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OPTIMIZITATION OF THE PRESSURE PATH IN SHEET METAL HYDROFORMING

Asghar SHAMSI-SARBAND [1], Sayyed Abolfazl ZAHEDI [2], Mohammad BAKHSHI-JOUYBARI [3],
Seyed Jamal HOSSINIPOUR [4], Dorel BANABIC [5]

[1] Babol University of Technology, Iran
[2] Loughborough University, UK
[3] Babol University of Technology, Iran
[4] Babol University of Technology, Iran
[5] Cluj-NapocaTechnical University, Romania
E-mail: banabic@tcm.utcluj.ro

Fluid pressure is the most important parameter in hydroforming deep drawing process. In this manuscript, we present the results obtained from FE modelling using genetic algorithm to determine the optimum fluid pressure for the production of a two-stepped workpiece in the deep drawing hydroforming process. It is suggested that a two-stepped workpiece can be manufactured in a single step which is a significant advantage compared to conventional sheet forming processes. It is also shown that the lowest pressure point in the optimization curve occurs at the step height, which has the potential to allow for a more accurate pressure path selection procedure at shorter times while reducing the number of trials.

Key words: hydroforming, optimization, pressure path, genetic algorithm, FE simulation.

1. INTRODUCTION

Sheet hydroforming is one of the metal forming processes used in industry to produce complex shapes with high limiting drawing ratio. In recent years, increasing attention has been focused on hydroforming technology due to the rapid development of automobile production and the aerospace industry [1]. Many methods of sheet hydroforming have been proposed to meet practical and theoretical applications, such as hydromechanical deep drawing [2], hydrodynamic deep drawing [3], aquadraw process [4], and hydroforming deep drawing [5].

In the hydroforming deep drawing process (HDD) which is shown in Fig. 1, the tool device is similar to a conventional tool but the die is replaced by a pressure container filled with a high pressure fluid. At the start of the process the blank is placed on top of the die. The blank holder is then lowered so that a gap of specified distance is maintained between the blank holder and the die. As the fluid pressure is increased, the blank is raised and clamped against the blank holder. During the downward movement of the punch by the press ram, the blank is drawn into the pressure container. The major difference between this process and the similar sheet hydroforming processes is the use of a diaphragm which leads to the separation of the fluid from the sheet and a uniform pressure distribution on the sheet surface. Some of the advantages of this process are higher drawing ratio, better surface quality, and greater dimensional accuracy, and formability of complex parts [6]. In the papers [7, 8] and [9] are reported some results concerning the advantages of the bulge test comparative with the deep drawing using solid punch.

Despite all the advantages of HDD over conventional methods, there are many challenges that must be addressed. For example, the forming limit of sheet metal must be maximized; the capacity of local deformation has to be improved. Moreover, the press costs associated with higher productivity, automation and the rate of changing of the dies must be maintained at minimum. Pressure path is the most important parameter for increasing the drawing ratio in HDD. Finding the appropriate fluid pressure-punch stroke path while avoiding rupture and wrinkling instabilities is a critical and difficult step. Low pressure results in wrinkling of the part and excessive pressure will tear the workpiece [10]. Optimization of this path has a direct effect on the quality of the manufactured part. Many researchers have worked on optimization in tube hydroforming process. Imaninejad et al. [11] used LS-DYNA and the optimization software LS OPT to optimize the internal pressure and axial feed of a T-joint design. They have shown that higher bulge height occurs by utilization of optimized loading paths. Fann and Hsiao [12] developed an optimization approach based on the conjugate gradient method utilizing FE simulations. The above code was utilized to optimize the loading trajectory of a T-shape process based on batch mode and sequential mode. Strano et al. [13] and Aue- U-Lan et al. [14] obtained the optimal loading path as a result of one single simulation by using an adaptive simulation approach. In their method, the loading path was adjusted sequentially by detecting the occurrence of tube wrinkling. In sheet hydroforming processes, Choi et al. [15] used the FEA technique coupled with a fuzzy control algorithm for optimization of the proper profiles of the hydraulic pressure and the blank holder force under warm hydroforming conditions at different punch speeds.

