Control of draw-in in the deep-drawing process by regulating the force on the blank holder

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Abstract. Sheet metal forming processes are strongly influenced by process parameters, moreover fluctuations during the process and in material properties often lead to robustness problems. Therefore, numerical simulations as a function of design and noise parameters are usually adopted to detect ahead critical regions. To ensure efficiency and quality, the new era of industry 4.0 aims to develop systems that can control critical issues online. The aim of this work is developing a methodology that allows to adjust the force on the blank holder to obtain an optimal draw-in profile. This latter assures a minimization of defects (e.g., compression areas, thickened areas, insufficient stretch areas, splits) on the final component, even when variability of friction coefficient and yield strength occur. This methodology is applied to the deep-drawing process of a component obtained from a DC05 steel sheet with a thickness of 0.75 mm. For this purpose, Finite Element (FE) simulations in AutoForm software have been performed as a function of the design parameter i.e., Blank Holder Force and of noise parameters i.e., friction coefficient and yield strength. The results explored to evaluate the quality of the stamped part are: (i) percentage of compression areas, (ii) thickened areas, (iii) insufficient stretch areas, (iv) excessive thinning areas and (v) areas with splits. The data collected from FE simulations were adopted to perform a multi-objective optimization by means of the desirability function approach. Consequently, the value of process parameters that minimize defects (high value of total desirability) were identified. In correspondence with this optimal solution, the optimal draw-in profile was obtained. Such optimal profile was compared with the draw-in profile which involves defects on the final component (non-optimal draw-in profile). This latter was obtained for a value of the force on the blank holder equal to the optimal one and for non-optimized values noise parameters. In fact, noise parameters are not controlled process parameter. Based on the point-by-point difference between the two draw-in profiles, a numerical control strategy was implemented using AutoForm and MATLAB software. This iterative strategy allows to modify step by step the force on the blank holder so that the non-optimal draw-in profile match with the optimal one. Finally, experimental tests on a 3000 kN hydraulic press were performed to verify FE results.

1. Introduction
Deep drawing is one of the most widely used processes in sheet metal forming. Generally, it is applied in the automotive industry for the manufacturing of car body parts. In the deep drawing process, the blank is formed into the die by the mechanical action of the punch. Generally, a blank holder is adopted
to control the sliding of the workpiece during the process [1-2]. The force on the blank holder is one of key parameter affecting the deep-drawing process [2-4]. A proper blank holder force can prevent defects on the final component such as splits, wrinkles, thinning and thickening. For example, an increase of the BHF can lead to a reduction of wrinkle. While, in the presence of zone with excessive thinning, a reduction of the BHF can avoid splits [5-6]. However, the quality of deep drawn component is also affected by material and process fluctuations, e.g., yield strength, and friction coefficient [7]. As a result, robust design is required. Academic and industrial fields are interested in studying process monitoring strategies and active control systems to minimize the effect of both type of fluctuations. The state variable most frequently chosen to detect defects is the draw-in [8]. This variable can be measured by means of laser triangulation [9], sensors based on electromagnetic field [10] or mechanical devices [11]. To adjust online the draw-in of the blank, Hardt and Fenn [12] proposed a closed-loop control technique to realize real-time control of BHF. With the aim of adopting this latter control strategy, in this work a numerical methodology, in AutoForm environment, is developed to adjust step-by-step the force on the blank holder to obtain an optimal draw-in profile that minimize defects.

2. Material and Method
The deep drawing process of a T-joint was considered as case study. Figure 1a shows the geometry of the T-joint. This component was chosen by partners of the PICO & PRO project as a formability test able to highlight typical surface defects of cold sheet metal forming due to insufficient stretch. Figure 1b shows the tools, designed by CRF (Centro Ricerche Fiat, Italy), to deep draw the T-joint during experimental tests. Tools were manufactured by Tiberina Company. For experimental tests, a 3000 kN hydraulic press machine was adopted. Press machine was produced by the Gigant Italia company.

