SHI PENGTAO
LI YAN
YANG MINGSHUN
and
YAO ZIMENG

Influencing factors of AZ31B magnesium alloy thermal incremental forming bottom convex

Bottom convex is one of the important factors that affects the precision of single-point incremental forming workpiece. In this paper, numerical analysis and experimental verification are combined to study the influence of the bottom side length, forming temperature, interlayer spacing and other factors on the convex, the causes of the convex and the influence rule of each factor on the convex are also analyzed. The results show that the smaller the side length of the bottom surface, the smaller is the convex caused. The smaller is the interlayer spacing, the smaller the convex caused;The convex is affected by the forming temperature through changing the forming property of the material, and the influence of the bottom side length shall also be taken overall consideration for the size of the convex.

Keywords: Magnesium alloy, incremental forming, precision, convex

1. Introduction

Thermal incremental forming of magnesium alloy sheet is a kind of warm, dieless and flexible forming technology[1] . Firstly, the magnesium alloy sheet is heated to a certain temperature to make the sheet metal have good formability. Then, the three-dimensional shape is divided into a series of two-dimensional layers along the contour line by using the idea of delamination, and the final shape is obtained after local deformation of the sheet metal layer by layer. This technology does not need special mould, and helps to shorten the development period of metal sheet metal parts, save the massive cost of mould manufacturing, and this technology can be applied to sample trial and multi-kind and small-quantity production. It has a broad application prospect in aviation, automobile, ship and other manufacturing industries.

However, in the process of thermal incremental forming of magnesium alloy, a phenomenon of curved convex towards the positive normal line of the machining face at the bottom surface of the formed part will be occurred. And under certain technological parameters, this phenomenon is very obvious, and becomes one of the important reasons of affecting the precision of formed parts, thus affects the practicability of thermal incremental forming technology. Therefore, the problem of convex has attracted the attention of some Chinese and overseas scholars to carry on studies. LD Napoli et. al studied the phenomenon of convex and considered that the main reason for the convex is the plane stress inside the formed part, but no systematic research has been done[2]. G. Hussain et. al studied the height of convex of various materials with different properties during incremental forming process, but the influence of various technological parameters on the height of convex has not been taken into account[3]. Cui Zhen et. al studied the problem of convex with the experimental method, and analyzed the influence of forming angle of parts, diameter of tool head, thickness of sheet metal et. al on the convex, but did not carry on the in-depth study to the causes of the convex[4]; Shi Xiaofan et. al analyzed the causes of convex phenomenon from the macroscopic view, and considered that the bottom convex was occurred by the horizontal force of tool head, but did not take into consideration the effect of bending stress of sheet metal on convex[5]. Therefore, there are still many deficiencies in the research of convex phenomenon, which requires more in-depth study of convex phenomenon, understanding of the factors that affect the size of convex, so as to control the height of convex, and achieve the purpose of improving the precision of formed parts. In this paper, the effects of forming temperature, interlayer spacing and bottom side length on the convex are studied by the method of numerical analysis and experimental verification, and the causes of the convex are analyzed, which provides a theoretical basis for further reducing the convex and improving the precision of the formed part.

2. Finite element analysis

2.1. Material constitutive model

The AZ31B sheet was selected and tested by inductive coupling plasma emission spectrograph (ICP-OES) and other equipment. The component content is as shown in Table 1. The tensile test for sheet metal was carried out by means of microcomputer controlled electronic universal testing

Messrs. Shi Pengtao, Li Yan, Yang Mingshun*, Yao Zimeng, School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China, and Mr. Shi Pengtao is also with College of Mechanical & Electrical Engineering, Shaanxi University of Science & Technology, Xi'an 710021, China
* Corresponding author

machine, and the material performance parameters were obtained, as shown in Table 2. At the same time, the tensile and compressive curves of different angles were obtained.

Table 1. Experimental sheet component content

Type	Al(%)	Zn(%)	Si(%)	Fe(%)	Mn(%)	Mg(%)
AZ31B	2.5	0.707	0.146	0.0137	0.276	Margin

Table 2. Material performance parameters of experimental sheets at different temperatures

Temperature (°C)	Modulus of elasticity (Gpa)	Tensile strength (Mpa)	Yield strength (Mpa)	Poisson's ratio
100	36.1	222	144	0.35
150	26.2	194	118	0.38
200	25.0	159	101	0.42
250	23.4	122	83	0.45

Magnesium alloy has close-packed hexagonal crystal structure, its plastic deformation exists two kinds of deformation mechanism of dislocation glide and twinning, which lead to large tension-compression asymmetry of magnesium alloy. In addition, the texture phenomenon inside extruded magnesium alloy also shows remarkable anisotropy characteristic. In order to improve the accuracy of numerical simulation, in this paper, a CPB06 constitutive model, which can take into account both tension-compression asymmetry and anisotropy, is adopted to predict the process of thermal incremental forming. The yield criterion[6] is:

$$F = (|\Sigma_1| - k \cdot \Sigma_1)^\alpha + (|\Sigma_2| - k \cdot \Sigma_2)^\alpha + (|\Sigma_3| - k \cdot \Sigma_3)^\alpha \quad (1)$$

In the formula: F denotes representation yield surface size, k as the parameter to describe the asymmetry of tension-compression of the material. α is the order of the homogeneous equation, and for magnesium alloy material α=2[7]; Σ_1, Σ_2, Σ_3 are the 3 principal values of the stress tensor. Σ =C[S] is the tensor after linear variation made to Cauchy deviatoric stress tensor S, C denotes the anisotropic parameter, describing the linear transformation tensor of anisotropic yield, as shown in formula (2).

Considering the homogeneity of the yield surface function and the characteristics of linear transformation, assume that C_{11}=1, because the uniaxial tension and compression tests are carried out along the in-plane, assume $C_{44} = C_{55} = C_{66}$[7].