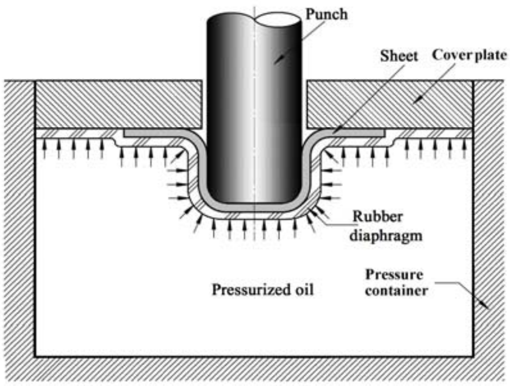

Fig 1 – Hydroforming deep drawing process (HDD) [5].

Genetic algorithm as an optimization approach has also attracted the attention of many researchers [16]. In this method, each optimization starts with a randomly generated population of individuals. These individuals form a generation which then enters into one loop. This process is repeated for all generations. The important step is to evaluate the objective value (i.e., performance) of each individual and assign a fitness ranking that will drive the selection process. Evaluation of the objective value is typically the most time-consuming step of the genetic algorithm procedure as it involves multiple simulations (one for each individual). By repeating this algorithmic process, stronger individuals are identified and then the design variable approach is used to achieve the optimum state [17].

The reports on the application of genetic algorithm in HDD processes are scarce. The main advantage of genetic algorithm in HDD is that it could calculate the optimum pressure path. Once this is determined, many complex shapes can be manufactured in a simple single step. A two-stepped workpiece is considered to be a good example of a complex shape which cannot be manufactured in a single step in conventional sheet forming processes. In this article, it is proposed that a two-stepped workpiece can be produced in one step by using genetic algorithm based on FE simulation. The genetic algorithm is used to optimize the pressure path in HDD process and to calculate the optimum pressure. The algorithm is written in the PYTHON language using ABAQUS software.

2. RESEARCH METHOD

2.1. Simulation

FE simulation of the HDD process was performed by using ABAQUS 6.11. The process involved three main parts: a circular blank, blank holder and the punch. The diameter and the thickness of the blank were given as 80 and 1.5 mm, respectively, while the aluminum was selected as blank material. The mechanical properties of blank are given in Table 1. The dimensions of the punch and blank holder are given in Fig. 2a.

In the simulation, the tools (punch and blank holder) were considered as rigid, while the sheet was deformable. The S4R element was chosen for the sheet model and R3D4 for rigid parts. In order to include the effect of wrinkling, the simulation model was performed in the form of a 30° sector (Fig. 2b). To model the fluid pressure, an extended load under the sheet was used. A pressure-time curve comprising of 4 segments was selected. Fig. 3 shows the pressure path that was used in the simulation procedure. It must be noted that Hollomon hardening law and Hill'48 yield criterion were employed in simulation.

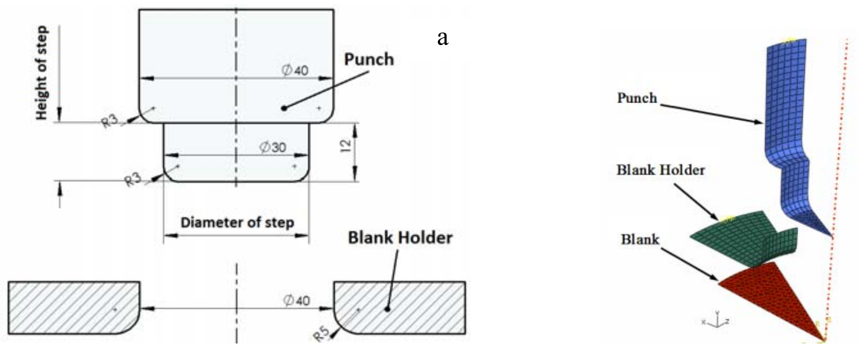

Fig. 2 – a) Dimensions of the punch and blank holder; b) finite element model.

Table 1

Mechanical properties of aluminum sheet [5]

Yield Strength	Ultimate Tensile Strength	Strength Coefficient	Strain Hardening Exponent
25 MPa	80 MPa	180 MPa	0.2

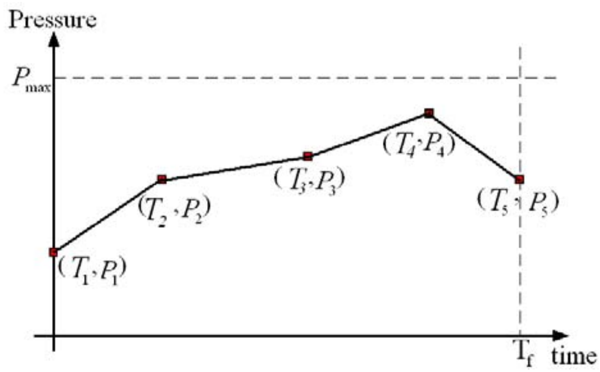

Fig. 3 – Pressure time path.