![Figure 1. (a) Geometry of the stamped T-joint. (b) Tools adopted for the deep-drawing of T-joint.](image)

For this study, the methodology summarized in the graphical abstract in Figure 2 was adopted. Specifically: (i) A Finite Element (FE) model was developed in the commercial software AutoForm R10 to numerically simulate the deep-drawing process. The process was studied by varying the design parameter, i.e., the force on the blank holder (BHF) and noise parameters, i.e., the friction coefficient ($\mu$) and yield strength ($\sigma_0$). FE simulation predicted the quality of the final component in terms of percentage of compression areas, thickened areas, insufficient stretch areas, excessive thinning areas and areas with splits. Moreover, FE draw-in of the blank in critical points was evaluated. (ii) The data collected from FE simulations were processed with the MATLAB DACE toolbox to obtain kriging metamodels. Interpolated response surfaces (IRS) show how process and noise parameters variations affect the quality of the component at the end of the drawing phase. (iii) A multi-objective optimization, by means of desirability function, was performed to identify values of process parameters that minimize defects such as compression areas, thickened areas, insufficient stretch areas, excessive thinning areas and areas with splits. (iv) Once optimal solution was found, the corresponding optimal draw-in profile of the blank in critical points was derived. By setting the force on the blank holder at the optimal value and varying values of noise parameters, non-optimal solutions (deep drawn component with defects) were obtained. The draw-in in same critical points was also
measured for non-optimal solutions. Finally, optimal draw-in profile and non-optimal one was compared. Based on the point-by-point difference between the two draw-in profiles, a control strategy was implemented using AutoForm and MATLAB software. This strategy modifies step by step the force on the blank holder so that the non-optimal draw-in profile match with the optimal one. (v) At the end, experimental test of deep drawing of T-joint were carried out to verify FE results. Below details on each step of the adopted methodology are explained.

2.1. Material: DC05
The deep drawing of the T joint was performed on blanks obtained from DC05 steel sheets with a thickness of 0.75 mm. Chemical composition of the steel is listed in Table 1. Figure 3 shows the mechanical characteristics of the investigated material. Specifically, Figures 3a-b-c show, respectively, hardening curve, yield surface and Formability Limit Curve (FLC). The hardening curve was defined using the Swift and Hockett-Sherby approximation. While, Hill 48 model was adopted for the yield surface.

| Table 1. Chemical composition of steel (wt.%). |
|-----------------|-----------------|-----------------|-----------------|
| DC05            | C, %            | Mn, %           | P, %            | S, %            |
|                 | 0.06            | 0.35            | 0.025           | 0.025           |

The mechanical characteristics shown in Figure 3 were assumed constant, however it should be noted that at the yield strength parameter a variability was assigned and consequently, the tensile strength was also varied, keeping constant the ratio between yield strength and tensile strength (0.5).
2.2. *Finite Element (FE) modelling*

The deep-drawing process was modelled using the commercial Finite Element (FE) software AutoFormR10. Tools geometries, i.e., die, punch and blank holder, the initial blank, their reference systems, the material and the production plan were defined. Figure 4 shows the tools modelled in AutoForm.

![Figure 4. Punch, blank holder and die in FE-model.](image)

The die and the punch were defined as rigid tools, while the blank holder was defined as a force-controlled tool. The initial blank is rectangular with dimensions of 450 mm x 680 mm. Numerical simulations were carried out by setting process parameters as in Table 2. The final quality of the component was evaluated as a function of the force on the blank holder, the friction coefficient and the yield strength. These two last parameters, were chosen as noise parameters since in deep drawing process, fluctuation of lubricant condition and in material properties, due to different coil or supplier, can occur. The nominal values of design and noise parameters and their variability are shown in Table 3. For FE-simulations, Coulomb lubrication model was adopted, although it is an approximation of the real friction behaviour during deep-drawing process. The value of BHF was chosen as a function of design data of the press machine. Moreover, preliminary FE simulations allowed to fix the range variability for such parameter. On the other hand, the value of yield strength was set according to the material datasheet. Finally, values of the friction coefficient were considered in the common range in deep drawing process [13].

**Table 2. Settings of process parameters.**

| Process parameters   | Value  |
|----------------------|--------|
| Forming velocity     | 8 mm/s |
| Press stroke         | 250 mm |
| Forming stroke       | 30 mm  |

**Table 3. Nominal value and variability range of noise and design parameters.**

| Process parameters | Nominal value | Variability range |
|--------------------|---------------|-------------------|
| Design parameter   |               |                   |
| BHF (kN)           | 550           | 350-750           |
| Noise parameter    |               |                   |
| μ                   | 0.1           | 0.05-0.15         |
| Noise parameter    |               |                   |
| σ0 (MPa)           | 145.9         | 116.7-175.1       |