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & & & \\ C_{21} & C_{22} & C_{23} & & & \\ C_{31} & C_{32} & C_{33} & & & \\ & & & C_{44} & & \\ & & & & C_{55} & \\ & & & & & C_{66} \end{bmatrix} \quad (2)$$

Set up an error function as shown in formula (3). It is given the yield stress σ_b^T, σ_b^C of biaxial tension and compression, the uniaxial tension and compression yield stresses along the rolling direction and transverse direction σ_0^T, σ_0^C, σ_{90}^T, σ_{90}^C, the plastic strain ratio r_0^T , r_0^C , r_{90}^T, r_{90}^C and 9 independent anisotropic parameter of C and the value of k can be determined by genetic algorithm optimization calculation. The anisotropic parameters of magnesium alloy AZ31B at 200°C are shown in Table 3, and the anisotropic parameters at other temperatures can be obtained in the same way. By comparing the in-plane tensile yield stress in different directions with the measured data, this constitutive model has a certain prediction accuracy. Based on the user material subroutine interface (VUMATT) of Abaqus/Explicit module, this constitutive model is compiled into a corresponding subroutine, which is applied to finite element analysis.

$$E = \sum_i \left(\sum_j \omega_j \left[\frac{\hat{\sigma}_{ij} - \sigma_{ij}}{\sigma_{ij}} \right]^2 + \sum_l \omega_l \left[\frac{\hat{r}_{il} - r_{il}}{r_{il}} \right]^2 \right) \quad (3)$$

Table 3. Anisotropic parameters of CPB06 yield function (200°C)

k	C_{11}	C_{12}	C_{13}	C_{22}	C_{23}	C_{33}	C_{44}	C_{55}	C_{66}
-0.1421	1	-1.9548	-1.0712	-0.6471	-1.0475	-2.0174	1	1	1

2.2. Finite element modelling

In order to study the convex problem in thermalincremental forming of magnesium alloy, the finite element model was established by using ABAQUS software, and the numerical simulation of single point thermal incremental forming was carried out. The inverted cone is selected as the test model, as shown in Fig. 1. The tool header is set to a discrete rigid body without deformation by default. The size of the sheet metal is 150 × 150mm, the thickness is 1.5mm, the compressive area is divided at the edge of the sheet, and the degree of freedom of X and Y direction is restrainted to replace the upper platen. The lower platen is placed below the sheet, which restraint all degrees of freedom and supports the edge of the sheet. As shown in Figs. 2 and 3, the surface to surface contact algorithm is adopted during analysis, the tool head is the main surface, and the forming area of the workpiece is the slave surface. The feed speed of the tool head is set to 600mm/min, the motion curve is contour line, and the processing depth is 25mm, as shown in Fig. 4.

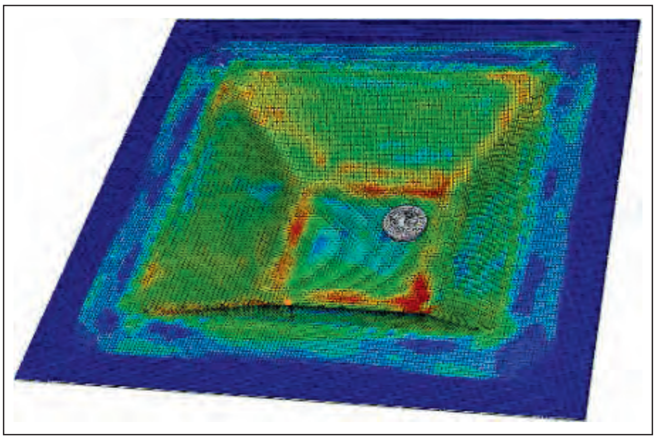

Fig. 1: Finite element analysis model

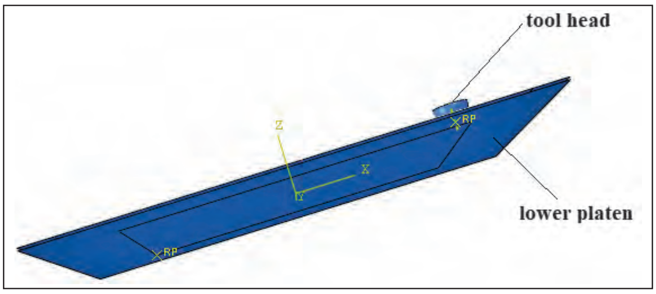

Fig. 2: Assembly of finite element model

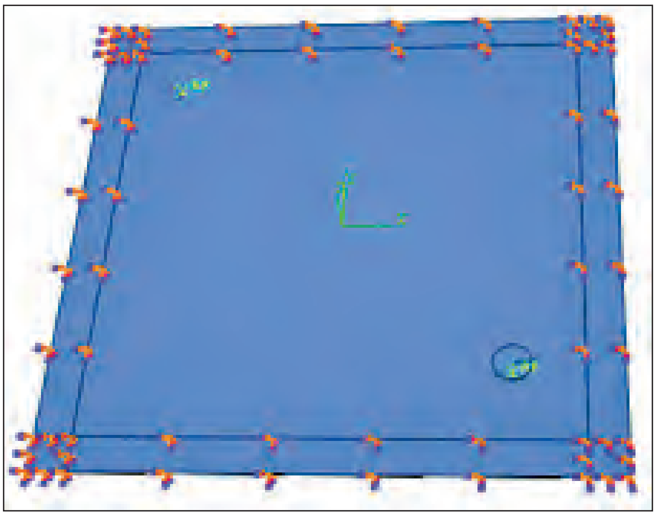

Fig. 3: Sheet metal model edge fixed

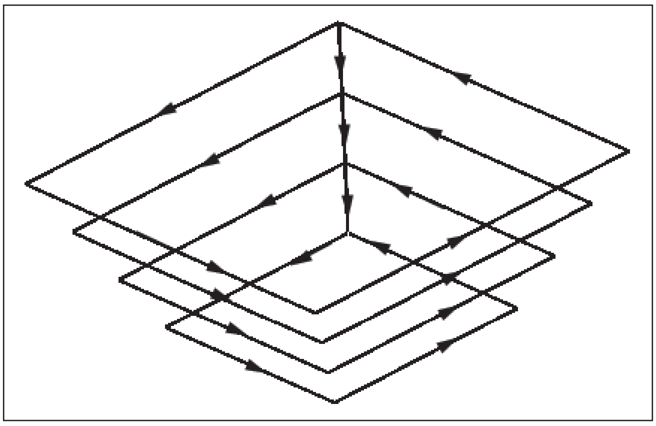

Fig. 4: Inverted cone path

2.3. Calculation of convex

The calculation method of bottom convex is shown in Fig. 5. After forming process, two points closest to theoretical profile A (x_1, z_2), B (x_n, z_n) are found on the left side and right side of the bottom surface respectively, then linear equation of AB, as shown as formula (4), and the slope is shown as formula (5).

$$z = \left(\frac{x - x_1}{x_n - x_1}\right)(z_n - z_1) + z_1 \tag{4}$$

$$K = \frac{z_1 - z_n}{x_1 - x_n} \tag{5}$$

Z_i can be measured by substituting the C-point x coordinates into the formula (6), then we can get z_i'.

$$\Delta z_i = z_i - z_i' \tag{6}$$

We can get from Fig. 5:

$$h_i = \Delta z_i \cos\left[\arctan\left(\frac{z_1 - z_n}{x_1 - x_n}\right)\right] \tag{7}$$

Then the convex h is:

$$h = \max\ (h_i) \tag{8}$$

The formulas (4), (5), and (6) are substituted into (7), and the bottom surface convex value can be obtained by selecting the maximum value.

