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Some aspects of blank-holder force schemes in deep drawing process

A. Wifi *
co-operating with
A. Mosallam
Department of Mechanical Design and Production,
Faculty of Engineering, Cairo University, Giza 12316, Egypt
* Corresponding author: E-mail address: aswifi@yahoo.com

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Analysis and modelling

ABSTRACT

Purpose: This paper presents a finite element-based assessment of the performance of some non-conventional blank-holding techniques. This includes friction actuted, pulsating, and pliable blank-holding techniques.
Design/methodology/approach: A 3-D explicit-finite element analysis is used to investigate the influence of various blank-holder force (BHF) schemes on sheet metal formability limits especially wrinkling and tearing rupture. The role of relevant parameters of each blank-holding technique are also investigated. Three non-conventional blank-holders are considered,namely friction-actuated,elastic and pulsating blank-holders.
Findings: For the conditions considered in this study, comparison with fixed BHF scheme revealed that slight improvements in the formability are observed for the three BHF schemes under consideration.
Research limitations/implications: Only 5182 Al-alloy circular cups are considered. Further investigations should consider different materials and non-circular shapes because of their effect on sheet metal formability.
Practical implications: Cylindrical cups' drawing is responsible for the manufacture of billions of metal containers. This study can help improve working conditions leading to defect free products.
Originality/value: The 3D-explicit finite simulations presented for a number of non-conventional blank-holding techniques are useful in the assessment of their performance.
Keywords: BHF schemes; Deep drawing; Sheet metal forming; Finite element analysis; Optimization

1. Introduction

Failure of sheet metal parts during deep drawing processes usually takes place in the form of wrinkling and/or necking. Wrinkling normally occurs at the flange and is generated by excessive compressive stresses that cause the sheet to buckle locally. On the other hand, fracture or necking occurs in a drawn part which is under excessive tensile stresses.Wrinkling and tearing rupture thus define the deep drawing prcess limits [1-3]. For a given problem, many variables affect the failure of a stamping. These include material properties, die design, and process parameters such as friction conditions, the drawing ratio as well as the blank- holder force (BHF), and the careful control of these parameters can delay the failure of the part. Among these process and design variables, one in particular, the blank-holder force (BHF) scheme, has been shown to greatly influence the growth and development of part defects. Studies have shown that a deep drawn part's quality is affected significantly by the flow of metal into the die cavity .The force exerted by the blank holder on the sheet supplies a restraining force which controls the metal flow. This restraining action is largely applied through friction. Excessive flow may lead to wrinkles within the part, while an insufficient flow can result in tearing. A properly chosen BHF scheme (i.e. BHF-punch travel trajectory) can prevent wrinkling and delay fracture in drawn part [2]. Defects due to wrinkles and excessive localized thinning alter the product geometry from the designed one causing difficulties in joining and assembly of sheet products and limits the product serviceability.

Obermeyer and Majlessi[3] presented a comprehensive review of the advances in the application of blank-holder force (BHF) schemes to improve sheet metal formability. Conventionally, constant BHF were used and their results were compared in relation to failure due to both necking and wrinkling of the formed part and an optimum value of the BHF was reached. On the other hand,many studies dealt with the control and/or optimization of variable BHF profiles – with both linear and non-linear schemes being considered. In the following a brief review of some of the accomplishements in this field is presented, with amphasis on what could be considered as non-conventional blank-holding (BH) techniques.

Thiruvarudchelvan et. al [4] introduced a non-conventional friction-actuated blank-holders, in which an annular urethane pad is used to generate the BHF such that it is roughly proportional to the punch force throughout the process. They concluded that this method was effective in preventing early fracturing and wrinkling of the sheet. In contrast to this, closed-loop strategy adopted by Kergen and Jodogne [5,6] suggested a BHF that is inversely proptional to the punch load. Recently, using friction actuated segmented BH techniques is finding great interest[7].

Contradicting effects of increasing and decreasing BHF schemes on fromability is common in the literature[3]. Recently, Gahrib and Wifi et al emphasized that optimized linear BHF schems could be increasing, decreasing or constant depending on the drawing ratio[8].

