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ORIGINAL ARTICLE

Optimization of springback in L-bending process using a coupled Abaqus/Python algorithm

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Abstract Sheet metal L-bending processes are widely used for mass production. The design of L-bending processes is connected with time-consuming and costly experiments. Therefore, the finite element simulation of the process could be a helpful tool for the designer and quality assurance of the products. In L-bending process, springback is an important phenomenon, and its accurate prediction is important to control the final shape of the workpiece when the punch is removed. In this study, an optimization algorithm using Gauss–Newton method was developed by coupling the Abaqus/standard code and Python script which is an object-oriented language. For a given bending process problem, the proposed algorithm allows for the optimization of a set of material and/or process factors in order to minimize the workpiece springback. Python scripts allow the direct parameterization of the design variables to be optimized in the finite element input file, and hence an easy use of the procedure within the framework of industrial application. An example is presented in order to optimize three process parameters, namely, die corner radius, punch–die clearance, and the blank holder force. The results demonstrate the reliability of the proposed approach and the fast convergence of the algorithm.

Keywords L-bending · Optimization · Springback · FEM · Script

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1 Introduction

In L-bending process, springback affects the final shape of the workpiece when the punch is removed [1–5]. Since all materials have a finite modulus of elasticity, plastic deformation is followed by some elastic recovery when the load (here the punch) is removed; this phenomenon is called springback [6] (Fig. 1). Several papers have been published dealing with springback prediction. Minimization of the springback can be approached by numerical [7–9] or experimental [10–14] analysis. These approaches are applied in industrial practice where the determination of optimum process parameters had been typically carried out according to trial-and-error procedure by invoking the designer's empirical know-how [15]. Moreover, this traditional process of design could be laborious and time-consuming. Consequently, the development of the finite element method becomes an important purpose to reduce time and the cost of the products. On the other hand, to help the designer, numerical analysis is used to investigate tool design or process sequences which are of main importance for the final shape. The numerical simulation largely contributed to the development of this technology and allowed to predict the final shape of workpieces in a precise way [16–22].

Furthermore, optimization of process parameters by the classical numerical method involves changing one inde-

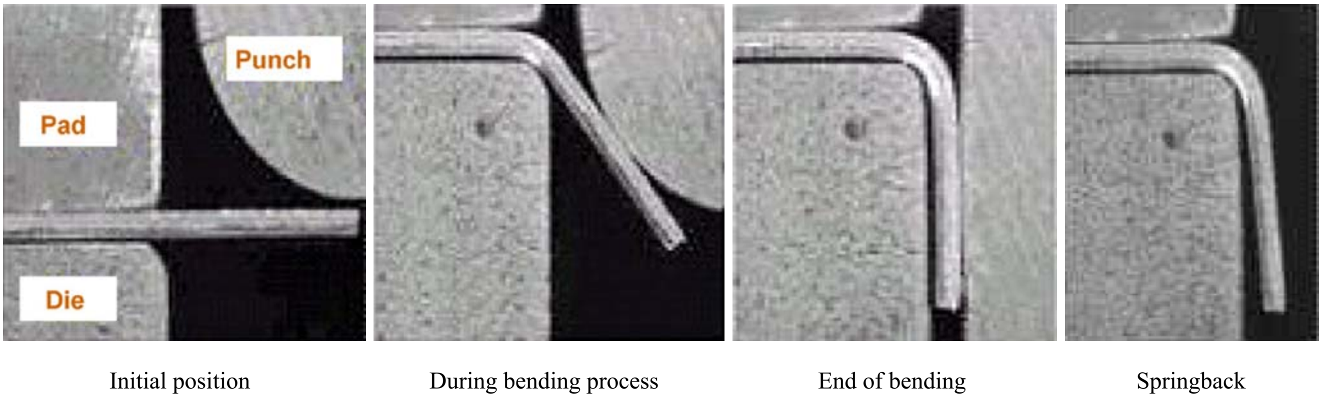

Fig. 1 Process steps during bending and springback [10]

pendent variable (radius, clearance, etc.) while keeping all others at a fixed level [23–25]. Therefore, more efficient methodologies via optimization must be developed to avoid this non-trivial task.