3. Numerical analysis results

3.1. Effect of bottom area on convex

By setting the forming temperature to 200°C, forming angle to 45°, inter layer spacing to 1mm, the bottom side length t50mm, the finite element analysis is carried out. The convex analysis with processing depth being 2mm, 12mm, 17mm and 25mm is carried out respectively. The results is shown in Fig. 6. The bigger the processing depth is, the smaller is the bottom convex. This is because with the increase of the depth, the side length of the bottom surface decreases, which results in the reduction of the bending degree of the bottom surface and the reduction of the convex.

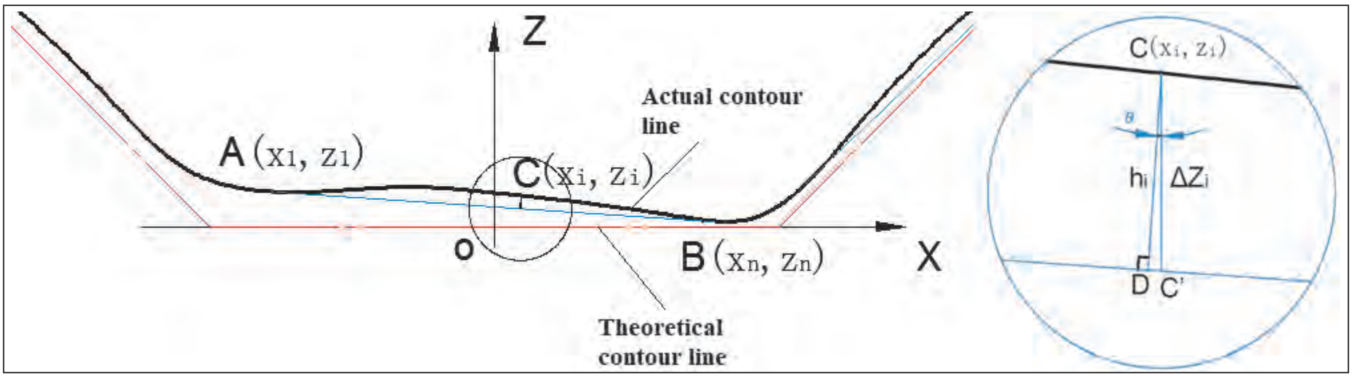

Fig. 5: Calculation method of convex

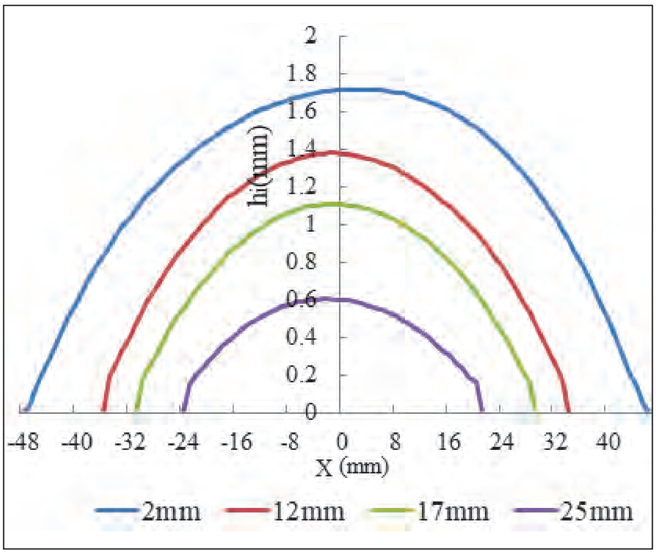

Fig. 6: Convex value of different processing depth

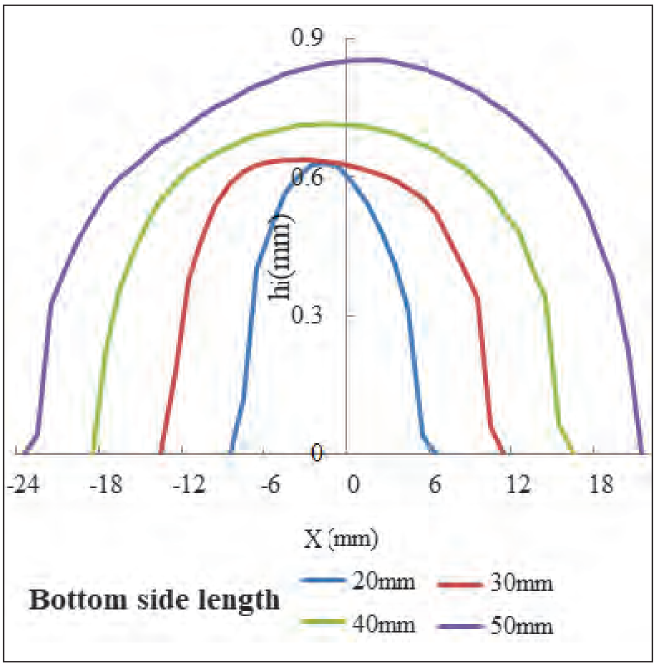

Fig. 7: Convex value of formed parts with different bottom area

By setting the forming temperature to 200°C, the forming angle to 45°, the spacing between layers to 2mm, the bottom side length to 20mm, 30mm, 40mm and 50mm, the finite element analysis is carried on respectively, the results as shown in Fig. 7, the smaller the bottom section side length is, the smaller is the bottom convex value. Therefore, the convex value is proportional to the bottom side length.

3.2. Effect of forming temperature on convex

By setting the forming angle to 45°, the interlayer spacing to 1mm, and the forming temperature to 100°C, 150°C, 200°C and 250°C, the finite element analysis is carried out respectively. The convex after processing is shown in Fig. 8. It can be seen from the figure that the lower is the forming temperature, the smaller is the convex. However, the study results of convex at different processing depths do not conform to this rule, as shown in Figs. 9, 10 and 11. At the initial stage, the lower the forming temperature is, the bigger is the convex. When processing depth reaches to 12mm, the effect of forming temperature on the convex is as same as that of the initial stage, but the value of the convex is very close. When processing depth reaches to 17mm, the law of influence has changed partly. When the processing is finished, the effect of forming temperature on the convex is contrary to the that of initial stage. Therefore, the size of the convex is affected not only by the forming temperature, but also by the bottom area.

