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Research Paper

A New Geometry Modification Algorithm for Blank Shape Optimization in the Deep Drawing Process

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Abstract

Deep drawing is a popular process in sheet metal forming. The goal of shape optimization of the initial blank which is considered in the present work is to find the shape of the blank in a manner in which after a deep drawing process the contour of the edges of the produced part meets a target contour. Such problems are highly nonlinear because the simulation consists of large deformation, plastic deformation, and contact. Therefore, the general approach to solving such problems is using iterative methods which are based on numerical simulation. Such an approach is also followed in the present work and a new algorithm for geometry modification of initial blank in each iteration is proposed. In the proposed algorithm, the normal distance between the final contour and target contour is used as a criterion to modify the initial blank. To evaluate the proposed algorithm a computer program is developed and to automatically execute the iterative process. One numerical example solved and the results are compared with those reported in the literature. One of the benefits of the proposed algorithm is its insensitivity to the initial guess. Therefore, to evaluate the effect of the initial guess on its performance the example was solved using different initial guesses. The results show that the proposed algorithm is robust regarding the initial guess and convergence to the optimum shape will be achieved by starting from an initial guess.

Keywords

Deep Drawing, Shape Optimization, Blank Optimization, Finite Element Method

1. Introduction

Deep Drawing is the most popular metal forming methods available to industrialists. The use of blanks with optimum geometries offers many advantages in deep drawings, such as reducing the production cost, improving the process quality, thickness distribution, and formability of the part, minimizing forming defects such as wrinkling and rupture and decreasing the number of trial and error steps in the product development process. In deep drawing, a flat blank of sheet metal is formed by the action of a punch forcing the blank into the die cavity. Often, the part of the blank that remains outside does not develop a favorable shape and should be recut. The second cutting process creates two main issues of increasing wastes and involving complexities that can raise the production cost. Therefore, production costs remain lower if additional cutting can be avoided or at least minimized. An optimum blank geometry can realize this objective. Blank optimization refers to selecting an initial blank geometry that develops the desired shape after deep drawing without or with minimal need for additional cutting. Regarding the time-consuming and costly nature of the trial and error-based blank optimization methods, researchers have attempted to use numerical approaches to designing an optimum blank. The numerical simulation of the sheet metal forming process is integral to the study of the feasibility of production by deep drawing and the initial design of a new part with complex three-dimensional geometry.

Among the various methods for optimizing the shape of the blank, iterative methods based on numerical simulation are more widespread. Because in these methods, complex geometries, large deformations, complex models of material behavior, complex models of friction, complex models of contact, dynamic behaviors, and others can be simulated with optimal accuracy. Of course, the disadvantage of iterative methods based on numerical simulation is that due to the nature of iterative methods, they include volumetric calculations. The development of efficient optimization algorithms can reduce the number of iteration steps and reduce the computational volume. Therefore, the main purpose of this paper is to propose a new and efficient optimization algorithm and its implementation along with a finite element numerical method to design the shape of the initial blank in the deep drawing process.

Among the first published reports on the application of iterative methods based on numerical simulation to optimize the shape of the blank in deep drawing, we can mention the reference [1] in which the finite element method is used for numerical simulation of the deep drawing process and a geometric correction algorithm Based on the flow pattern of the material used in it. The disadvantage of this method is that due to the nonlinear behavior of the deep drawing process, the flow pattern of the material is not a suitable reference for developing a geometric correction algorithm. Because when the initial guess is far from the optimal blank, the convergence of the method faces problems. In the references [2-3], the theory of ideal sheet formation has been used to develop a geometric correction algorithm. Although this method can be used in cases where the drawing depth and deformation of the sheet is small, in case of increasing the drawing depth and severe deformation in the sheet, it reduces the convergence rate. In reference [4], the relative initial velocity of the boundary nodes is used to develop a geometric correction algorithm. In paper [5], an algorithm called the push-pull method is proposed. In the reference [6], an algorithm based on the error between the final shape and the target shape is proposed to correct the location of the boundary nodes. One of the major problems that the algorithms mentioned above face is the inefficiency of the algorithm in cases where the initial guess is far from the optimal shape of the blank. In other words, the convergence of the algorithm becomes problematic if the initial guess is not close enough optimally. For example, in the reference [6] to deal with this problem, an innovative method has been used to determine the initial guess to enter the optimization algorithm. Such techniques are completely dependent on the problem being solved and their use reduces the generality of the method and its application in various problems.