In previous studies dealing with bending process optimization, different approaches have been developed. Inamadar et al. [26] developed an artificial network to predict springback in air via bending, and Lepadatu et al. [27] proposed a concept of experimental design and response surface methodology to predict optimum springback.

The main problems in applying such methods are the complexity and the long time needed to parameterize the design variables and to link the finite element code to the optimization algorithm.

In the proposed study, an optimization algorithm using Gauss–Newton method was developed by coupling the Abaqus/standard code and Python. Python is an object-oriented language strongly suggested by Hibbitt, Krlsson and Sorensen, Inc. (HKS) [28] to parameterize the Abaqus file. The developed Python algorithm performs optimization loops and controls the iterative Abaqus calculations and the design variables within the input file.

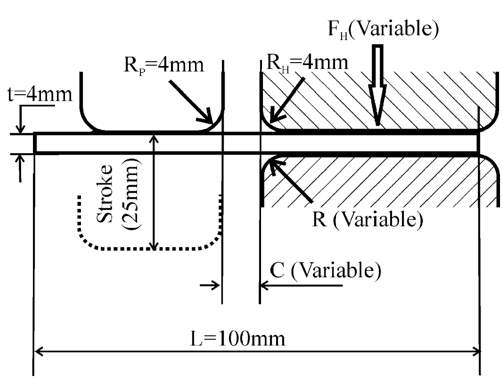

Fig. 2 Bending process geometry and parameters

In order to validate the algorithm, a comparative study is proposed between numerical and experimental results. Three process parameters (die radius, punch–die clearance, and the blank holder force) of an L-bending operation are treated as factors to be optimized in order to minimize the springback phenomenon. The effect of all other parameters (stroke, lubrication, friction, etc.) is ignored in this work.

The comparative study shows that the model is reliable and efficient with reduced number of iterations.

2 Simulation of L-bending process

The problem studied here consists in L-bending of a 4-mm sheet thickness (X6CrNiTi1810 stainless steel). The dimensions of the specimen is equal to 100×30 mm^2, the punch radius R_p=4 mm, the blank holder radius R_H=4 mm, and the stroke punch H=25 mm. Figure 2 describes the

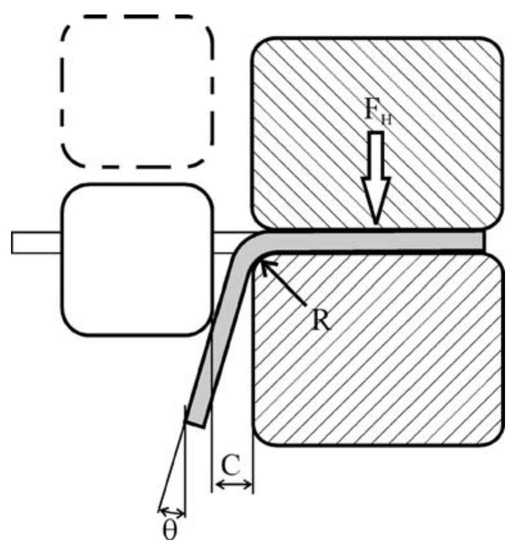

Fig. 3 Definition of the process and springback parameters

Table 1 Material characteristics of X6CrNiTi1810 stainless steel [4]

E (MPa)	ν	σ_y (MPa)	σ_u (MPa)	K (MPa)	n
210,000	0.3	287	630	1,540	0.58

parameters and the geometry of the process. Three parameters are considered for optimization: die corner radius (R), punch–die clearance (C), and force applied to the blank holder (F_H). The springback is usually quantified by the angle θ (Fig. 3).