The pressure-time curve is characterized as regular double pairs, as shown in Eq.1

$$\text{Pressure-time curve} = \{(T_1,P_1),(T_2,P_2),(T_3,P_3),(T_4,P_4),(T_5,P_5)\}, \quad (1)$$

were replaced by T_3 according to the following equation

$$T_2 = T_3/2 \ ; \quad T_4 = (T_3 + T_5)/2 . \quad (2)$$

2.2. Genetic algorithm

2.2.1. *Chromosomes coding*

In this research, each generation includes 20 chromosomes; each chromosome has 6 variables, with 5 variables representing the pressure path and 1 variable representing the time corresponding to median pressure during the process. Eqs. (3) specifies the coding formalism.

$$\begin{aligned} &\text{Pop} = \{c_1, c_2, ...c_i, ..., c_{20}\} \quad ; \quad c_i = \left[p_{1,i}, p_{2,i}, p_{3,i}, p_{4,i}, p_{5,i}, t_i\right] \\ &i = (1, ..., 20) \quad ; \quad j = (1, ..., 5) \quad ; \quad 0 \le p_{i,j} \le 1 \quad ; \quad 0 \le t_i \le 1. \end{aligned} \tag{3}$$

In the aforementioned relation, Pop, c, j, i, and $p_{i,j}$ indicate the random population, chromosome, number of the chromosomes, variables counters and dimensionless pressure values, respectively. The variable t_i is the time of the $p_{3,i}$. For calculating the pressure path, coherent numbers of dimensionless pressure were multiplied in maximum pressure (in this paper 50 MPa), and dimensionless time was multiplied in whole time (T_f) as shown in Eqs. (4).

$$p_{i,j} = \frac{P_{i,j}}{P_{\max}} \; ; \; t_i = \frac{T_i}{T_f} \; ; \; f = (1, ..., 5). \tag{4}$$

By considering Eqs. (1–2), the pressure-time curve is obtained, as follows:

$$\text{pressure-time curve} = \left\{(0, P_{1,i}), (T_i/2, P_{2,i}), (T_i, P_{2,i}), \left[(T_i + T_f)/2, P_{4,i}\right], (T_f, P_{5,i})\right\}. \tag{5}$$

Since the velocity of the forming process was a chosen to be constant, the pressure-punch stroke curve is obtained as follows:

$$\text{pressure-punch stroke curve} = \left\{(0, P_{1,i}), (X_i/2, P_{2,i}), \left[(X_i + X_f)/2, P_{4,i}\right], (X_f, P_{5,i})\right\}. \tag{6}$$

2.2.2. *Fitness function*

In sheet forming processes, the main parameters which show the final quality of the workpiece are minimum thickness and final form of the part. For the thickness parameter the relation $S_{\min}/S_0$ has been used where S_0 and $S_{\min}$ are initial and minimum sheet thickness, respectively. To convert the workpiece shape parameter to a mathematical relation, the C_{Area}/C_{Area0} was used, where C_{Area} indicates the contact surface between the sheet and the punch at the end of the process and C_{Area0} is the initial area of the sheet. Eq. (7) shows the fitness function which is the linear combination of the aforementioned two parameters. Weight coefficients W_1 and W_2 are determined with respect to the required quality of the workpiece.

$$f(c_i) = S_{\min,i}/S_0 \times W_1 + C_{Area\ i}/C_{Area\ 0} \times W_2. \tag{7}$$

The objective is for the fitness function to equal the summation of W_1 and W_2. As the thickness parameter has a greater influence in comparison with the contact surface, the values of W_1 and W_2 are chosen to be 1.5 and 1, respectively.

2.2.3. *Selection*

The selection operator determines which of the current generation chromosomes are allowed to transfer their genetic characteristic to the next generation. The selection rule in this research is the Roulette Wheel Selection (RWS) [18].