The forming temperature affects the height of the convex by changing the processability of the sheet metal. The magnesium alloy has a close-packing hexagonal crystal structure, and only three slip systems on the basic plane can be started at room temperature which is far lower than the requirement of at least five independent slip systems for uniform deformation of polycrystals. With the increase of forming temperature, the non-base slip systems are activated, accompanied with dynamic recrystallization that leads to fundamental ductility transformation of the forming properties of magnesium alloys. Thus, the plastic property of magnesium alloy is enhanced and deformation resistance of magnesium alloy is reduced[8]. When the bottom area is larger, the convex of sheet metal with low forming temperature and high deformation resistance is larger. When the bottom area is small, the convex of sheet metal with high forming temperature and low deformation resistance is larger.

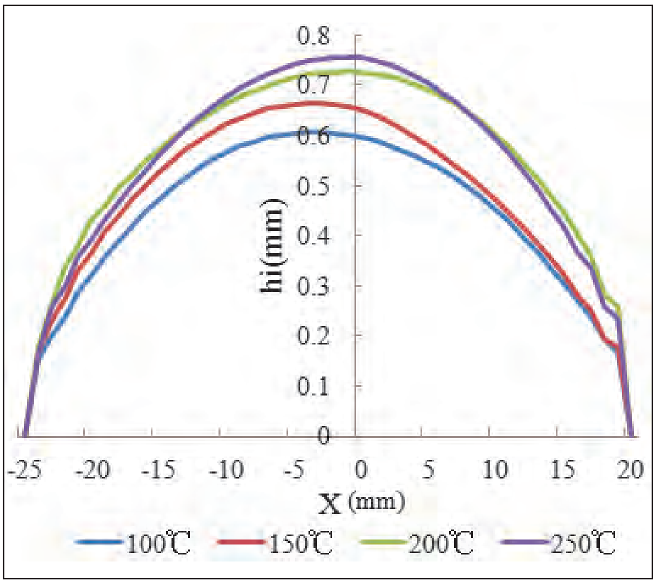

Fig. 8: Convex figure with processing depth 25mm

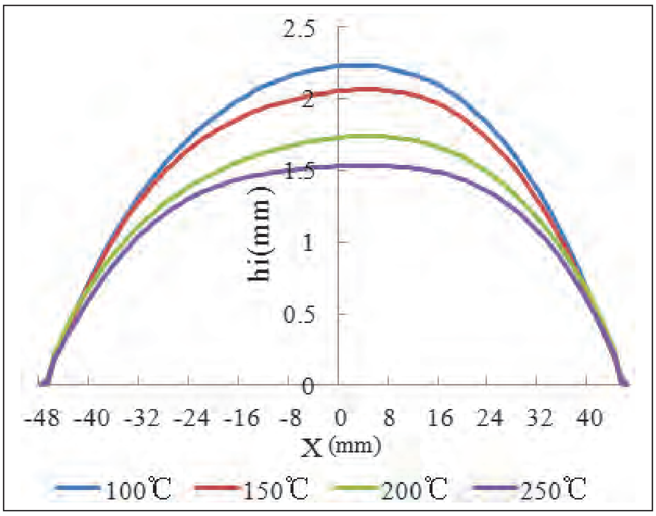

Fig. 9: Convex figure with processing depth 2mm

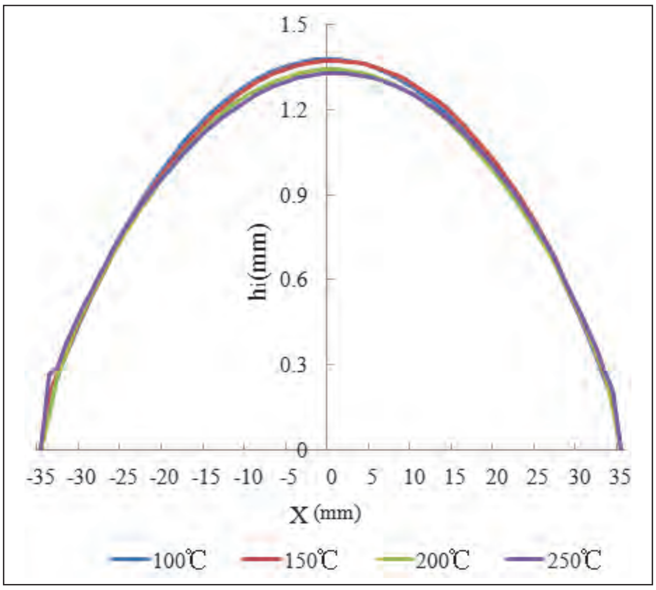

Fig. 10: Convex figure with processing depth 12mm

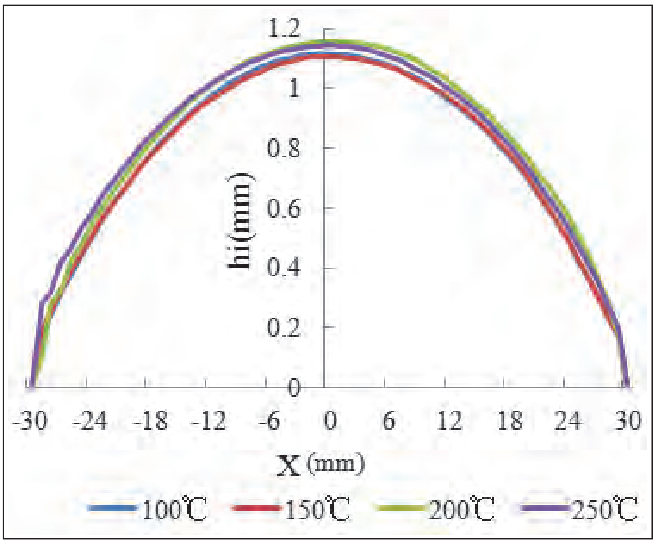

Fig. 11: Convex figure with processing depth 17mm

3.3. Effect of interlayer spacing on convex

By setting the forming temperature to 200°C, the forming angle to 45°, and the interlayer spacing to 1, 1. 5, 2, 2.5mm, finite element analysis is carried on. Fig. 12 is convex at different interlayer spacing after processing. With the increase of interlayer spacing, the bottom convex increases. Fig. 13 shows the convex when processed to the second layer, it can be seen from the figure that the larger the interlayer spacing is, the greater is the curvature of the bottom surface and the bigger is the convex after forming.