As mentioned above, the most important problem of existing algorithms is their lack or reduction of convergence in the face of cases where the initial guess is far from the optimal answer. Therefore, the main purpose of the present study is to achieve an algorithm that can be used to answer the optimization problem starting from any initial guess. In the proposed method in the present paper, the vertical distance of the points located on the final contour to the target contour has been used as a criterion for developing the optimization algorithm. For numerical simulation of the deep drawing process, the finite element method and ABAQUS commercial software are used and the optimization algorithm is implemented using Python programming language. Finally, to evaluate the efficiency of the proposed method, two numerical examples are solved by considering different initial guesses and the results are compared with the results in the references.

2. Numerical simulation

In order to numerical simulate the deep drawing process in the present study, the finite element method and ABAQUS commercial software have been used. The die, punch, and blank holder are assumed to be rigid. Four-node elements of thin shells are used to simulate sheet deformation. The large deformations and the geometric nonlinear effects are considered. The contact constraint between all contact surfaces is defined and the Coulomb friction is applied through the penalty method. The behavior of the material is considered as plastic elastic without considering the strain rate and temperature effects. Before starting the optimization process, the appropriate number of elements is obtained by performing network analysis and investigating the effect of network coarseness on the sheet thickness change. Network analysis guidelines are available from a variety of the paper [7] and are not provided here to reduce the size of the article.

Shape optimization problems are classified as problems with variable amplitude and it is necessary to determine the geometric shape of the problem amplitude in the solution process. In such cases, an unknown boundary is often parametrized to search in a space with a limited number of dimensions. This is done by selecting several key points on the boundary and connecting them. In this case, the unknown boundary will be established when the coordinates of the key points are determined. In general, parameterization of the boundary is a technique that is used in most problems with variable amplitude and reduces the number of unknown variables, and simplifies the solution process. Regarding the parameterization of the boundary, as an example, we can refer to the references [8, 9]. In the present paper, the parameterization of the boundary is done by selecting several key points on the boundary and connecting them with the right segments.

3. An iterative method based on numerical simulation

Solving shape optimization problems begins with an iterative method based on numerical simulation by selecting an initial guess. Then, by performing a numerical simulation, the behavior of the model is measured and the geometric shape of the problem amplitude is modified accordingly. This process continues until the goal of the problem is achieved. In the present article, a similar path has been followed. First, an initial guess is made for the shape of the blank, which is called the initial contour here, and then the deep drawing is simulated using this initial guess and the shape of the final piece (final contour) is obtained. Obviously, at this stage, the final contour does not match the target contour. Therefore, by defining an error parameter, the degree of mismatch between the final contour and the target contour can be quantified. To continue the algorithm and move towards error reduction, it is necessary to modify the geometric shape of the initial contour and repeat the simulation of the deep drawing process. This is repeated in the same way to achieve convergence and reduce the error to a certain extent. The general flowchart of the optimization steps shown in Figure 1.

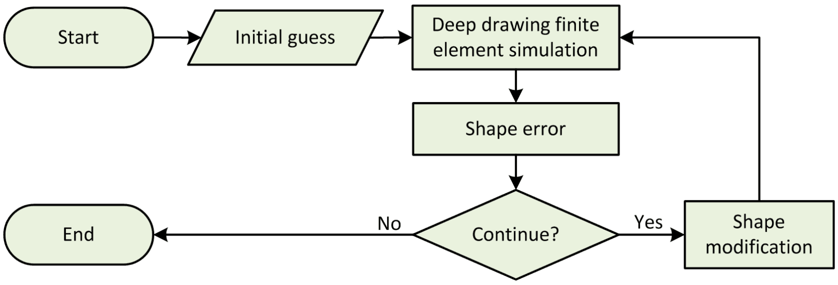

Figure 1. Flowchart of the shape optimization process

Figure 2 shows a schematic diagram of a part of the initial contour of the blank, the final contour, and the target contour. Also, in this figure, the key points are shown on the initial contour and the final contour. In general, the purpose of solving the optimization problem is to determine the initial location of the key points in such a way that after performing a deep drawing, the final contour matches the target contour.