2.2.4. *Crossover*

By using the following relations two new chromosomes ware made where a and b are random integer numbers between 1 and 5 and the cross over operator is applied on the 80% chromosomes of these two chromosomes. R is a random number between 0 and 1. For the states when the calculated values are more than 1 or less than 0 the values of 1 and 0 are replaced, respectively [19].

$$\begin{cases} p_j^{child\ 1} = \left(p_j^{parent\ i} + p_j^{parent\ 2}\right)/2 + \left|p_j^{parent\ i} + p_j^{parent\ 2}\right| \times R \\ p_j^{child\ 2} = \left(p_j^{parent\ i} + p_j^{parent\ 2}\right)/2 + \left|p_j^{parent\ i} + p_j^{parent\ 2}\right| \times R \end{cases} \; ; \; j = (a, ..., b). \tag{8}$$

2.2.5. *Mutation*

The mutation operator allows the genes that did not have the chance to be present at the primary population to enter the generation. In this work, the mutation is selected 5% and is applied using the following equation, on genes chosen randomly

$$\dot{p}_{j,i} = \left(P_{j,i} + R\right)/2. \tag{9}$$

The aforementioned operators (i.e., production of new generation) simulation and calculation of the fitness function, crossover, mutation and finally production of the next generation, are all performed in the ABAQUS software. The algorithm was run until a threshold of 200 generations. The PYTHON programming language was used to implement the genetic algorithm. Fig. 4 shows the flow chart of the optimization procedure.

3. RESULTS AND DISCUSSION

3.1. Simulation verification

Fig. 5 illustrates the force-punch stroke curve that resulted from the FE simulation and experimental results for the two drawing ratios of β = 2 and β = 2.43 reported by Kandil [5]. As shown in the graph, in order to verify these results, they were compared with the two specific experimental results reported by Kandil [5], namely, aluminum cups with diameters of 70 and 85 mm (i.e. drawing ratios of β = 2 and β = 2.43) and 1.5 mm in thickness [5].The trends demonstrated in the simulation and experimental results indicated acceptable conformity.

3.2. Optimization results

The variations in the fitness function with respect to the number of generations for a step height (h) of 12 mm are shown in Fig. 6a while the optimum pressure path for this step height is depicted in Fig. 6b. The selected values of W_1 and W_2 allowed for the determination of the maximum possible value for the fitness function which calculated as 2.5 (the sum of W_1 and W_2). However, since the thickness decreased in the process and the involved area between the punch and sheet was less than the initial area, the fitness function value never reached 2.5.

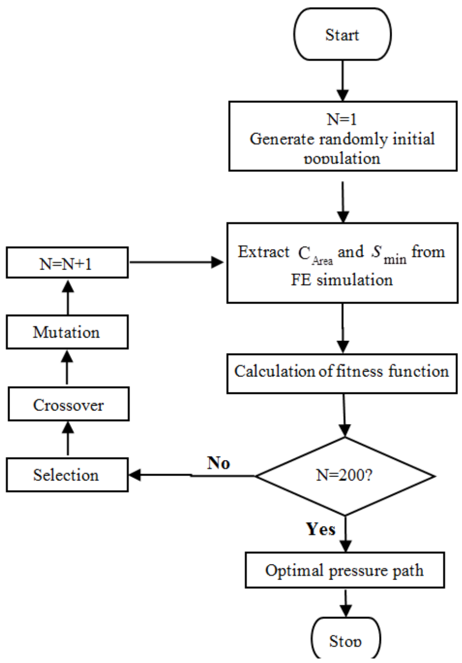

Fig. 4 – Flow chart of the optimization procedure.

As illustrated in Fig. 6b, the pressure-punch stroke curve shows an initial pressure of 12 MPa (point A) that generates a pre-bulging in the part. This phenomenon has been shown to have a positive effect on the drawing process [11] resulting in a better material flow. After the pre-bulging step, the pressure remains constant until point B in $X_i/2$ (Eq. 7). From B to C (X_i), the pressure drops gradually until the drawing depth is almost equal to the first step height. At this point (X_i) the lowest pressure is registered. Changing the pressure at this step has significant effect on the workpiece quality as higher pressure would cause tearing in the workpiece. At the end of the process, point C to D ($X_i + X_f/2$) and D to E (X_f), pressure increases significantly so that the contact between the sheet and the punch reaches a maximum. Finite element simulation of the process is shown in the Fig. 7.

