Finite Element Study on Forming Metal Sheets with an English Wheel

K J Fann
Department of Mechanical Engineering, National Chung Hsing University, 250, Kuokuang Road, Taichung 40227, Taiwan, R.O.C
E-mail: kjfann@nchu.edu.tw

Abstract. Because of the application trends of Industry 4.0, small-volume large-variety production becomes the daily life in the manufacturing industry. Techniques to flexibly shape sheet metal parts are therefore more and more inquired. This paper is thus aimed to have a preliminary glimpse at the shaping process made by the English wheel, which is broadly used by craftsmen, via Finite Element Analysis. As a result, the parts shaped by an English wheel with a zigzag path show a curved surface having a homogeneous curvature. The more the impression from the bottom roll onto the sheet metal, the smaller the radius of the bottom roll, and the thinner as well as the more compliant the sheet metal, the larger the curvature of the shaped metal part.

1. Introduction
Recently, more and more large sheet metal membrane covering made in curved surfaces are applied to modern architecture, either on the roofing or on the façade [1]. It thus needs a corresponding process to fabricate the sheet metal to precisely demonstrate the architect’s design as well as construction demand. There are two types of traditional equipment, which can allow craftsmen to create such unusual or unique shape into metal sheets by flexible cold forming, the power hammer [2] and the English wheel [3]. The metal sheet is shaped by locally pushing the material aside, in that a compressive force is applied on the sheet metal to reduce the thickness directly either by impacting of the hammer or by rolling through the rolls. After the technique of the Incremental Sheet Forming (ISF) [4] is brought into the industry, a process combining ISF and impacting [5] along with an industrial robot has been introduced to more flexible shape the metal sheet as well. This encourages industry to extend the application of English wheel directly by using artificial neural networks in conjunction with an industrial robot [6]. However, the technique of the application of the English wheel is still not detailed. Thus, there is literature discussing the response on the sheet metal to the small impulse path of rolls. It is still worth to investigate the process parameters of the English wheel on the shape of the applied sheet metal, though. On this point of view, this paper is aimed to preliminarily investigate the parameters such as roll radius, impression, and path for a curved surface.

2. Setup of experiment and simulation
The process to flexibly cold shaping sheet metal parts with an English wheel can be illustrated in figure 1. A metal sheet is clamped with two rolls by lifting the bottom roll to impress the metal sheet. Via pushing or pulling the sheet metal to or away from the rolls, the rolls rotate because of the relative movement and the friction between the sheet metal and the rolls. A new impression onto the metal sheet
is therefore continuously applied, where the metal is shifted between the rolls. The metal sheet will be dented and the material will spread out and thus become thinner there. Under different stress state along the thickness, the sheet will be bent and a curvature is thus created there.

To demonstrate the process of the flexible shaping metal sheet parts with the English wheel, this study created a finite element model according to the equipment made by Baileigh Industrial, which provides a throat depth of 750 mm, a flat upper roll having the width of 75 mm and a diameter of 250 mm, and several bottom rolls having the same width as the upper roll and the same height of 75 mm. In this study, three bottom rolls have been taken into account. They have the radii of 50 mm, 100 mm, and 200 mm, respectively. The metal sheet is a square having 500 mm each side. Two different thicknesses, 1 mm and 2 mm, were operated in the study. Two different metals, DC04 and A6061-T6, were used as well. Two impressions, a half and a quarter of the thickness, were developed by lifting the bottom die into the sheet metal. Three different paths were applied in this study, as shown in figure 2. An angle of 4.5° for case (a) the sawtooth zigzag path or 9° for case (b) the triangle zigzag was applied on the paths, so that the distances between turn points are the same for case (c) the rectangle zigzag path. There are some spaces between the contact center and the edge of the sheet metal. In this study 20 mm is set.

Figure 3 shows the typical model used in this study. The metal sheet is modelled with shell elements, which are in square shape having the mesh size of 5 mm. The top and bottom rolls are modelled with square shell elements as well. Each element has a central angle less than 4.5°, so that the geometry detail of the rolls can be revealed accordingly. However, they are regarded as rigid. 0.15 has been set for the friction coefficient between the sheet metal and the rolls. The Finite Element Analysis was conducted with the commercial explicit code LS-DYNA.
3. Results and Discussion

Figure 4 shows that the effective plastic strain obtained on the final shape of a DC04 sheet in thickness of 1 mm out of the sawtooth zigzag path impressed by the English wheel having the bottom roll in 25 mm of radius with an impression of 0.5 mm. It can be observed that the part is crowned and the area having a significant plastic strain conforms to the process path. However, not on all the surface covered by the rolls a significant plastic strain has been achieved. It seems that the process has a dominant effect on the areas around the turning points, while a less effect is acted on the middle of the path between the turning points. The inhomogeneous plastic strain distribution might cause the fluctuation shown in figure 5, which shows the curvature radius profile on the sliced cross-sections defined in figure 6 and calculated according to Modified Least Square Method [7] for every 25 mm or every 5 elements along the cross-sections. It can be seen, that the radius along the cross-sections at the path middle point (Y = 239 mm) fluctuates not so much as those calculated at the turning points (Y = 4 mm and 438 mm). The average radius at the path middle point is 505 mm, while 921 mm and 727 mm are read for the turning points at 40 mm and 438 mm, respectively.

**Figure 4.** Effective plastic strain on the shaped sheet metal parts shaped with the sawtooth zigzag path.

**Figure 5.** Calculated curvature radius along the cross-sections sliced perpendicular to the process path.

**Figure 6.** Position of the sliced cross-sections defined for the curvature radius calculation.

**Figure 7** Reaction force on the sheet metal in the thickness direction (impression force) and on the panel (shifting force) under the sawtooth zigzag path.