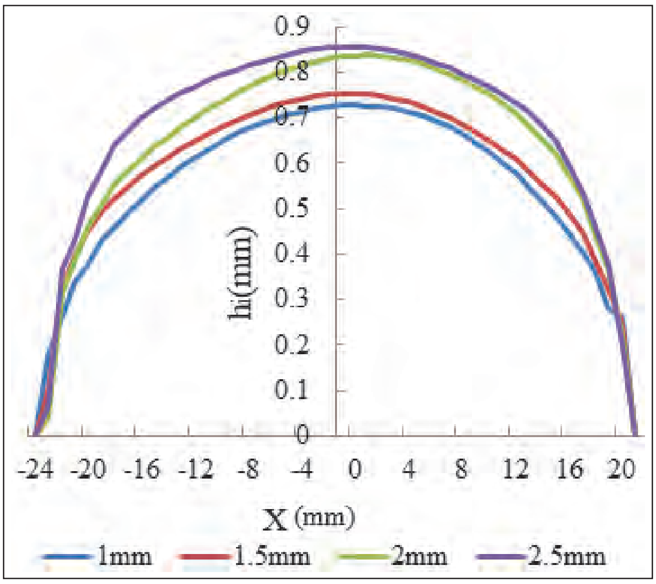

Fig. 12: Convex of different layer height after the forming process

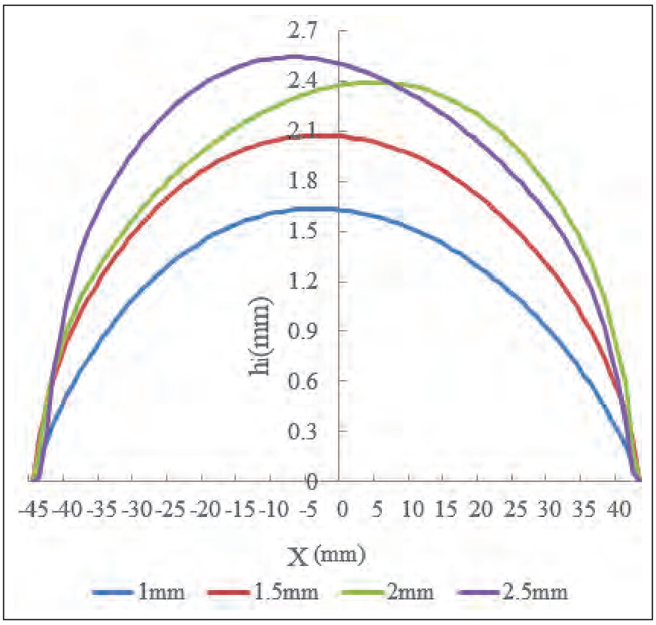

Fig. 13: Convex being processed to the second layer

Although when the interlayer spacing is large, the processing depth is larger, and the side length of the bottom surface of the formed part is smaller, which affects the convex. However, since the interlayer spacing is very close, the effect of bottom side length is not enough to change the effective law of interlayer spacing on convex. Therefore, the influence of interlayer spacing on convex is mainly due to the greater curvature of the bottom surface when the interlayer spacing is larger. When the processing depth is 25mm, though bottom area changes, the convex value decreases significantly, but the effective law of interlayer spacing on the convex is not changed.

4. Experimental verification

4.1. Forming principle

The thermal incremental forming principle of liquid medium heating is shown in Fig. 14. The liquid is filled into a incremental forming device so that a sealed liquid pool is formed at the bottom, which is connected to the outside hydraulic circuit. By adjusting the overflow valve in the hydraulic circuit, the liquid can maintain a certain pressure, which plays a certain supporting role to the sheet metal. At the same time, the liquid is heated by the heating device in the sealed liquid pool, and the temperature is controlled through the control system. Before processing, the liquid is heated and the temperature gradually rises to the set value, and the temperature is kept constant through the control system. The sheet metal is heated by liquid and gradually reaches a certain equilibrium temperature. By this time, the forming tool head moves according to the predetermined track under the control of the NC programme, the sheet metal is extruded layer by layer and deformed, and the deformation gradually accumulates to form the workpiece[9].

4.2. Forming device

The forming device is mainly composed of NC machine of CY-VMC850 machining center, single-point incremental forming device, heating plate, overflow valve, pressure gauge, insulation material, temperature control instrument, hydraulic oil and so on, as shown in Fig. 15. The upper and lower blank holder is used to fix the processed sheet metal and the heating plate is used to heat the sheet metal through heating the inner hydraulic oil. The internal hydraulic oil uses No. 320 heat conductive oil, the tool head material is tungsten carbide-cobalt cemented carbide, the hardness is 65-68 HRC.

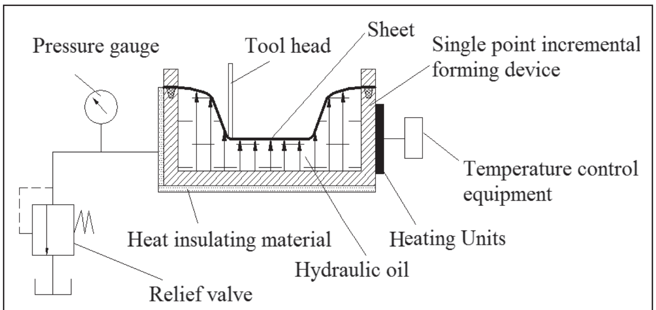

Fig. 14: Schematic diagram of experimental platform for thermal incremental forming

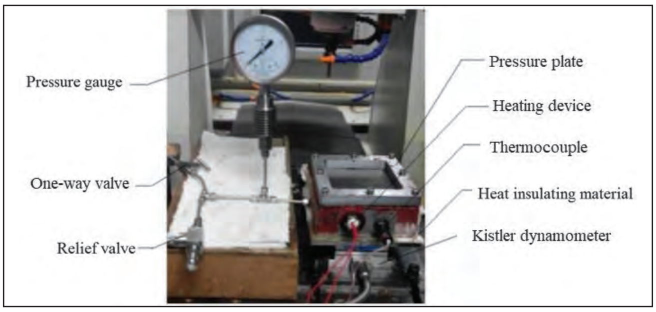

Fig. 15: The experimental platform diagram of thermal incremental forming

4.3. Results of experiments

With the above experimental device, the same parameters as the finite element analysis are set, and the single point incremental forming process is carried out. After processing, the Laser RE6003 laser scanner is used to scan the formed sheet metal. With the point cloud after scanning, modelling the cross section curve of the actual formed part in 3D software. By comparing and calculating the theoretical curve with the method of section 2.3, the true height of the bottom convex h is obtained. To reduce the measurement error, the steps above are repeated 10 times, taking the average as the final measurement result, as shown in the Figs. 16, 17, 18 and 19, the results are in agreement with the results of finite element analysis.