In order to investigate the effect of decreasing pressure from B to C, a pressure path was selected in which there was no change in pressure from B to C (Fig. 8a). This pressure path is shown as path 1. Sheet thickness distributions of two different pressure paths showed that path 1 resulted in more variations in thickness. This confirmed that original decrease in the pressure from B to C yielded a better distribution as shown in Fig. 8b.

Optimized pressure curves obtained from genetic algorithm for the step heights (*h*) of 8, 12 and 16 mm are shown in Fig. 9(a). As shown in the figure, the initial pre-bulging pressure is the same for different step heights. A significant feature in all three samples is that the lowest pressure point in the optimization curve occurs at the step height. This could have significant implication in the HDD process as it would map out a more accurate pressure path selection procedure at shorter times while reducing the number of trials.

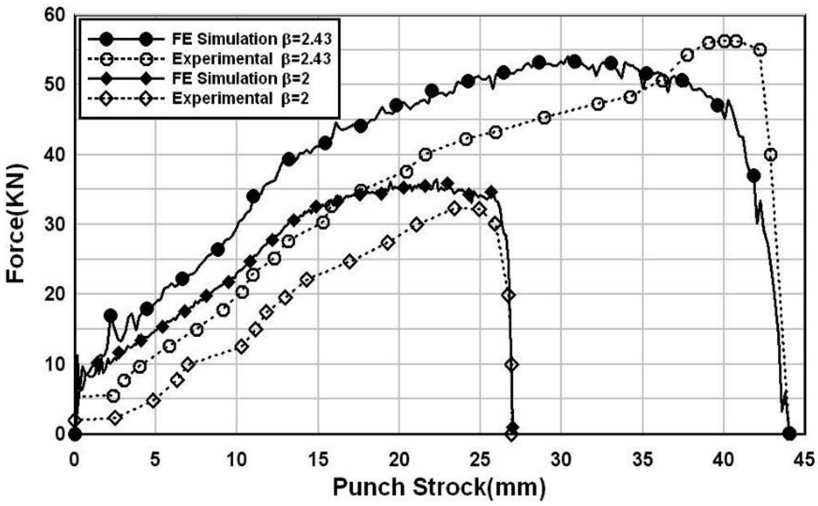

Fig 5 – Force- punch stroke curves obtained from simulation and those of experiments [5].

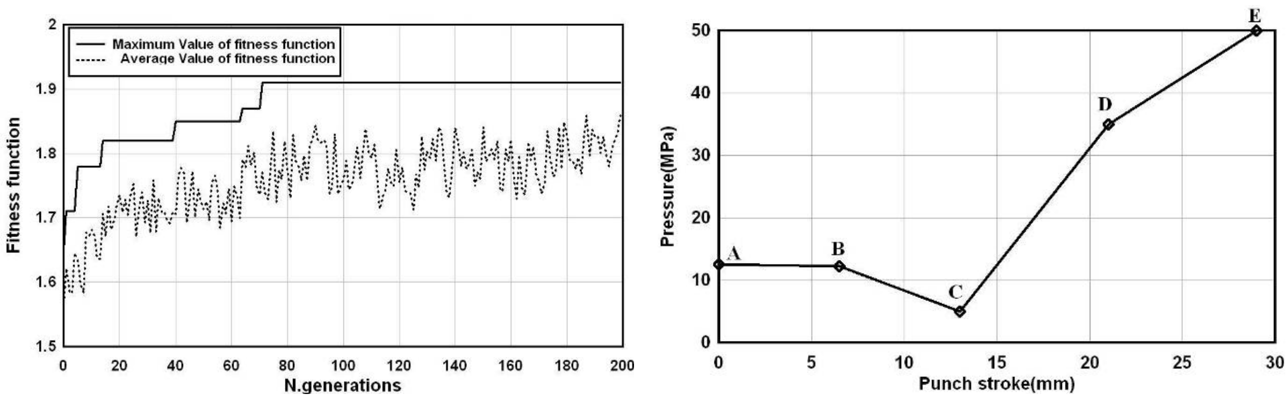

Fig 6 – a) Value of fitness function; b) optimum pressure path obtained by genetic algorithm.