The reaction force on the metal sheet can be regarded as the force needed for the process as shown in figure 7, in which the relative movement of a reference point on the metal sheet to the rolls shown at the bottom area of figure 7 is used as reference to indicate the state of the process. There are two kinds of reaction forces, the impression force and the shifting force. The impression force comes in the thickness direction of the metal sheet and is reacted to the both rolls because of the impression of the
bottom roll into the sheet metal. The shifting force is formed on the sheet panel by pushing (positive shifting force) or pulling (negative shifting force) the metal sheet to build up the process path. Peaks of the reaction forces can be observed at the turning points of the process path. It might be caused by the acceleration and the deceleration during shifting and rotating the metal sheet around the turning points. Currently, the shifting velocity is set at 5,000 mm/s and the rotating speed is set at 131 rad/s to reduce the process (computing) time.

Similar results can be found in the other processes under the above mentioned parameter settings. For example, figure 8 shows that the effective plastic strain on the sheet parts shaped with the triangle zigzag path, while that with the rectangle zigzag path is shown in figure 9. The area covered with the significant plastic strains conforms to the process path again. Both of the shaped sheet metal parts are flatter than that shaped by the sawtooth zigzag path as shown in figure 4. It can be attributed that the area covered by the significant plastic strains are smaller and sparser.

**Figure 8.** Effective plastic strain on the sheet metal part shaped with the triangle zigzag path.  
**Figure 9.** Effective plastic strain on the sheet metal part shaped with the rectangle zigzag path.

Figure 10 shows the curvature radius calculated from the sliced cross-sections perpendicular to the process path with the above mentioned parameter settings. Some results from three zigzag process paths have been shown in Figure 4 to 9. However, regarding the curvature radius, the most densely covered sawtooth path has the smallest radius than the sparsely covered triangle and rectangle paths.

**Figure 10.** Calculated curvature radius on the sliced cross-sections of the sheet metal parts shaped with different parameter settings.  
**Figure 11.** Effective plastic strain on the sheet metal part shaped by an impression in one quarter of the thickness.

A further process setting without replacing the tools or the sheet metal is to reduce the impression of the bottom roll to a quarter of the sheet thickness, which is shown in dashed blue line with the legend “I25%” in Figure 10 and has the largest curvature radius of all shaped sheet metal parts. Figure 11 shows this shaped sheet metal part fringed with the plastic strains in a scale just one tenth used in the other Figures. That means that only few plastic strain is carried out on the sheet metal part and thus a marginal curvature is brought on the part.
However, if a thicker metal sheet, such as 2 mm (with the legend “T2” in Figure 10), is shaped by the English wheel with the same parameter settings as before under an impression of a half of the thickness, the curvature radius brought into the shaped sheet metal is not smaller than that of 1 mm, even severe plastic strains are already covered onto the sheet part. That means that the plastic strain brought into the sheet metal might be a dominant but not the only one parameter on the curvature brought into the sheet metal part shaped by the English wheel. A thicker sheet metal might have some stiffer characteristics than a thinner sheet, so that a further curvature might not be easily brought into the thicker metal sheet.

If an aluminum alloy sheet A6061-T6 is shaped with an English wheel, only a remarkably small curvature radius onto the part can be achieved in comparison to the steel sheet DC04, as shown in Figure 10. Less plastic strain is carried out than on the steel sheet shaped with an impression of one quarter of the thickness as shown in Figure 11. Only few plastic strain is brought onto the aluminum alloy sheet can be attributed to that the aluminum alloy has a Young’s modulus only one third of steel. For a relative totally small amount of the strain impressed by the rolls, the elastic part of the strain is not negligible in comparison to its plastic part. Thus, for a certain total strain, the lower the Young’s modulus, the more the elastic part of the strain. The wrinkling shown on the side along the last process path might be caused by the numerical error from hourglass energy, which is no significant influence on the result regarding to the curvature of the shaped sheet part.

If the impression roll is switched with a roll having another radius like 100 mm or 200 mm instead of 50 mm, a larger curvature radius can be obtained on the steel sheet part, as shown in Figure 10 with the legends “R100” and “R200.” There is no significant difference on the curvature radius brought by these two rolls. The width of the stripes covered with the significant plastic strain along the process path is wider than that shaped with a roll having a diameter of 50 mm as shown in Figure 4. Nevertheless, the curvature radius of the shaped part is larger, even more area of the shaped sheet metal part covered with the significant plastic strain. This is the other evidence for the above mentioned statement, that the plastic strain achieved on the sheet metal might not be the only one parameter on the curvature shaped by the English wheel. It might be concluded that the sharper the indentation or the impression is, the smaller the curvature radius can be achieved.

4. Conclusion
This paper has preliminarily demonstrated the flexible cold sheet metal shaping process carried out by the English wheel, which is broadly used by craftsmen for making creative surfaces of the metal sheet, via Finite Element Analysis with an explicit code LS-DYNA. Study on the curvature of the shape metal part has been conducted in this paper by using different process parameter settings, such as the process path, the thickness, the material, the impression, and the geometry of the impression roll.

As a result, more curvature can be brought into the sheet metal part by using the sawtooth zigzag path than by using the triangle or rectangle zigzag path. The more impression applied to the metal sheet from the bottom roll, the more curvature can be carried out in the part. The smaller the diameter of the impression roll, the more curvature can be achieved as well. However, the thinner and the stiffer the sheet metal, the more curvature can be realized onto the shaped sheet metal part.

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