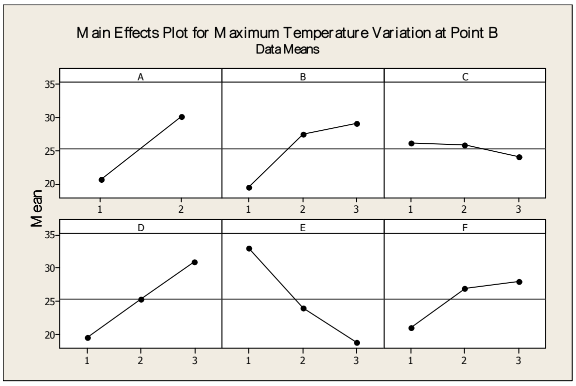

Fig. 4. Response graph of main effects of six forming parameters on temperature at point B.

42°C at point B. The same tendency, that is, the temperature at point A is higher than that at point B, can also be observed in Figs. 2(b)-(d). In each case, temperature increased from room temperature to a peak, then decreased to room temperature; this finding occurred as a result of initial decrease and then increase in the distance between the measured points and rotating forming tool. The tool was separated from the sheet. The maximum temperature measured by thermocouple A is higher than that by B because the latter was closer to the heat source. The maximum temperature variation between the peak temperature and the room temperature was selected as objective criterion to eliminate the influence of initial room temperature. Each temperature measurement was performed in duplicate at two different edges of the formed part. The sum of maximum temperature variations in points A and B was obtained in each run of OA by using the average of two replications, and the results are presented in Table 2.

3.2 Response table and response graph

Tables 3 and 4 present the response tables for points A and B, respectively, which were used to obtain the average temperature variation in each forming parameter level. The range (*R*) in Tables 3 and 4 was modified by Eq. (1) because factor A has two levels and the other three factors have five levels [19]. The modified range (*R'*) was used to determine the influence of the forming parameters on the objective criterion. According to Table 3, the modified range of factor E (feed rate) is the largest, followed by A (sheet thickness), D (spindle speed), B (tool vertical step), F (wall angle), and C (tool diameter). The result shows that tool feed rate exhibits maximum influence on the temperature of the sheet at point A in frictional stir ISF, followed by sheet thickness, spindle speed, tool vertical step, wall angle, and tool diameter. However, Table 4 shows that sheet thickness exerts the maximum influence on the temperature of the sheet at point B, followed by feed rate, spindle speed, tool vertical step, wall angle, and tool diameter.

The effects of each forming parameters at each level are shown in Figs. 3 and 4.

- Temperature increases with increasing sheet thickness, tool vertical step, spindle speed, and wall angle.
- Decreased feed rate significantly increases the temperature.
- Tool diameter minimally influences the temperature.

$$R' = dRn^{0.5} \qquad (1)$$

where R and R' represent the range and the modified range in Tables 3 and 4, respectively; d is the conversion coefficient, which equals to 0.71 when a factor has two levels and equals to 0.52 when a factor has three levels; and n is the number of

Table 5. Analysis of variance of maximum temperature variation for point A.

Source	DOF	Sum of square	Mean square	F-value	p-value	Significant
A	1	563.92	563.92	13.77	0.01	Yes
B	2	508.7	254.35	6.21	0.035	Yes
C	2	53.01	26.51	0.65	0.556	
D	2	706.32	353.16	8.62	0.017	Yes
E	2	1630.66	815.33	19.91	0.002	Yes
F	2	237.07	118.53	2.89	0.132	
Error	6	245.69	40.95			
Total	17	3945.38				

Table 6. Analysis of variance of maximum temperature variation for point B.

Source	DOF	Sum of square	Mean square	F-value	p-value	Significant
A	1	406.6	406.6	23.43	0.003	Yes
B	2	324.47	162.23	9.35	0.014	Yes
C	2	14.35	7.18	0.41	0.679	
D	2	396.22	198.11	11.41	0.009	Yes
E	2	630.15	315.07	18.15	0.003	Yes
F	2	170.74	85.37	4.92	0.054	
Error	6	104.14	17.36			
Total	17	2046.66				

factors in OA.

3.3 Analysis of variance

Analysis of variance (ANOVA) was employed to determine the forming parameters that significantly influence temperature of the sheet in frictional stir ISF. The results of ANOVA for the response objective are listed in Tables 5 and 6 for points A and B, respectively. The results show that feed rate, sheet thickness, spindle speed, and tool vertical step (p-values are less than 0.05) significantly influence the temperature of the sheet.

4. Discussion

In this study, the effects of six forming parameters, namely, sheet thickness, tool vertical step, tool diameter, spindle speed, feed rate, and wall angle, on the temperature of sheet in frictional stir ISF were investigated.

The effects of forming parameters on the temperature were ranked (Tables 3 and 4). The ranks of sheet thickness and feed rate vary at different measured points; hence, the interaction of sheet thickness and feed rate significant influences the temperature. Further experiments considering interactions among forming parameters will be performed to elucidate the ranks of the parameters. Although the rank of the influence of forming parameters on the temperature cannot be determined, the significance of such parameters can be obtained.