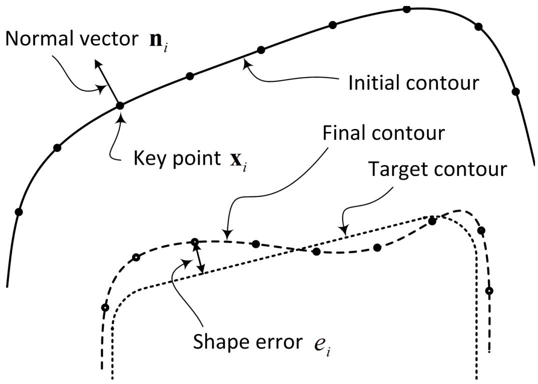

Figure 2. Schematic diagram of initial contour, final contour, target contour, key points, and shape error

Each iteration step starts from an initial contour and the deep drawing simulation is performed based on it and the final contour is obtained. Before the optimal shape is obtained, the final contour does not match the target contour and will be spaced from it. In this paper, the vertical distance between the key points on the final contour to the target contour is defined as the shape error. The shape error is expressed in the i^{th} key point and is schematically shown for a key point in Figure 2. A conventional algebraic sign is also considered for shape error. If the final position of a key point is outside the target contour, its error will be positive and if the key point is inside the target contour, its error will be considered negative.

4. Geometry modification algorithm

The most important part of the flowchart shown in Figure 1 is the part where the location of the key points is corrected in each iteration step. The main innovation of this paper is to present a new algorithm for correcting the location of key points, which is described below.

As shown in Figure 2, x_i it represents the coordinates of the i[th] key point on the initial contour and e_i the magnitude of the shape error at this point after the deep drawing simulation is completed. In other words, it represents the vertical distance between the final contour and the target contour at the key point i (Figure 2). As previously stated, a positive value e_i indicates the amount of sheet that is located outside the target contour after the deep drawing. Therefore, it is necessary to reduce the area of the blank at this point to reduce the error. If $\widetilde{x_i}$ indicates the modified coordinates of the key point i, Equation (1) is suggested to correct the location of the key points.

$$\widetilde{x_i} = x_i - \xi e_i n_i \tag{1}$$

In this equation, n_i is the unit vector perpendicular to the initial contour (Figure 2). Since the deep drawing has a highly nonlinear behavior due to very large deformations and the plastic behavior of the material, it is necessary to use the coefficient in the key point correction to prevent non-convergence or oscillating behavior of the problem. This coefficient is shown in Equation (1) to ξ .

5. Numerical Example

To evaluate the efficiency of the proposed method, a numerical example is solved and the results are compared with the results in the references. Figure 3 displays all geometric details and dimensions (in millimeters) of the tools[6]. The depth of drawing was considered 20 mm and a 9800 N blank holder force was applied, which remained constant throughout the process. The target contour is considered such that a 2 mm uniform flange was formed all around the part. The thickness of the sheet is 0.85 mm and its mechanical behavior is considered plastic elastic. To express the strain stress relationship in the plastic region, an exponential relationship as shown in Equation (2) has been used.

$$\sigma_p = k(\varepsilon_0 + \epsilon_p)^n \tag{2}$$

where ϵ_p and σ_p represent the plastic strain and stress, respectively. The die, punch, and plate holder was modeled as rigid parts. The only deformable part was the plate and the four-node shell elements were used to simulate the sheet metal forming process. The elastic properties and coefficients expressed in Equation (2) are given in Table 1 [6]. Table 2 reports the coefficients of friction between contacting surfaces [6].