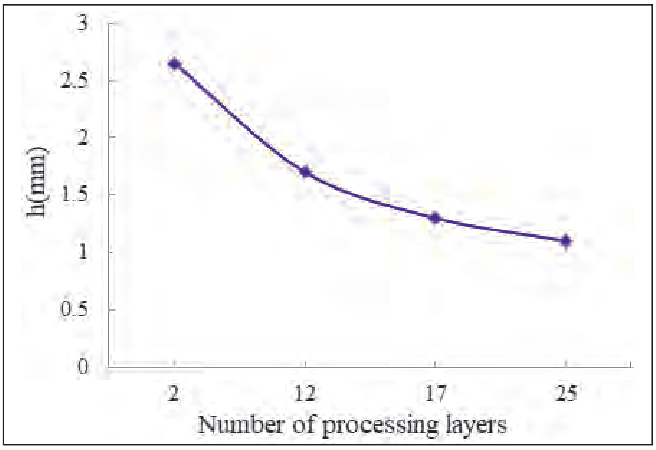

Fig. 16: Convex of formed parts with different number of machining layers

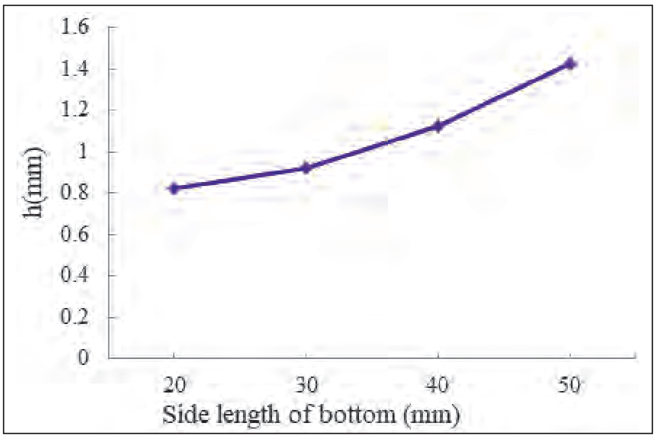

Fig. 17: Convex figure of formed parts with different side length of bottom surface

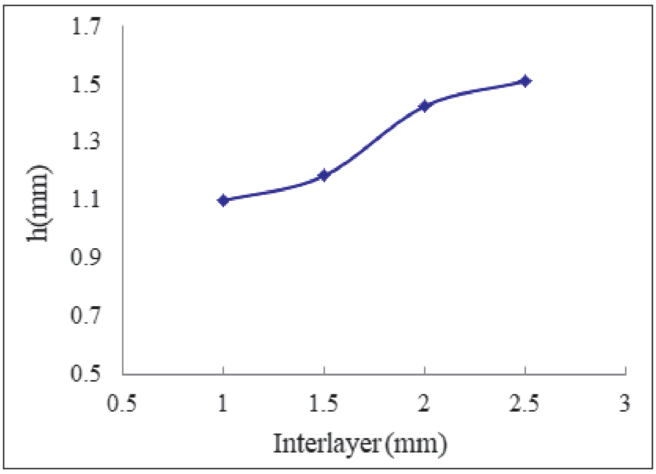

Fig. 18: The convex of formed parts with different interlayer spacing

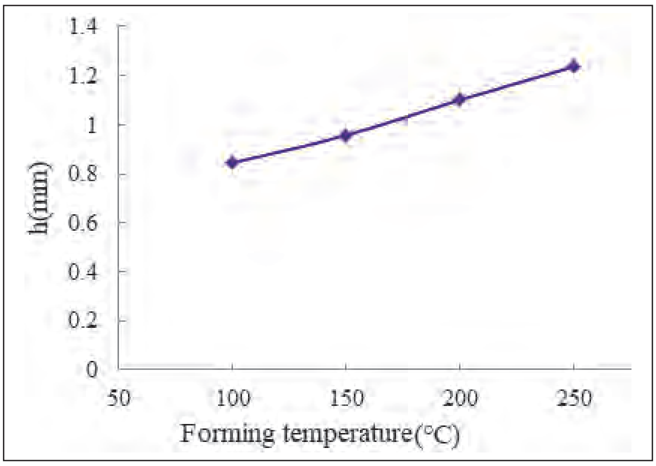

Fig. 19: The convex of formed parts with different forming temperature

It can be seen from the figures that when the opening side length is 100mm and the processing depth is 25mm, the higher is forming temperature, the larger is interlayer spacing and the larger is bottom side length will increase the bottom convex. In the actual forming process, the shape and thickness of the workpiece are often determined, and the smaller interlayer spacing and the smaller bottom side length will reduce the convex. If the forming depth is small, the higher forming temperature will help to reduce the convex. The higher forming depth and lower the forming temperature can reduce the convex.

5. Analysis of the causes of convex

From the above finite element analysis, it can be seen that the factors influencing the size of convex in thermal incremental forming of AZ31B magnesium alloy sheet metal are forming temperature, interlayer spacing, bottom side length and so on. The stress direction of the sheet metal section is shown in Fig. 20. In Fig. 21 is the σ_{11}, σ_{22}, σ_{33} stress distribution with the forming temperature 200°C, the forming angle 45°, the side length of the bottom section 50mm and the interlayer spacing 1mm. It can be seen from the figure that during forming processing, the upper surface of the workpiece is subjected to pressure stress and the lower surface of the workpiece is subjected to tensile stress in the vicinity of the forming tool head, and far from the area of the tool head, the upper surface of the workpiece is subjected to tensile stress, and the lower surface of the workpiece is subjected to pressure stress. The stress distribution law in three directions is basically the same. This is a kind of bending stress state, the different stress state leads to the different plastic strain of the upper and lower surface, which lengthen the upper surface of the formed part, and shorten the lower surface of the forming part, thus the phenomenon of convex is occurred.Therefore, the main cause of convex phenomenon is the bending stress in sheet metal processing, which makes the upper and lower surfaces suffer the stress difference caused by different sizes of stress.