According to the results of ANOVA (Tables 5 and 6), feed rate, sheet thickness, spindle speed, and tool vertical step significant influence the temperature of the sheet. However, tool diameter and wall angle exhibit minimal effects on the temperature. Furthermore, high values of sheet thickness, spindle speed, and tool vertical step remarkably increase the temperature. In addition, high values of feed rate significantly decrease the temperature of the sheet.

Formulas proposed by previous researchers are presented to further analyze the results. In frictional stir ISF, temperature variation in sheet is mainly determined by heat generated by friction on the contact area between the rotating tool and the sheet. Xu et al. [20] proposed a formula to express the friction generated heat Q_i at an arbitrary contact point i as Eq. (2). Total friction heat depends on Q_i as well as on the contact area between the tool and the sheet metal:

$$Q_i = f_i V_i t_t = f_i (r_i \omega + v) t_t \tag{2}$$

where f_i and V_i are the frictional force and the resultant linear velocity at contact point i, respectively; ω is the spindle speed of tool; r_i represents the corresponding radius of contact point i; v is the feed rate of tool; and t_t is the duration of contact time at point i.

In this study, the feed rate is lower than the spindle speed. Thus, Eq. (2) is simplified into Eq. (3):

$$Q_i = f_i r_i \omega t_t \, . \tag{3}$$

According to Eq. (3), friction-generated heat increases as the spindle speed increases. In addition, high values of feed rate decrease contact time, which determines the decrease in friction-generated heat. Thus, high values of spindle speed and low feed rates can increase the temperature of the sheet. Moreover, friction force positively influences the temperature variation from Eq. (3). Further discussion on the influence of forming parameters on friction force and contact area may explain the effects of other parameters, except spindle speed and feed rate, on the temperature of the sheet.

The forming parameters significantly influence the forming force in ISF. Aerens et al. [21] proposed two empirical formulas to predict the steady state vertical force and radial force of truncated cones for several metallic materials [Eqs. (4) and (5), as follows]:

$$F_z = 0.0716 R_m t^{1.57} d_t^{\,0.41} \Delta h^{0.09} \alpha \cos\alpha \tag{4}$$

$$F_r = F_z \tan\frac{\alpha + \beta - 17.2(d_t / 10)^{-c}}{2} \tag{5}$$

where F_z and F_r represent the vertical force and radial force, respectively; R_m is the ultimate tensile strength of materials; t represents the initial thickness of sheet; d_t is the diameter of tool; α is the initial wall angle; c is constant, which equals to

2.54 for aluminum alloys and DC01 steel and 1.20 for AISI 304 steel; β is the scallop angle; and Δh is the scallop height, which have relationship with the tool vertical step (Δz) as Eqs. (6) and (7), shown as follows:

$$\beta = \arcsin(\Delta z / (d_t \sin\alpha)) \quad (6)$$

$$\Delta z = 2\sin\alpha[\Delta h(d_t - \Delta h)]^{0.5} \approx 2\sin\alpha[\Delta h d_t]^{0.5} . \quad (7)$$

Although geometries formed in this paper are different from those reported by Aerens [21], the forming forces are similar; Eqs. (4) and (5) are still used to explain the effects of forming parameters in this paper. Assuming that friction coefficient is a constant in ISF, friction force is determined by the resultant force of vertical force and radial force.

Regarding the initial sheet thickness, its increment goes to increase the temperature of sheet. The explanation of such result is that the vertical force and the radial force increase with the increment of initial sheet thickness, resulting in the increment of the friction force, according to Eqs. (4) and (5). In addition, in Eq. (4), the initial sheet thickness (t) has a large exponent value of 1.57, which indicates that the factor has a significant influence on the temperature.

Regarding the tool vertical step, though it has a little influence on the vertical force, increasing it causes marked increment of the contact area, resulting in a significant increment of the temperature.

Furthermore, regarding the wall angle, its effect is not significant and its increment goes to increase the temperature; these results can be explained by considering that the influence of wall angle on friction force is complex and non-monotonic, according to Eqs. (4) and (5). Increasing the wall angle causes the vertical force to first increase and then decrease. In addition, contact area between the tool and sheet increases with increment of the wall angle. It is may be that the comprehensive influence of the wall angle accounts for the insignificant effect on the temperature.

Finally, the influence of the tool diameter can be negligible; this result is clear and it is due to small diameter difference among the three tools used in the present experiments, resulting in little difference among the friction stresses and the contact areas.

In this investigation, we have not considered interactions among forming parameters. In the future, we will study the effects of parameters with interactions in frictional stir ISF, and repeat those experiments using a wider range of forming parameters.

5. Conclusions

This study investigated experimentally the effects of six forming parameters on the temperature of sheet in frictional stir ISF. Within the experimental range of variation, the effects of the forming parameters can be obtained as follows:

(1) Feed rate, sheet thickness, spindle speed, and tool vertical step significantly influence the temperature, whereas wall angle and tool diameter have insignificant influence.

(2) High values of sheet thickness, tool vertical step, spindle speed, and wall angle lead to high temperatures of the sheet.

(3) High values of feed rate have negative effects on the temperature of sheet.

Acknowledgment

This work was supported by the National Natural Science Foundation of China under Grant No. 51205217.

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