Output parameters considered for the analysis of the deep-drawing process were: (i) percentage of compression areas, (ii) thickened areas, (iii) insufficient stretch areas, (iv) excessive thinning areas and (v) areas with splits. These output parameters allowed to evaluate the quality of the stamped component as a function of the force on the blank holder under noise factors (variability of the friction coefficient and the yield strength). Since the investigated T-joint was chosen to optimize the areas with insufficient stretch, greater importance was given to this output variable in the optimization phase. Finally, FE model was also adopted to calculate the daw-in in critical points during the process in all investigated conditions.
2.3. Post-processing analysis for kriging meta-modelling and multi-object optimization

Once the process parameters were set in the FE model, a simulation plan based on a Latin Hypercube Sampling (LHS) was performed. For the case study, the plan sampling included 63 numerical simulations. For each simulation, outputs described in section 2.2 were evaluated. Data collected from FE-simulations were processed by means of MATLAB DACE toolbox (2.0, Technical University of Denmark DK-2800 Kgs, Lyngby, Denmark) to derive metamodels with kriging technique [14]. A second order polynomial was chosen as regression function and Gaussian correlation function was adopted. A grid of points on which to evaluate the new (untried) sites was generated. Specifically, a 39x39 mesh of points distributed in the area defined by the lower and upper limits of the parameters F, μ, and σ0 was chosen. Interpolated response surfaces were obtained. These IRS show the influence of the design and noise parameters on the outputs. Subsequently, with the data collected from FE simulations, a multi-objective optimization with the Desirability Function Approach (DFA) [15] was carried out in MATLAB. According to the DFA, the most desirable solution (optimal solution) is a compromise one which provides the best satisfaction in the presence of conflicting objectives. During the optimization phase, for each output parameter, the criterion "lower the better" was chosen. Desirability function (d) correlated to each output parameter \( Y_i \) was calculated, assigning an exponent \( s \) greater than one (1.5) for the calculation of the desirability function associated with the percentage of areas with insufficient stretch and an exponent equal to one for the calculation of the desirability functions associated with the other output variables.

\[
d_i(Y_i) = \begin{cases} 
1 & \text{if } Y_i(x) < T_i \\
\left(\frac{Y_i(x) - U_i}{T_i - U_i}\right)^s & \text{if } T_i \leq Y_i(x) \leq U_i \\
0 & \text{if } Y_i(x) > U_i
\end{cases}
\]

where \( T_i \) target \( i \)th value and \( U_i \) maximum \( i \)th value

The multiplication between each desirability function gave the total desirability (D). The optimal solution is the one for which the value of total desirability is maximum. In correspondence with the optimal solution, the FE model allowed to measure the draw-in profile in critical points. These profiles were defined as optimal.

2.4. Development in AutoForm of a control strategy for BHF

The optimal draw-in profile was compared with those measured at the optimal BHF value by varying the noise parameters outside the optimal range. In this way, it is possible to simulate the industrial drawing process during which material and process fluctuations can occur. An iterative routine was developed in MATLAB; such routine compares for selected discrete instants of the deep drawing process the optimal profile with non-optimal one. If the difference between the two draw-in exceeds a minimum value, the BHF is adjusted. Such minimum value was chosen by evaluating, by means of FE simulations, the variability of the draw-in which guarantees a component free from defects. FE-simulations for the variability analysis were performed by setting BHF and σ0 to the optimal values and varying the value of μ from the minimum value (0.05) to the maximum value (0.15). BHF is increased if the non-optimal draw-in exceeds the optimal one, on the other hand, the BHF is reduced if the non-optimal draw-in is lower than the optimal one. BHF is increased or decreased proportionally to the difference between the two compared draw-in. Finally, the new BHF value obtained from MATLAB routine is imposed in AutoForm model to derive the new draw-in profile. By performing this procedure iteratively, a closed loop on-line control of the draw-in was numerically simulated.

3. Results and Discussion

3.1. Influence of process and noise parameters

FE results were collected and processed with the kriging technique. Figures 5a-b-c-d show, respectively, metamodels of the areas percentage of insufficient stretch, compression, thickened and splits, as a function of the force on the blank holder and the friction coefficient. These metamodels were obtained by setting σ0 to the nominal value. It is possible to observe that: (i) The percentage of insufficient stretch areas increases as the BHF and friction coefficient decrease (Fig.5a). (ii) For low values of the friction
coefficient, the percentage of the compression areas reduces as the BHF increases. Instead, for high values of the friction coefficient, the percentage of the compression areas increases as the BHF increases (Fig. 5b). (iii) The percentage of thickened areas reduces as the force on the blank holder and the friction coefficient increase (Fig. 5c). (iv) The percentage of areas with splits increases as the force on the blank holder increases for high values of the friction coefficient (Fig. 5d). Same considerations can be done observing the metamodel of the area percentage with excessive thinning, because splits and excessive thinning metamodels show the same trends.