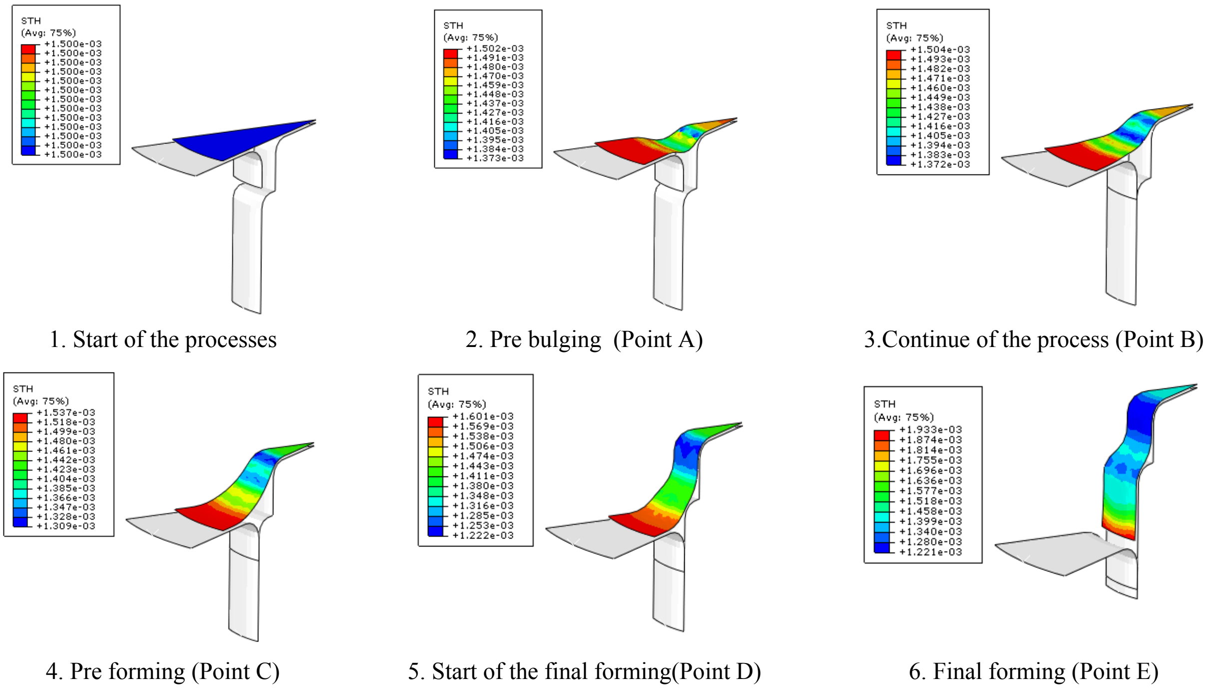

Fig 7 – Simulation of the workpiece in hydroforming process in ABAQUS software

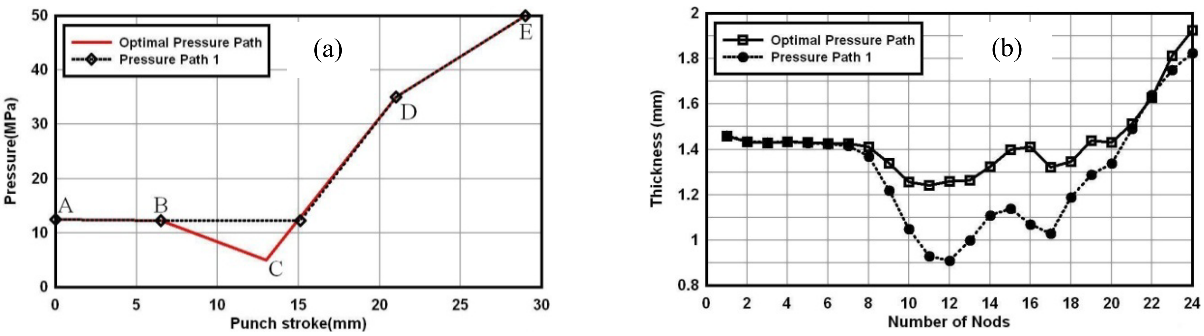

Fig. 8 – a) Pressure path 1; b) sheet thickness distribution.

