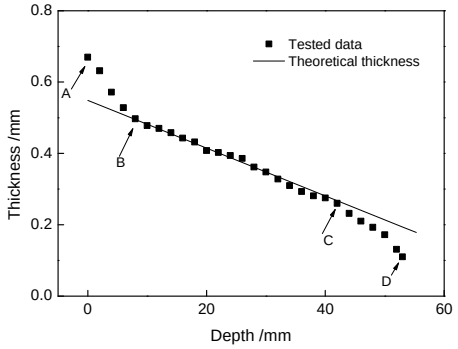
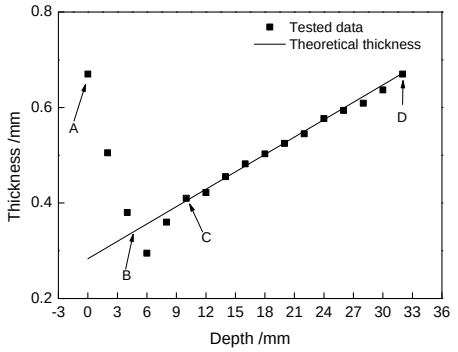
observed in other experiments when the forming angle is bigger than an angle decided by material[6].



(a) The truncated cone



(b) The sphere crown

Figure.6 The thickness of the formed parts along the depth

C. Forming limit angle

According to the Eq.(1), the wall thickness of parts decreases as the forming angle increases. In SPIF, parts fracture when the forming angle is bigger than a forming limit angle which is often expressed as $\theta_{\max}$. Many experiments were performed to get the forming limit angel of different materials by processing the cone or pyramid of fixed forming angle in SPIF. The maximum angle of the fixed angle part that can be formed will be defined as the forming limit angle. Hussain[7] found that the fractured angle of a truncated cone which generatrix is a curve is often bigger than the forming limit angle. But the forming angle at the thickness transition point (like the point C in Fig.6(a)) is very close to the forming limit angle from processing fixed angle parts. Hussain[7] also deduced a formula to compute the forming angle according to the depth of a formed truncated cone which generatrix is a curve. The formula can be expressed as[7]:

$$\theta = \cos^{-1}\left(\frac{y_1 - h_D}{R}\right) \qquad (2)$$

where θ is the forming angle, y_1 is the vertical distance between the opened location of the truncated cone and the center of the generatrix, h_D is the depth at the measured point, R is the radius of the generatrix.

According to the Eq.(2), the fractured wall angle of the formed truncated cone at the point D (see Fig.6(a)) was obtained to be about 73.2° . Followed Hussain[7], the wall angle of the formed truncated cone at the point C (see Fig.6(a)) is the forming limit angle of TRIP590 sheet with 0.67mm in thickness in SPIF, and is about 66.5° .

IV. CONCLUSION

1) Two kinds of parts of TRIP steel which wall thicknesses were incrassate and reduced respectively were formed by SPIF. The results show that the TRIP steel sheet can be processed by SPIF.

2) The wall thickness of the formed truncated cone which generatrix is a curve can be divided into three segments that are the segment thicker than the theoretical thickness, the segment equal to the theoretical thickness and the segment thinner than the theoretical thickness successively.

3) The wall thickness of the formed sphere crown can also be divided into three segments. Unlike the truncated cone, the three segments of the sphere crown are the segment thicker than the theoretical thickness, the segment thinner than the theoretical thickness and the segment equal to the theoretical thickness successively.

4) The forming limit angle of TRIP590 steel with 0.67mm in thickness in SPIF was got and equal to about 66.5.

REFERENCES

[1] J. Jeswiet, F. Micari, G. Hirt, a. Bramley, J. Duflou, and J. Allwood, "Asymmetric Single Point Incremental Forming of Sheet Metal," CIRP. Ann-Manuf. Techn., vol. 54, pp. 88–114, 2005.

[2] S. B. M. Echrif, and M. Hrairi, "Research and progress in incremental sheet forming processes," Mater. Manuf. Processes., vol. 26, pp. 1404–1414, 2011.

[3] J. Jeswiet, "Metal forming progress since 2000," CIRP-JMST., vol. 1, pp. 2–17, 2008.

[4] G. Ambrogio, L. Filice, and F. Gagliardi, "Formability of lightweight alloys by hot incremental sheet forming," Mater. Des., vol. 34, pp. 501–508, 2012.

[5] Y. Ji, and J. Park, "Formability of magnesium AZ31 sheet in the incremental forming at warm temperature," J. Mater. Process. Technol., vol. 201, pp. 354–358, 2008.

[6] L. Manco, L. Filice, and G. Ambrogio, "Analysis of the thickness distribution varying tool trajectory in single-point incremental forming," P. I. MECH. ENG. B-J. ENG., vol. 225, pp. 348–356, 2011.

[7] G. Hussain, L. Gao, and N. U. Dar, "An experimental study on some formability evaluation methods in negative incremental forming," J. Mater. Process. Technol., vol. 186, pp. 45–53, 2007.