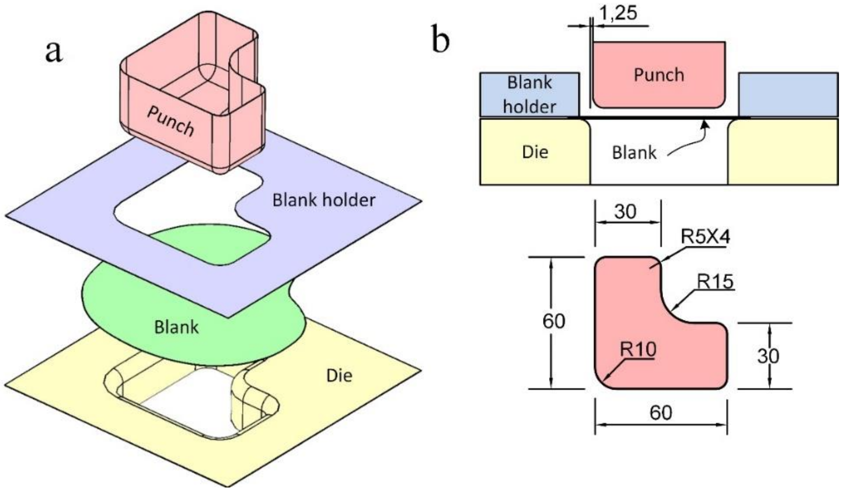

Figure 3. a. Sheet metal forming tools assembly; b. Dimensions of the tools

Table 1. Mechanical properties of the blank [6]

Parameter	Symbol	Value
Young modulus	E	200 GPa
Poisson ratio	ν	0.3
Stress constant	k	514 MPa
Strain constant	ϵ_0	0.001
Strain exponent	n	0.2
Elastic limit	S_y	129.11 Pa

Table 2. Coefficients of friction between contacting surfaces [6]

Contacting surfaces	Coefficients of friction
Blank and punch	0.24
Blank and die	0.12
Blank and plate holder	0.12

To solve the optimization problem, the proposed algorithm is developed in ABAQUS software with Python programming language and the problem is solved for the initial three guesses of the blank in the form of a hexagon, circle, and square. The selection of three initial guesses has been done to evaluate the efficiency of the proposed method starting from different initial guesses. In all cases, the following coefficient of ξ is considered equal to 0.6 [6]. The die, blank holder, and punch are rigidly modeled and sheet with shell elements. The average size of the shell elements is 2.5 mm. The criterion for stopping the algorithm to reach the maximum shape error is less than 0.5 mm. In all cases, to achieve an acceptable error, it was observed that the minimum number of repetitions required to achieve the optimal answer is equal to four iterations.

As stated, the problem is solved for three different initial guesses. In the first guess, a regular hexagon was chosen. Figure 4(a) shows the initial selective guess and the target contour. The initial guess must be larger than the target contour. Here it was deliberately tried to distance the initial guess far from the optimal form to measure the efficiency of the algorithm. This figure shows the key points and the deformed shape of the sheet along with the material flow paths. As can be seen, since the initial guess is far from the optimal shape, the deformed shape is also significantly different from the target contour. Figure 4(b) shows the element grid used on the three-dimensional shape of the deformed sheet. The large distance of the deformed sheet from the target piece is also evident in this figure.

Figure 5(a) shows how to change the shape of the blank from the initial guess to the optimal shape in different stages. As can be seen in this figure, the convergence has been achieved in four stages of iteration and the implementation of the algorithm has been completed in this stage. At this stage, the maximum of the shape error is 0.45 mm and the average shape error among all key points is 0.11 mm. Figure 5(b) shows the shape of the deformed sheet in different iteration steps. As can be seen in this figure, the shape of the deformed sheet for the initial guess is significantly different from the target contour, but as the iteration steps progress, it quickly approaches the target contour. In other words, the proposed algorithm is optimized in only four iteration steps. The small number of iteration steps is one of the advantages of the proposed method because the small number of iteration steps indicates the low computational volume of this method and its high efficiency. In Figure 6(a), the optimal blank shape obtained from the proposed algorithm in the present paper is compared with the optimal blank shape presented in reference [6]. As can be seen in this figure, the blank obtained from the present work is very close to the shape presented in the reference. Figure 6(b) also shows the element grid on the deformed sheet.