Another important aspect of the optimized pressure path obtained in this work is to assign a maximum value to the step height that can be used in HDD process of a two-step workpiece. This can be best explained by the fitness function and its variations with changing step height. The variations in fitness function with respect to step height are shown in Fig. 9b. It is clear that by increasing the step height of the punch, the fitness function decreases. In other words, increasing the step height reduces the forming accuracy. These findings identifies that one of the limiting factors in the production of a two-step workpiece by HDD is the step height of the punch.

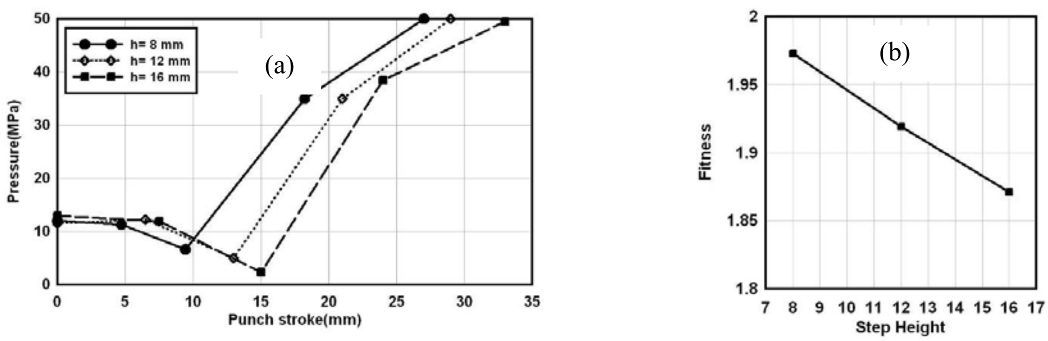

Fig. 9 – a) Optimized pressure curves obtained from genetic algorithm at different step heights of the punch; b) variations of the fitness function *versus* step height.

In addition to the effect on step height in the optimization process, the effect of step diameter was also investigated. Fig. 10a shows the diagram of optimization pressure for different diameters of step. As it clearly shows, while initial pressures are different at different step diameters, the minimum optimum pressure does not change drastically by varying the step diameter.

The variations in fitness function with respect to step diameter are shown in Fig. 10b. Increasing the step diameter increased the fitness function hence the forming accuracy. This suggests that higher step heights can be used if larger step diameters are employed. Further work is required to examine the different punch height/diameter ratios under optimized corresponding pressure paths.

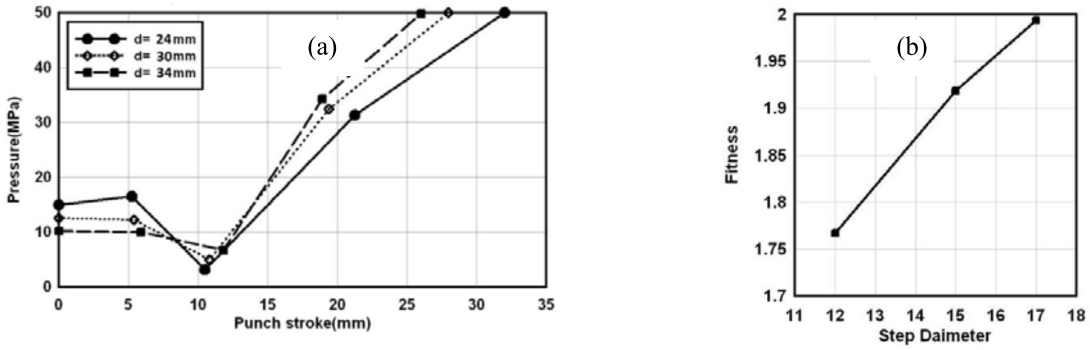

Fig. 10 – a) Optimization curve result by genetic algorithm in different diameter of the punch; b) variations of fitness function with respect to step diameter.

4. CONCLUSION

Identification of optimum pressure path in HDD processes is a crucial factor. Genetic algorithm is a promising method to calculate this pressure. By using FE modeling it is suggested that a two-stepped workpiece can be manufactured in a single step which is a significant advantage compared to conventional sheet forming processes.

An optimized pressure path for forming the two-stepped workpiece have the following three main characteristics phases: Primary pressure, decreasing pressure, and increasing pressure. The application of a pressure path increases the possibility of producing a proper and accurate two-stepped workpiece in sheet hydroforming. This can be achieved by determining the geometry of the punch as the optimum pressure is obtained at the step height. This has the potential to determine a more accurate pressure path selection procedure at shorter times while reducing the number of trials.

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