Instead of simply increasing or decreasing the BHF, Mori and Uchida [9] introduced a vibrating blank-holder with different frequencies. In their experimental work, the blank holder vibration was given by a cam mechanism and the effect of changing the frequency on the deep drawing process was thoroughly studied. The work concluded that the increase of the frequency of the vibration leads to increase in the drawability.Wifi et al [10], used solid axisymmetric finite element model to investigate this scheme and compared it to other BHF schemes including decreasing, increasing trajectories as well as a BHF that is proportional to the punch load. It has been found that the vibrating blank holder resulted in a general decrease in thining in comparison to the constant BHF. The use of the vibrating blank holder has also lead to an increase in the LDR. Siegert and Ziegler [11], suggested a pulsating BHF scheme that could lead to a reduction of the friction forces between the blank and blank–holder , without increasing the danger of wrinkling.This enlarges the working window between wrinkling and tearing rupture and thus enhnces drawability.

Ragab and Sommer[12] developed an elastic (pliable) blank-holder which could maintain contact with the flange inspite of its thickening. The BHF is transmitted to the upper surface of the flange through a rubber cushion. Recently Mohamad [13] demonstrated that such pliable blank-holder can reduce thinning and wrinkling in cylindrical cups.Using finite elements, Cao and Boyce [14] optimized the process of deep drawing a conical cup by a variable BHF history to avoid both wrinkling and tearing. Also, Sheng et al.[15] Optimized the BHF scheme for a conical cup by adjusting the magnitude of the BHF continuously during the finite element simulation process. So, they were able to predict the suitable BHF scheme in a single process simulation.

Browne and Hillery[16] found that the BHF, punch and die profiles, lubrication, and position of lubrication are significant factors on the punch force. A similar conclusion was reached by Colgan and Monaghan [17] who concluded that the geometry of the tooling is generally most important, especially the die radius. The smaller the die radius the greater the drawing force induced and the greater is the overall thinning of the cup sidewall.

Recently, Lucas [18] , developed an optimization strategy for finding the optimum BHF-punch travel scheme which minimizes punch work and avoides the working limits of tearing, wrinkling, and spring back in deep drawing process. Optimization code was written in the Python programming language and integrated with the ABAQUS finite element software package. The developed method was successfully applied to cylindrical cup, square pan, and open channel geometries for the determination of optimum linear BHF profiles there.

However, the use of finite elements to evaluate the opimization objective function consumed a lot of time. Therefore, a less time consuming approach seems to be more reasonable and practical if optimization or process design is the objective[8]. To overcome this, Wifi and his co-workers adopted two alternative approaches for cylindrical cups. In the first, a finite difference incremental approach is merged with a genetic algorithm to search for an optimum BHF linear scheme through the control of process parameters[2,8]. The second approach merges the optimization algorithm with a rule-based computer-aided process planning expert system [19]. Both approaches seem to be promising prelude to full scale experimental and/or full 3-D finite elemnt analysis.

To conclude, one need not over emphasize that the assessment of the performance of various BH techniques continues to be of great interest reflecting the fact that it is so fundamental and crucial for successful stampings. The major part of this presentation will be on the finite element analysis of the influence of some non-conventional BH techniques on sheet metal formability. This includes, friction actuated BH, elastic or pliable BH, and pulsating BH and their relevant BHF schemes. These non-conventional models are compared with the case of a constant BHF and their effects on modes of failure as checked against forming limits are discussed. This work is part of a research work that is currently in progress under the supervision of the senior author on the assessment and search for optimized BHF schemes in deep drawing processes.

2. Finite element models for some non-conventional blank holders

In all models, ABAQUS-Explicit general purpose finite element code [20] is used with full 3-D capabilities to account for anisotropy of sheet metal and wrinkling of the cups. The blank is modelled using a 4-node doubly curved thin shell element with reduced integration, (S4R.). As shown in the sequel, except for the elastic blank-holder and the hyper-elastic polyurethane friction actuator, all tools are modelled as rigid analytical bodies. The blank is made of Al 5182 alloy and assumed to be elastic-plastic following Hill's anisotropic yield criterion. Friction is simulated using an average overall simple Coulomb friction model with Coefficient of friction = 0.1 between the blank and the tool. The punch speed is adjusted by gradually reducing its speed until a stabilized solution is obtained [21]. A modelling value of 3 m/s was found to be reasonable. The following data are used in the modelling:

- Flow Stress (Mpa) $\sigma = 371.2\ (3.24e\text{-}3+\varepsilon)^{0.17}$
- Anisotropic Lankford's coefficients R_0=0.73 R_{45}=0.68 R_{90}=0.65
- Blank thickness 1 mm
- Punch diameter 100 mm
- Punch nose radius 13 mm
- Die inner diameter 102.8 mm
- Die profile radius 5 mm
- Young's Modulus 70 Gpa
- Poisson's ratio 0.33

Here σ is the flow stress, ε is the effective strain and R is anisotropy coefficient.