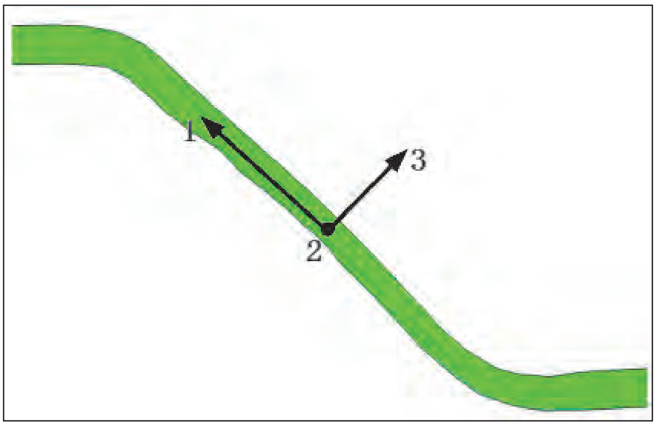

Fig. 20: Schematic diagram of stress direction of sheet metal cross section

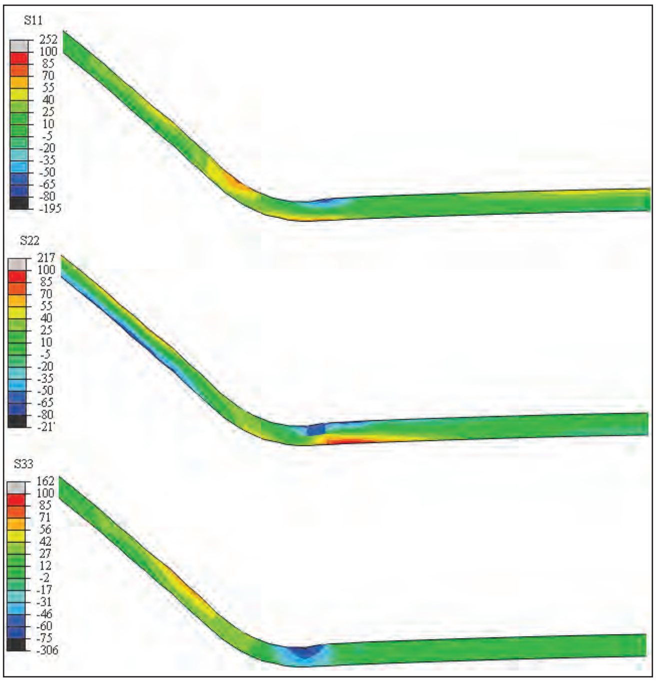

Fig. 21: σ_{11}, σ_{22}, σ_{33} stress distribution

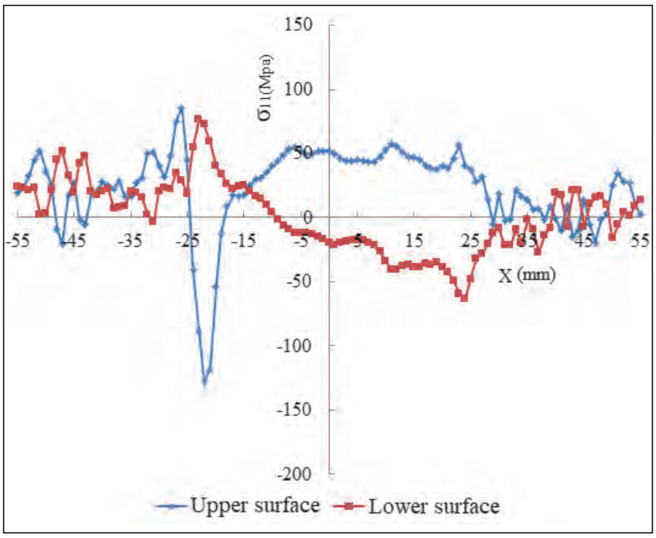

Fig. 22: σ_{11} stress distribution on upper and lower surfaces

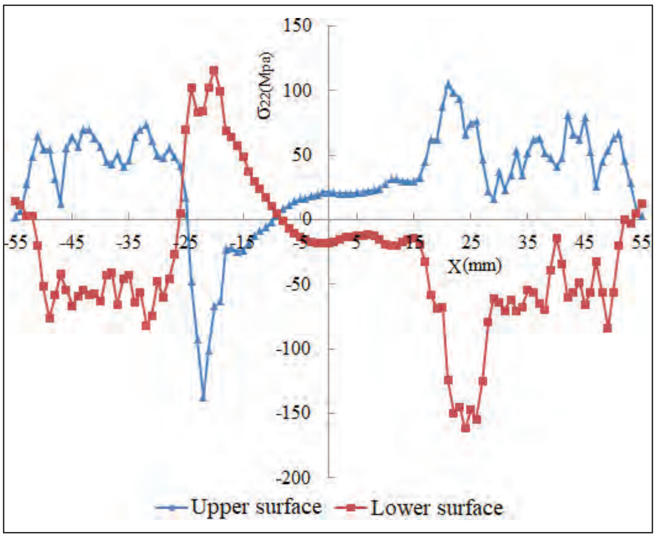

Fig. 23: σ_{22} stress distribution on upper and lower surfaces

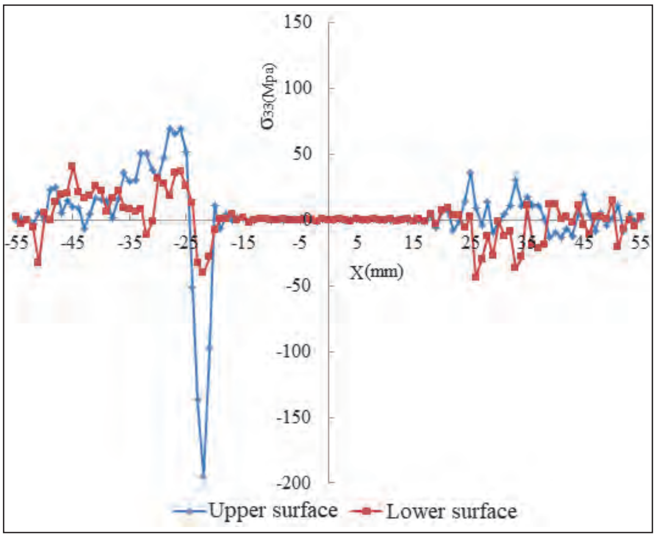

Fig. 24: σ_{33} stress distribution on upper and lower surfaces

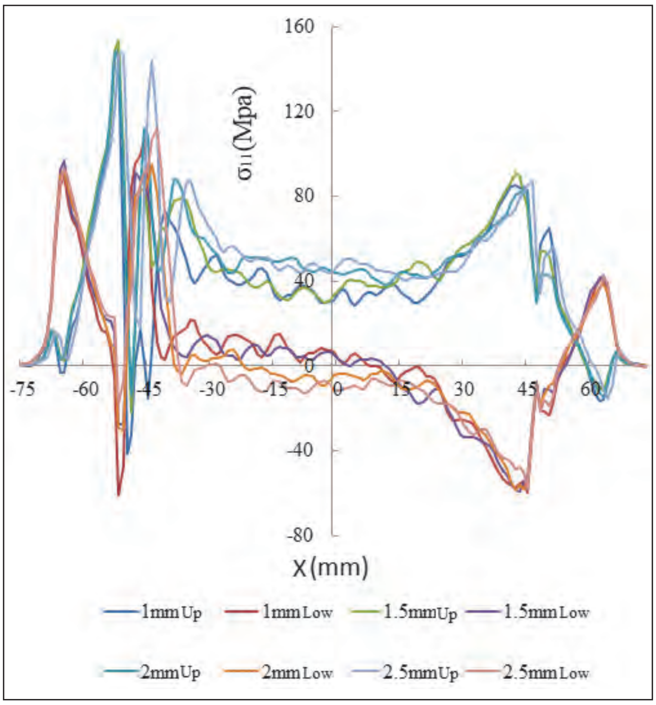

Fig. 25: σ_{11} figure of different interlayer spacing when processed to the first layer

Stress distribution of σ_{11}, σ_{22}, σ_{33} on upper and lower surfaces are as shown in Figs. 22, 23 and 24. Numerically, σ_{33} is much smaller than σ_{11} and σ_{22} during processing, so the convex is mainly caused by stress σ_{11} and σ_{22}. For the bottom surface, $|\sigma_{11}|$ is greater than $|\sigma_{22}|$, the upper and lower surface stress difference $\Delta \sigma_{11}$ caused by σ_{11} is much larger than $\Delta\sigma_{22}$, as shown in Figs. 22 and 23, therefore, the bottom convex is mainly caused by stress σ_{11}. Fig. 25 is the σ_{11} value of different interlayer spacing when the first layer is processed. From the figure, it can be seen that the larger the interlayer spacing is, the greater is the stress difference $\Delta\sigma_{11}$ between the top and bottom surface, so the bigger convex is caused.

The experimental results show that at the same forming temperature, the bottom side length has a significant effect on the convex, and the bottom bending can be simplified as the elastoplastic bending problem of simply supported beam. The larger is the bottom side length, the larger is the maximum deflection then the bigger is the convex[10]. The forming temperature affects the convex size by changing the processing performance of the material. When the processing depth is smaller, the lower the forming temperature is, the bigger the convex is due to the larger side length of the bottom surface. When the processing depth is larger, the bottom side length is smaller, then the higher the forming temperature is, the bigger is the convex. Therefore, if the processing depth of the formed parts is small, in order to reduce the convex, it is advisable to adopt a higher forming temperature. On the contrary, the bigger the depth is, the lower is the forming temperature which can reduce the convex. Under the same forming temperature, the convex can be reduced by reducing the side length of the bottom surface. Under the condition that the forming temperature and the side length of the bottom surface are both determined, the size of the convex can be reduced by reducing the interlayer spacing.

6. Conclusions