A series of L-bending experiments on X6CrNiTi1810 stainless steel have been carried out and springback of the sheet have been measured for different configurations of dies with different values of corner radii and clearances. The L-bending tests was carried out with Grimar-13675 press equipped with a force transducer of the type FN 300TC and incremental position sensor DX100.

2.1 Finite element model

The finite element approach is based on a 2D plane strain elastoplastic model. The plastic properties of the sheet metal part are assumed to be isotropic, described by the von Mises yield function.

Contact at the interfaces between the sheet and the tool is modeled by adopting a rigid body hypothesis using contact surface laws defined by a Coulomb friction law with a friction coefficient value of 0.1

The corresponding strain hardening law takes a non-linear form expressed by:

$$\sigma_0 = \sigma_y + K\left(\varepsilon_{eq}\right)^n \tag{1}$$

where σ_y, ε_{eq}, K, and n are, respectively, the yield stress, the equivalent plastic strain, the hardening modulus, and the strain hardening exponent.

Strain hardening law parameters and the elastic properties of the material have been obtained by a tensile test. In Table 1 are reported the material parameters, where E, ν and σ_u denote, respectively, the Young modulus, the Poisson's ratio, and the ultimate stress.

The meshing of the sheet is carried out by means of 420 quadrangular four-node continuum elements. Figure 4 shows the springback effects after the punch removal (Fig 4d). The validation of the finite element method (FEM) model was performed in previous work [27]. Good agreement has been obtained between the experimental springback curves for different clearances and different die radii and the numerical ones (Fig. 5). The deviations do not exceed 5%.

The proposed FEM was applied to investigate the influence of the three main process parameters on the springback variation. The obtained results depicted in Fig. 6 show that springback increases with the tool clearance. The same results were reported in [10, 29] by different authors.

Concerning the influence of the blank holder (BH) force, it has been experimentally observed that the springback decreases versus the increase of the BH force [21, 27]. This phenomenon can be explained by the fact that with low applied force, the punch mostly generates bending stresses in the sheet, but as the blank holder holds the blank more severely, the stresses induced by the punching phase become mostly tensile stresses.

Different investigations [21, 27, 29] showed that springback is very sensitive to the die radius. Decrease of die radius leads to a springback decreases. Die radius have significant effects on springback [21–29]. The trend is to use as small a die radius as possible to reduce springback. However, care must be taken to avoid a die radius smaller than the minimum bend radius of the alloy in order to prevent the bend external area from cracking.

3 Optimization algorithm

Former work [15] retained the die corner radius, punch–die clearance, and blank holder force as the main parameters to reduce the springback. The aim of this section is to associate an optimization algorithm to the previously developed finite element model to minimize the springback according to all parameters quoted above (R, C, F_H).