2.1. Process limits

In this study tearing and wrinkling are taken as the process limits. Failure by tearing is checked using the relevant forming limit diagram (FLD) of the used blank material and thickness [22].The parameter FLDCRT is defined as the ratio of the current major principal strain to the major limit strain on the FLD evaluated at the current values of the minor principal strain [20]. The damage initiates if FLDCRT =1. Because the material anisotropy ,the strains and FLD severity are evaluated in both zero and 90◦ directions; however the location of the maximum FLDCRT or minimum thickness strain may not present on one these directions. Thus, a search for the maximum severities is carried out all over the cup surface.

Winkling and waviness along flange circumference are monitored. Local wrinkles heights are measured as the difference in height of two consecutive nodes. The process maximum limit for wrinkling is taken to be 0.2 mm.

2.2. Friction-actuated BH

Fig. 1 shows an illustration of the finite element model for the friction actuated blank- holding technique suggested by Thiruvarudchelvan [4]. The punch was made of two parts, and an annual urethane pad was inserted in between. A clearance is set between the outer diameter of the pad and the inner diameter of the blank-holder. When the upper punch advances, the urethane pad is compressed and expands in the redial outward direction against the bore of the blank holder. Before filling the clearance between the blank-holder bore and the urethane pad, no contact exists between them and the BHF has zero value .Upon the advance of the upper punch, the pad starts to contact the blank holder and the friction between the urethane pad and the blank-holder bore actuates the BHF. The bottom part of the punch is subjected to the drawing force while the upper part carries the sum of the drawing force and the BHF.

The urethane pad is modelled as hyper-elastic material with an isotropic, nonlinear and an instantaneous elastic response up to large strains. The experimental data for the commercial polyurethane used in this study [24, 25] is found to fit the Marlow strain energy potential [20], Fig. 2.

The urethane pad is modelled using 8-node linear brick elements, with reduced integration (C3D8R). The friction-actuated BHF is evaluated as the summation of the frictional shear forces of the elements of the urethane pad in contact with the blank-holder.