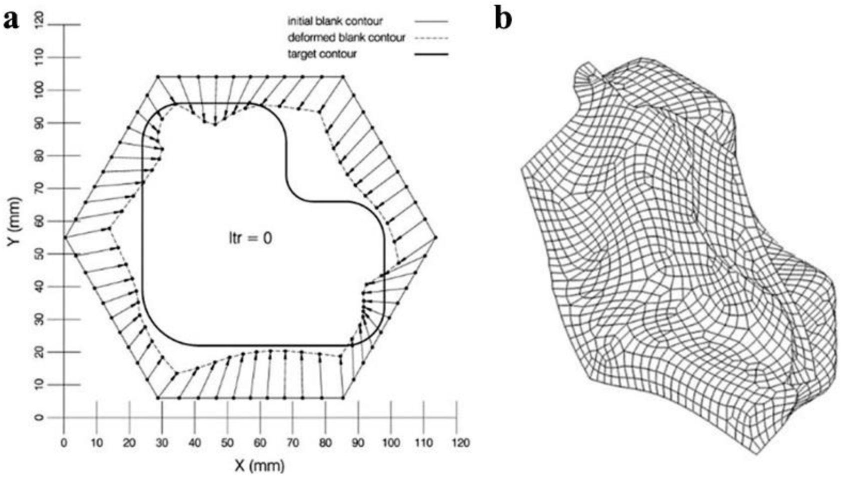

Figure 4. The initial guess of a regular hexagon; a. Initial guess, deformed shape, key points, target contour, and material flow paths; b. The element grid on the three-dimensional shape of the deformed sheet

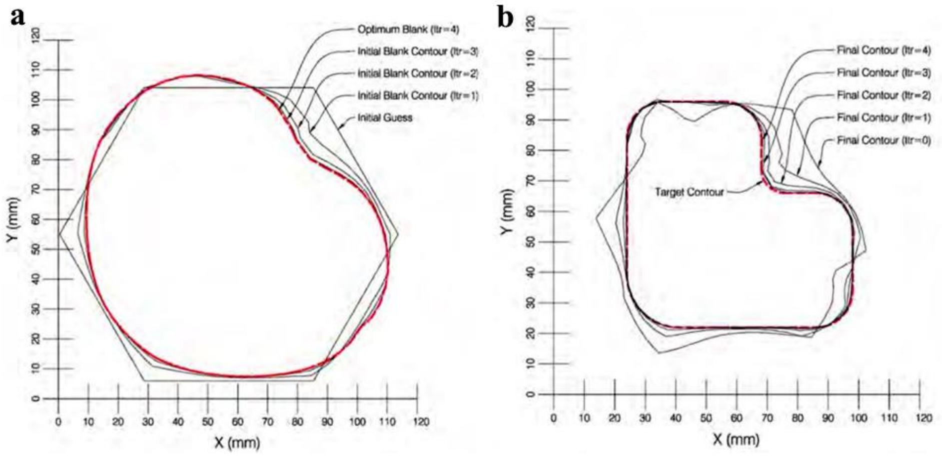

Figure 5. The initial guess of a regular hexagon; a. Blank shape in different iteration stages; b. The final shape of the deformed piece in different stages of iteration with the target contour