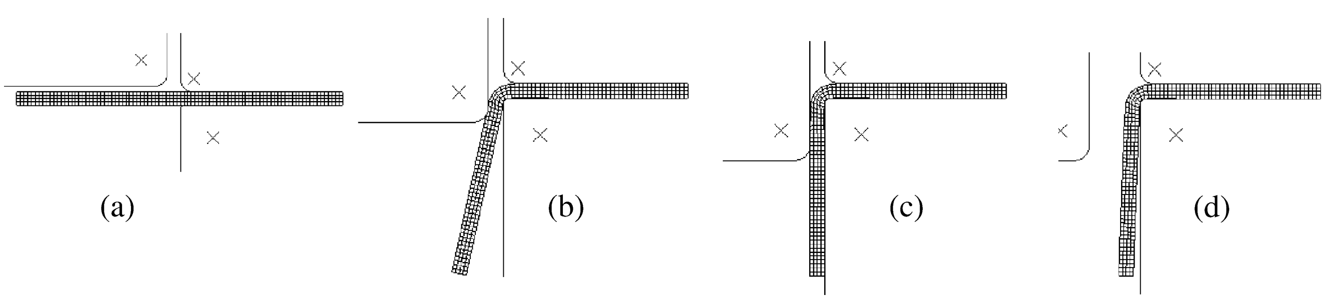

Fig. 4 Deformed configuration at different steps

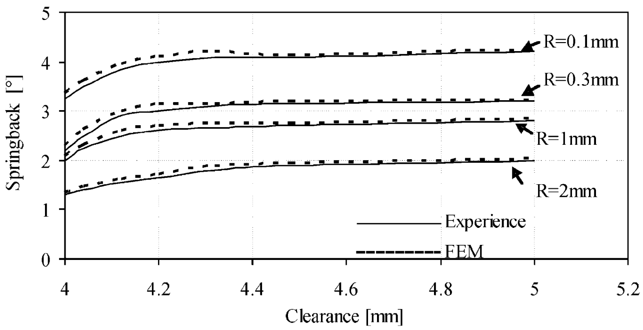

Fig. 5 Comparison between numerical and experimental values of springback for different values of clearances and corner die radii [4]

Since we cannot avoid springback during L-bending, the optimization algorithm consists in minimizing the objective function, which is the difference between a target value of springback $\theta^{\min}$ and the result of simulation by FEM [24].

If we consider $X = \{x_1, x_2, x_3\}$ be a set of design variables where $(x_1 = R,\ x_2 = C,\ x_3 = F_H)$, the objective function $\varphi = \varphi(X)$ can be expressed by:

$$\varphi(X) = \left(\frac{\theta^{FEM}(X) - \theta^{\min}}{\theta^{\min}}\right)^2. \tag{2}$$

The optimization problem consists in minimizing the objective function φ subjected to some constraints on X.

$$\min_x \varphi(X) X \in \mathbb{R}^3 \tag{3}$$

Subjected to the constraint $L \leq X \leq U$, with L and U being lower and upper bounds for design variables with: $1.2 \leq x_1 \leq 5$ mm, $1\% \leq x_2 \leq 15\%$, and $100 \leq x_3 \leq 1{,}500$ N.

The lower limit of the die radius (x_1) 1.2 mm corresponds to the minimum bend radius of the metal so as to prevent the bend area from crack.

Several optimization methods have been applied by different authors within the framework of metal forming optimization [22–24, 27, 30].

In the present paper, the Gauss–Newton method has been implemented and coupled with Abaqus code.

Starting with the approximation parameter value $X^{(k)}$, each iteration provides a new approximation $X^{(k+1)}$ based on the first-order Taylor approximation of the above system in $X^{(k)}$. Then, $X^{(k+1)}$ is computed to reach "$\theta^{FEM}\left(X^{(k+1)}\right) - \theta^{\min} \approx 0$." This linearization leads to an over-determinate system:

$$\underline{\underline{\nabla}}\left(X^{(k+1)} - X^{(k)}\right) = \left(\theta^{\min} - \theta^{FEM}\right) \tag{4}$$

where:

$$\underline{\underline{\nabla}} = \frac{\partial \theta^{FEM}}{\partial X}. \tag{5}$$

This equation is solved with a least-square method to give the new approximation point:

$$X^{(k+1)} = X^{(k)} - \left(\underline{\underline{\nabla}}^T\ \underline{\underline{\nabla}}\right)^{-1} \underline{\underline{\nabla}}^T \left(\theta^{\min} - \theta^{FEM}\right). \tag{6}$$

In the present work, the optimization procedure is carried out in two steps with a Python script which controls the Abaqus runs and the optimization loops and returns to Abaqus newer values of design factors. In the first step, Abaqus performs the finite element calculation for a given set of process parameters. In the second step, the optimizer uses the objective function and updates the parameter values during the search for the optimum and returns the updated values to Abaqus for a new increment.

The general scheme coupling optimization algorithm and finite element model is described in Fig. 7.