(1) The length of the bottom side of the formed part has a significant effect on the size of the convex. The smaller the side length of the bottom surface is, the smaller is the convex, otherwise, the bigger is the convex.

(2) The increase of forming temperature can change the formability of the material, but the convex value is also affected by the bottom side length, and the size of the convex is the result of the comprehensive effect of the forming temperature and the bottom side length.

(3) In the process of single point incremental forming, the bottom surface is in a typical bending stress state.When the shape and forming temperature of the formed parts are both determined, the convex is mainly caused by the stress difference $\Delta\sigma_{11}$ between the upper and lower surfaces, and the value of the convex is proportional to $\Delta\sigma_{11}$. The bigger the interlayer spacing is, then the bigger is $\Delta\sigma_{11}$, so the bigger is the convex value.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51475366, No. 50975229).

References

1. Su Chunjian, Li Tiantian (2015): “New Process Law of AZ31B Magnesium Alloy Axisymmetric Parts Single - Point Die Free Thermal Incremental Forming”. *Materials and Engineering of rare Metals*, 444(3), 649-655.
2. Napoli L De, L. Filice, M. Muzzupappa, G. Ambrogio (2005): “A simple approach for reducing profile diverting in a single point incremental forming process”. Proceeding of the Institute of Mechanical Engineers Part B. *Journal of Engineering Manufacture*, 219(11), 823-830.
3. Hussain G., L. Gao, N. U(2007): “Dar. An experimental study on some formability evaluation methods in negative incremental forming”. *Journal of Materials Processing Technology*, 186(1),45-53.
4. Cui Zhen, Gao Lin, Xu Yan, Xu Aijun, Lu Qijian, Xu Ziran (2008): “Analysis of Convex Issue in NC Incremental Forming”. *Mechanical Science and Technology*, 12, 1581-1585.
5. Shi, X., Xu, Y., Gao, L., Shen, C., & Lu, R. (2012): “Investigation on error compensatory process of pyramidal parts formed by single point incremental forming”. *China Mechanical Engineering*, 23(18), 2248-2252.
6. Cazacu, Oana, B. Plunkett (2006): “Orthotropic yield criterion for hexagonal closed packed metals”. *International Journal of Plasticity*, 22(7),1171-1194.
7. Wu Zhangbin, Gui Liangjin (2015): “Mechanical Properties and Constitutive Analysis of AZ31B Magnesium Alloy Extrusion material”. *Chinese Journal of Nonferrous Metals*, 25,293-300.
8. Zhang Qinglai, Xiao Fugui (2009): “Effect of Anisotropy on Incremental Forming and Microstructure Evolution of Magnesium Alloy sheet”. *Chinese Journal of Nonferrous Metals*, 1915,800-807.
9. Shi Pengtao, Li Yan (2016): “Research on Thermal Incremental Forming Springback of Liquid Medium Heated Magnesium Alloy”. *Hot Working Technology*, 19, 135-139.
10. Yu Tongxi (1992): “Plastic Bending Theory and Application”. Science Press.