![Metamodel percentage of (a) insufficient stretch areas (b) compression areas (c) thickened areas (d) areas with splits as a function of F and μ.](image)

**Figure 5.** Metamodel percentage of (a) insufficient stretch areas (b) compression areas (c) thickened areas (d) areas with splits as a function of F and μ.

### 3.2. Multi-object optimization and experimental tests

Values of the force on the blank holder, friction coefficient and yield strength corresponding to the optimized solution are equal to 550 kN, 0.1 and 145.9 MPa, respectively. The optimal solution is obtained for the maximum value of the total desirability which is equal to 0.975.

Figure 6 compares some results obtained with the FE model and with the deep drawing tests. A good correspondence between numerical and experimental results is observed. The part deep drawn with a BHF of 550 kN is similar to that obtained with the FE model, when the parameters of the optimized solution are used. Using the same friction coefficient and the same mechanical strength parameters of the optimized solution, a reduction of the blank holder force highlights an increase of the area percentage with insufficient stretching (tests with 450 kN). In the same hypotheses an increase of the blank holder force reduces the insufficient stretch areas and increases those with split and excessive thinning. Experimental result in Figure 6 shows that in correspondence of 600 kN blank holder force, the area percentage with insufficient stretching is minimal, but splits are observed in the lateral top part of the T-joint as shown in detail in Figure 7. FE result for BHF equal to 600 kN highlights a zone with excessive
thinning in the same region where split occurs during deep drawing experimental test. This is more clear in Figure 7a which shows the detail of the area with the greatest thinning and the formability limit diagram (FLD).

| F, kN | Numerical | Experimental |
|-------|-----------|--------------|
| 450   | ![Numerical](image) | ![Experimental](image) |
| 550   | ![Numerical](image) | ![Experimental](image) |
| 600   | ![Numerical](image) | ![Experimental](image) |

**Figure 6.** Comparison of numerical and experimental results in the deep drawn T-joint with different BHF.

**Figure 7:** Detail of the region in which split occurs for BHF equal to 600 kN: (a) FE results (b) deep drawing test.

During experimental tests, draw-in was measured by means of Keyence laser displacement sensors. Moreover, numerical prediction of draw-in was derived from FE-model. The draw-in was evaluated at critical points A-B-C, highlighted in Figure 8. Such points were defined as critical since greater blank
sliding occurs exactly at these points. As an example, Figure 9 compares the numerical draw-in and with the experimental one measured at point B. Point B was chosen as an example because it proved to be the point where the draw-in is most influenced by process parameters.

![Figure 8](image)

**Figure 8.** Critical points A-B-C where draw-in was evaluated.

![Figure 9](image)

**Figure 9.** Comparison between numerical and experimental measurement of draw-in at point B.

From figure 9 it is possible to observe that there is a good agreement between FE prediction of the draw-in profile and the experimental one. Considering the value of the draw-in at the end of the process, the percentage error between the numerical and experimental measurement is less than 5%.

### 3.3. Numerical results of BHF adjustment

By varying the friction coefficient between 0.05 and 0.15, the draw-in at the end of the punch stroke varies between about 12 mm and 6 mm, respectively (Figure 10). In this work results of regulation methodology is shown in the case corresponding to a reduction of the friction coefficient up to 0.05. These results are showed in Figure 11. Specifically, the red curve with circular makers represents the optimal draw-in profile at point B (curve a). The blue curve with square markers (curve b) represents the draw-in profile obtained by setting the BHF at the optimal value, $\sigma_0$ at nominal values and adopting the lowest value of the friction coefficient (0.05). The green curve with triangular markers (curve c) shows the curve obtained by adjusting the force on the blank holder using the iterative procedure.

![Figure 10](image)

**Figure 10.** Trend of blank draw-in during the process as the friction coefficient varies

![Figure 11](image)

**Figure 11.** a) optimized draw-in profile, b) draw-in profile with lower value of friction coefficient, c) draw-in profile after BHF adjustment
The force on the blank holder was adjusted starting from a difference between the optimal and non-optimal draw-in equal to 7%. It is observed that, thanks to the effect of the BHF adjustment, the curve b tends to approach the optimal draw-in profile (curve a).

Figure 12 shows the draw-in profile obtained after the BHF adjusting phase and the corresponding law of BHF adjustment. It should be observed that the force on the blank holder starts with the optimal value of 550 kN, after which it is increased first up to 700 kN and then up to 800 kN, leading to changes in the slopes of the draw-in profile.