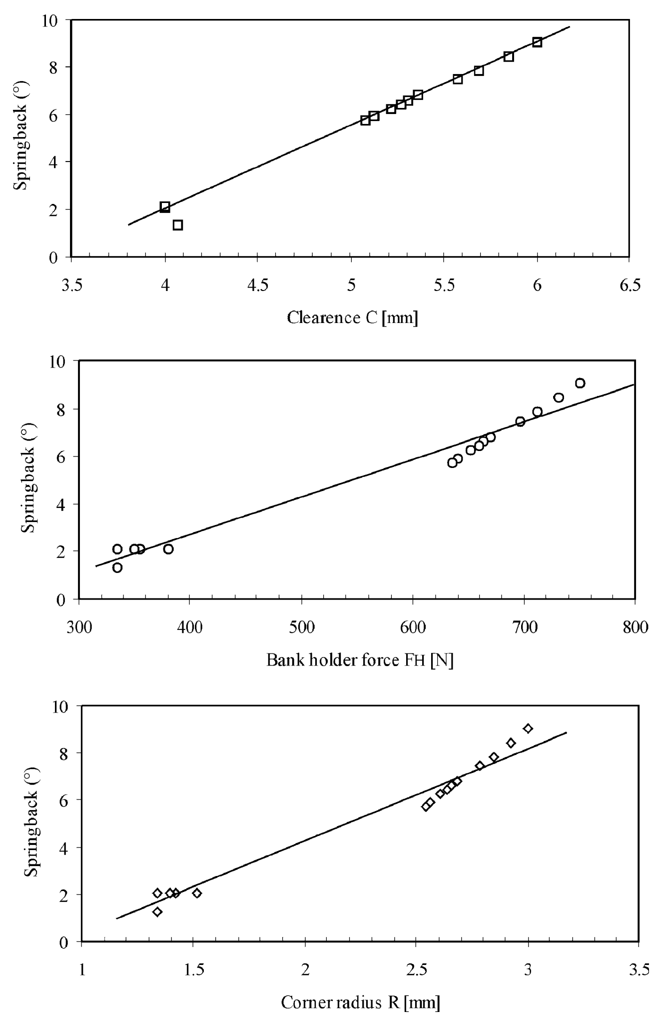

Fig. 6 Influence of clearance, blank holder force, and die corner radius on springback