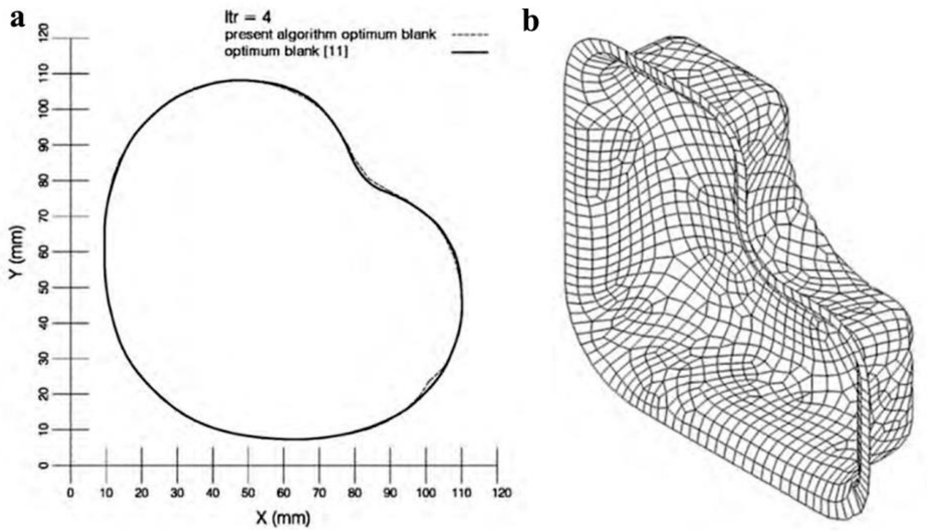

Figure 6. The initial guess of a regular hexagon; a. Comparison of the optimal blank shape obtained from the proposed method and the optimal shape presented in the source [6]; b. The three-dimensional shape of the deformed sheet using the optimal blank obtained from the proposed method

The second selected initial guess is considered to be a circle. Figure 7(a) shows the shape of the blank in different stages of iteration starting from the initial guess of the circular shape. As shown in this figure, in this case, the number of iteration steps is equal to four steps. Figure 7(b) shows the deformed sheet with the target contour for all four repetition steps. In this figure, it can be seen that due to the distance of the initial guess from the optimal shape, the deformed sheet is at a far distance from the target contour. As the iteration steps progress, after four steps, the shape of the deformed sheet is matched to the target contour.

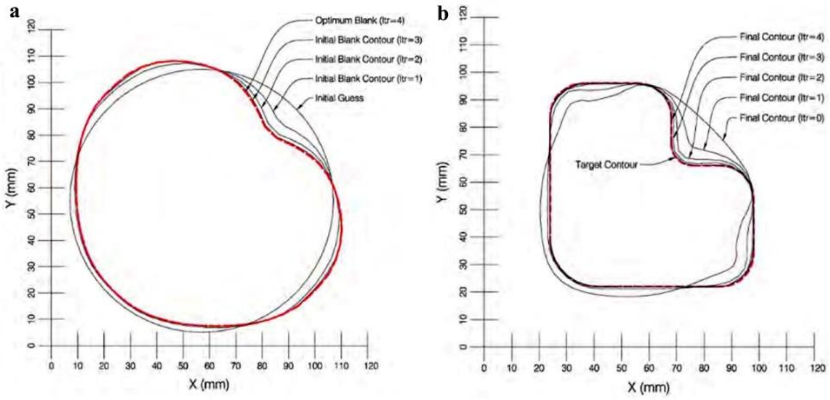

Figure 7. The initial guess of circular shape; a. blank shape in different iteration stages; b. The final shape of the deformed piece in different stages of iteration with the target contour

A square has been selected as the third initial guess. Figure 8(a) shows the initial square guess of the shape and the blank at different stages of iteration. Here, to evaluate the efficiency of the proposed method, the initial guess is chosen so that it has a considerable distance from the optimal form. In this case, five iteration steps have been performed to achieve the optimal form and to satisfy the stopping criterion. Figure 8(b) shows the deformed sheet with the target contour for all five iteration steps. In this figure, it can be seen that due to the distance of the initial guess from the optimal shape, the deformed sheet is at a distance from the target contour. As the iteration steps progress, after five steps, the shape of the deformed sheet is matched to the target contour.