The effect of the friction coefficient reduction leads to a greater sliding of the blank, in fact curve b is above curve a. Moreover, a reduction of the friction coefficient induces an increase of areas percentage of insufficient stretch. This aspect is highlighted in Figure 13a which shows the FE deep drawn part obtained with lower value of the friction coefficient. Figure 13b, on the other hand, shows the FE result at the end of the BHF adjustment phase. From the comparison between Figure 12a and Figure 12b, an improvement in the quality of the final component is observed. Furthermore, the component shown in Figure 12b is similar to that obtained in the optimal solution (Figure 6 – 550 kN).

4. Conclusions

The following conclusions can be drawn:

- A reduction in the BHF with respect to the optimal value leads to an increase in the areas percentage with insufficient stretch, instead, an increase in the BHF result in the reduction in areas with insufficient stretch. However, for higher value of BHF thinning and consequent risks of splits can occur. Such results were found both with numerically and experimentally investigation. A good numerical-experimental agreement was also observed in the trend of the draw-in profiles of the blank.
- FE results show that by setting the force on the blank holder to the optimal value, the variation of the noise parameters beyond the optimal values leads to draw-in profiles different from the optimal one. Consequently, deep drawn components with defects can be obtained.
The iterative procedure, developed for adjusting the force on the blank holder, allows to improve the quality of the component at the end of the drawing phase and to obtain a draw-in profile and deep drawn component similar to the optimal ones.

5. References
[1] Ramezani, M., and Z. M. Ripin. Deep drawing of sheet metals using the friction-actuated blank-holding technique. Rubber-Pad Forming Processes, Technology and Applications (2012): 119-147.
[2] Zhang, Hongsheng, JiJi Qin, and Liqin Cao. Investigation of the effect of blank holder force distribution on deep drawing using developed blank holder divided into double rings. J. Brazilian Soc Mech. Sci. and Eng. 43.6 (2021): 1-10.
[3] Krishnan, Neil, and Jian Cao. Estimation of optimal blank holder force trajectories in segmented binders using an ARMA model. J. Manuf. Sci. Eng. 125.4 (2003): 763-770.
[4] Ahmetoglu, Mustafa A., et al. Improving drawability by using variable blank holder force and pressure in deep drawing of round and non-symmetric parts. SAE Technical Paper (1993).
[5] Yagami, T., K. Manabe, and Y. Yamauchi. Effect of alternating blank holder motion of drawing and wrinkle elimination on deep-drawability. J. Mater. Process. Tech 187 (2007): 187-191.
[6] Wu, Peng, Youming Wang, and Peng Wan. Study on simulation of stamping process and optimization of process parameters of fender. Adv. Mater. Sci. Eng. (2019).
[7] Palmieri, Maria Emanuela, Vincenzo Domenico Lorusso, and Luigi Tricarico. Robust optimization and Kriging metamodeling of deep-drawing process to obtain a regulation curve of blank holder force. Metals 11.2 (2021): 319.
[8] Briesenick, David, Mathias Liewald, and Patrick Cyron. Potentials of an adaptive blank positioning to control material and process fluctuations in deep drawing. IOP Conference Series: Mater. Sci. Eng. 967. No. 1. IOP Publishing (2020).
[9] Braunlich, H., and R. Neugebauer. Closed loop control of deep drawing processes. SheMet (2001): 529-538.
[10] Mahayotsanun, Numpon, Jian Cao, and Michael Peshkin. A Draw-In Sensor for Process Control and Optimization. AIP Conference Proceedings 778. No. 1. American Institute of Physics (2005).
[11] Lo, Sy-Wei, and Tsu-Chang Yang. Closed-loop control of the blank holding force in sheet metal forming with a new embedded-type displacement sensor. Int. J. Adv. Manuf. Tech. 24.7 (2004): 553-559.
[12] Hardt, D. E., and R. C. Fenn. Real-time control of sheet stability during forming. (1993): 299-308.
[13] Fereshteh-Saniee, F., and M. H. Montazeran. A comparative estimation of the forming load in the deep drawing process. J. Mater. Process. Technol. 140.1-3 (2003): 555-561.
[14] Kleijnjen, Jack PC. Kriging metamodeling in simulation: A review. European journal of operational research 192.3 (2009): 707-716.
[15] Costa, Nuno R., Joao Lourenço, and Zulema L. Pereira. Desirability function approach: a review and performance evaluation in adverse conditions. Chemom. Intell. Lab. Syst. 107.2 (2011): 234-244.

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