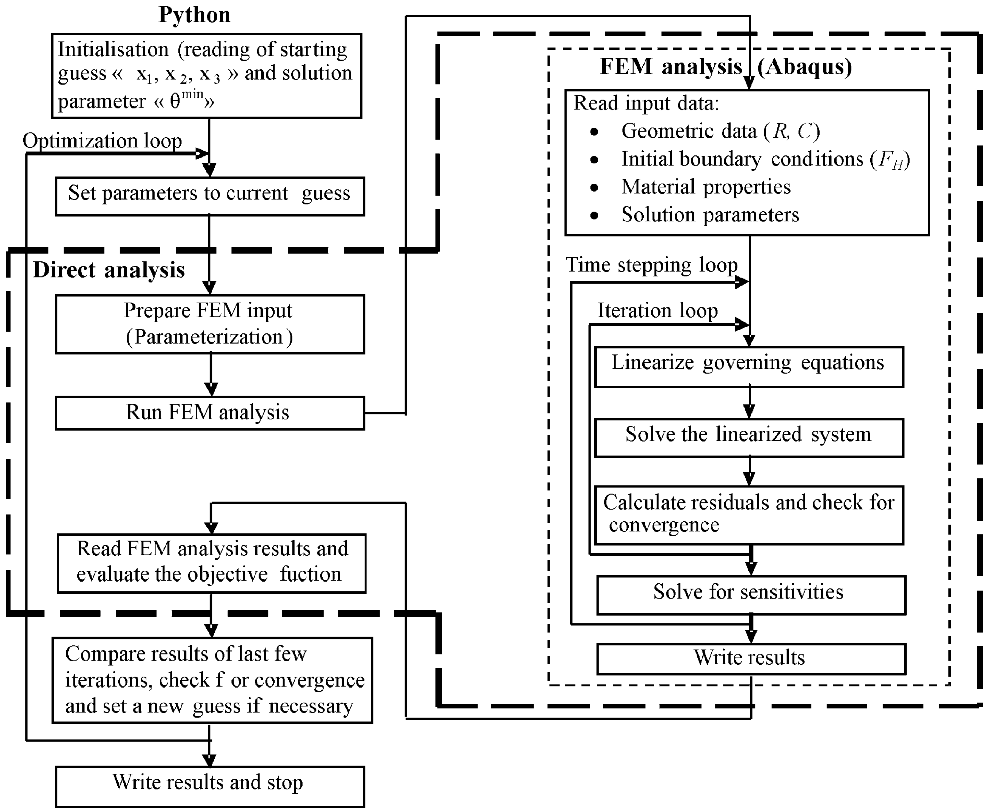

Fig. 7 Flow chart of the optimization algorithm. **a** Initial iteration, **b** seventh iteration, **c** 11th iteration, **d** optimal solution

3.1 Optimization analysis

The deformed workpiece after punch removal obtained by the optimization procedure at different iterations is presented in Fig. 8. We can observe the variation of the springback during the L-bending process. From the first iteration until optimal solution, the algorithm leads to minimization of the springback depending on the three process parameter values.

The optimal solution is obtained with a deviation about 1% from target springback angle value.

To assess the sensitivity of the proposed algorithm, different optimization calculation with different initial parameters values have been performed. The results showed that optimal result is reached in about 15–25 iterations with a deviation between the optimal parameters less then 5%. In Table 2 is reported a comparative study corresponding to three sets of initial values.

It is obvious, according to the results in Table 2, that the initial values have an effect on the number of iterations. The closer these values are to the optimal values, the more reduced is the number of iterations.

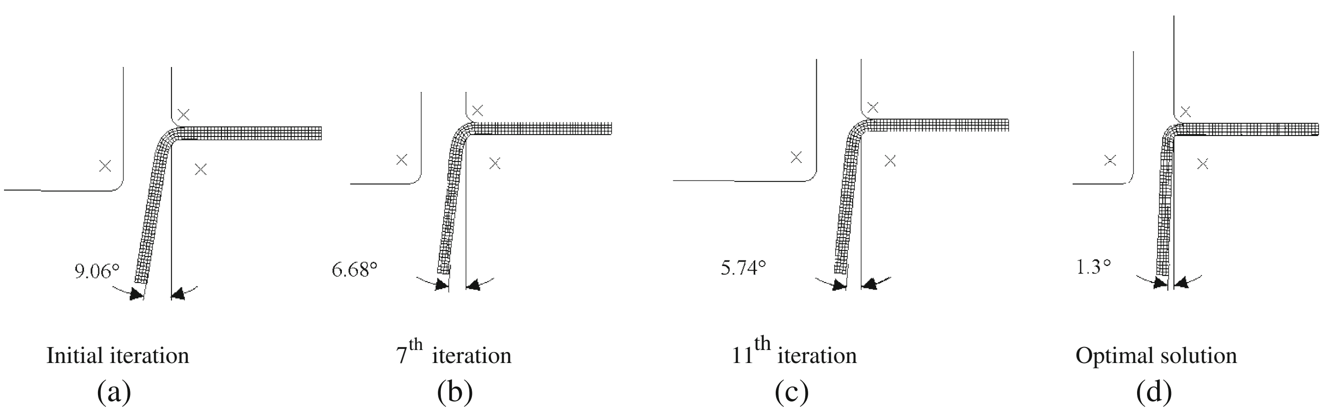

Fig. 8 Springback at different iterations. **a** Initial iteration, **b**, **c** intermediate iterations, and **d** optimum solution

Table 2 Optimization results for two different initial parameters guesses

	Guess 1 (19 iterations)		Guess 2 (15 iterations)		Guess 3 (23 iterations)	
	Initial values	Optimum	Initial values	Optimum	Initial values	Optimum
R (mm)	2	1.32	3	1.32	5	1.33
C (mm)	2	4.07	6	4.05	4	4.02
F_H (N)	250	336	800	338	400	334.8

Convergence tolerance error: tol.=1%

Figure 9 shows the evolution of the springback angle and the different design parameters versus the iterations numbers in the case of guess 2. It can be observed that the convergence is reached quickly after about ten iterations. The reduced number of iterations is due to the reliability of the proposed optimization procedure and the efficiency of the Gauss–Newton method in the resolution of a nonlinear function to several variables.