To investigate the effect of the initial guess on the final optimal shape obtained by the proposed algorithm and described above, all three of the above optimal shapes are plotted on a graph. This diagram is shown in Figure 9. As can be seen in this figure, the choice of different and far initial guesses has little effect on the final optimal shape, and all three resulting shapes are consistent. In other words, this figure indicates the capability of the proposed method to the initial guess.

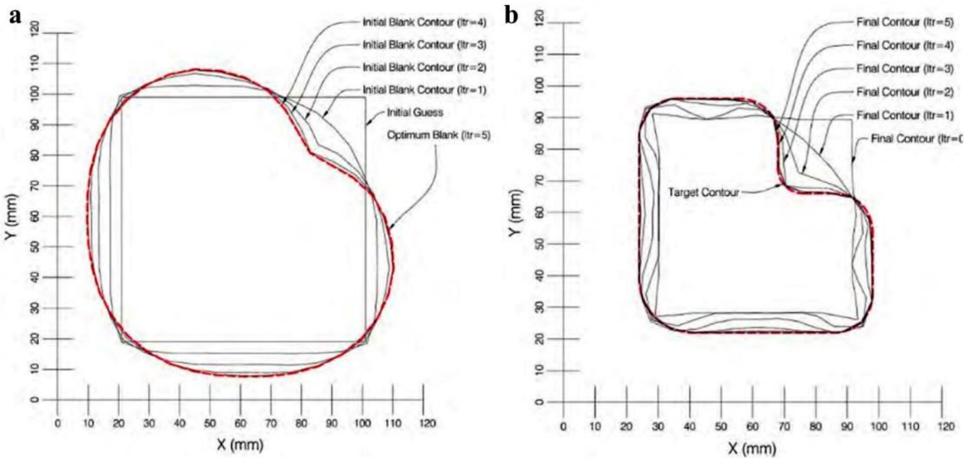

Figure 8: The initial guess of square shape; a. blank shape in different iteration stages; b. The final shape of the deformed piece in different stages of iteration with the target contour

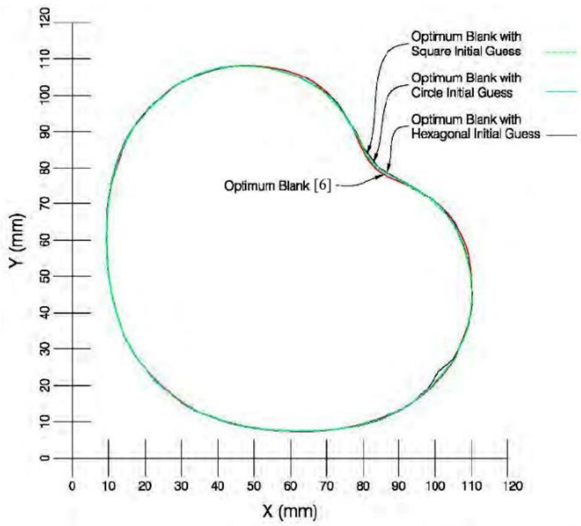

Figure 9: Comparison of the optimal shape of the blank using three different initial guesses

6. Conclusions

In the present study, a new algorithm is proposed to optimize the shape of the blank in the deep drawing process. This paper aims to find an algorithm that can be used to answer the problem of optimizing the shape of the blank in the deep drawing process starting from any initial guess. In the proposed algorithm, the shape of the blank is expressed by several key points, and starting from an initial guess and modification is achieved in an iterative process of optimal shape. In this algorithm, the location of key points is modified according to the value of the vertical distance of these points from the target contour, in the direction of the line perpendicular to the transient line from one point before and one point after the key point. This process continues until the stop criterion is met. Finally, to evaluate the efficiency of the proposed method, a sample problem is solved and the results are compared with the results in the references. This problem is solved with three different initial guesses and the performance of the proposed algorithm in the face of initial guesses not close to the optimal solution is evaluated. In the present study, it was seen that by using the proposed method, while reducing the number of iteration steps, the initial guess away from the optimal form can also be used.

7. References

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