4 Conclusion

In the present paper, an optimization algorithm coupling Abaqus finite element code and a Python script for engineering applications was developed in order to optimize workpiece springback during L-bending process. Three parameters were retained for the present investigation tool clearance, die radius, and blank holder force. The finite element model was previously validated with experimental results. The optimization procedure leads to optimal process parameters in less then 25 iterations. The obtained results are in good agreement with several published studies. The results show clearly that clearance, die radius, and blank holder force have significant effects on the springback response.

The main advantage of the proposed optimization approach is that the convergence is fast and less sensitive to initial values. In addition, Python is an object-oriented language which is strongly suggested by HKS. It allows an industrial easy use of the procedure based on factors parameterization. The Gauss–Newton method has been retained for its efficiency to perform the optimizations loops.

The proposed numerical can be applied for different metal forming processes like stamping and forging. Theoretically, there is no limitation of number of factors to be optimized. This can include process, material parameters, and lubrication (friction coefficient).

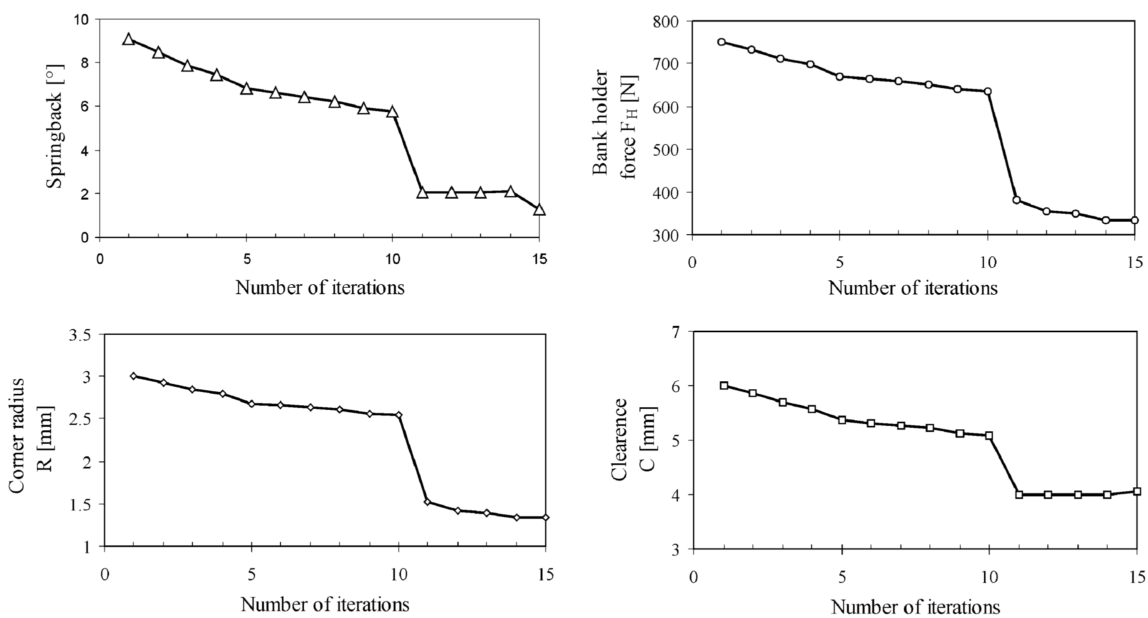

Fig. 9 Evolution of springback and process parameters values versus iterations

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