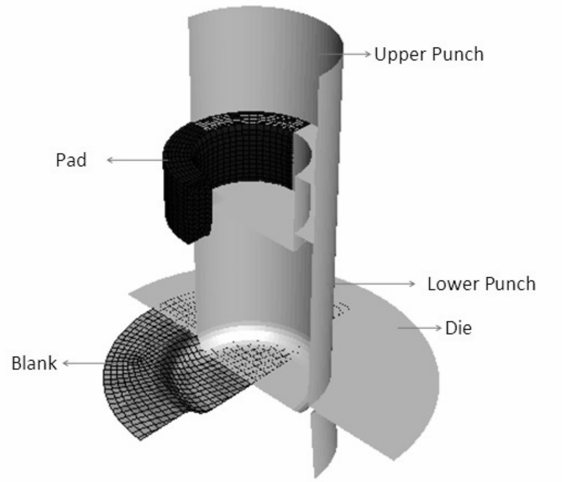


Fig. 1. Model of the friction actuated BH technique

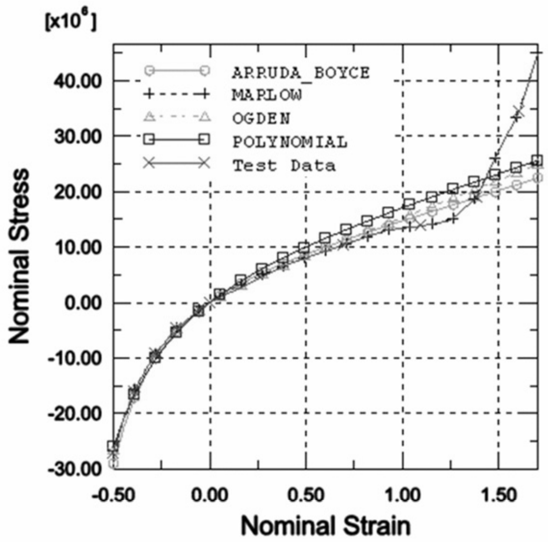


Fig. 2 Selection the forms of strain energy potentials

2.3. Elastic or pliable BH

Fig. 3 illustrates the model of an elastic (pliable) BH that resembles that suggested by Ragab and Sommer [12] for deep drawing of cylindrical cups. An elastically deformable thin steel annular plate (ring) is used instead of the ordinary stiff blank –holder. This ring is fixed at its outer edge such that an initial gap exists between the elastic blank-holder and the blank. Blank-holding is induced by applying a pressure on the upper surface of the elastic ring plate, which upon deflection would conform to the flange surface. This technique aims at enhancing more uniform contact conditions nearly all over the flange zone in contrast to the contact at the outer rim of the flange which is dominant in the case of the conventional rigid blank-holder because of the thickening there. A 4-node doubly curved thin shell, with reduced integration (S4R) element is used to model the steel elastic annular blank-holder plate of 1.5 mm thickness and , E=210 GPa.

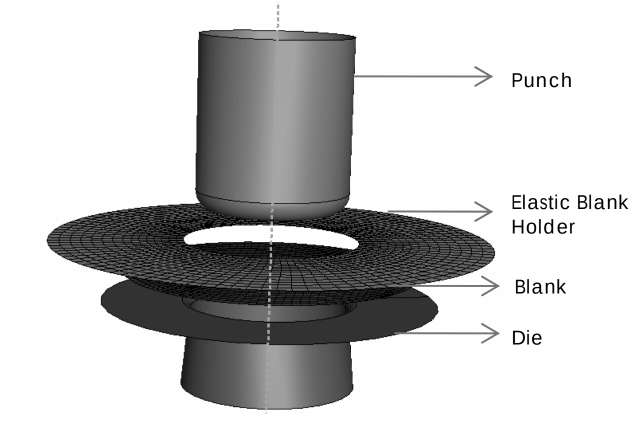


Fig. 3. An elastic (pliable) blank-holder model

2.4. Pulsating blank-holding

In this study, a pulsating BHF scheme in which a sinusoidal trajectory of the blank-holding force is considered, Fig. 4. The BHF varies between a minimum and a maximum value that depends on the amplitude of loading.

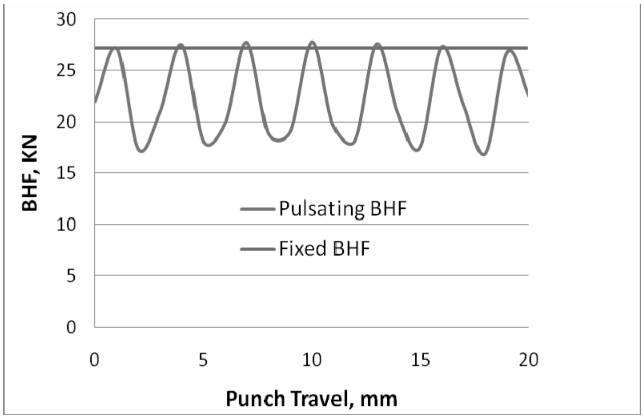


Fig. 4. Pulsating BHF scheme

3. Results and discussions

At the outset, the case of fixed BHF scheme is considered as reference case for the assessment of the various non-conventional BH techniques under consideration. The objective set here is to search for the limiting drawing ratio (LDR) for the fixed BHF case. A set of simulations were carried out where the drawing ratio was varied systematically to determine the maximum possible drawing ratio at a given BHF. Using different BHF and the previously defined severity criterion a limiting drawing ratio of 1.92 was obtained at a BHF of 27 kN. At this LDR, the severity index FLDCRT was 0.9906, minimum thickness was 0.8173 mm, and the maximum wrinkle height was 0.2 mm .The location of the maximum FLDCRT was found to coincide with the location having minimum sheet thickness near the punch nose.

3.1. Friction-actuated BHF

A crucial issue in this model is the determination of the frictional conditions at the urethane pad-steel blank-holder interface. An adjustment procedure to determine the coefficient of friction there is followed. A value of 0.3 was found to be acceptable. A validation of this value is indicated in Fig. 5 to Fig. 7, where the results of the present finite element model are compared with the experimental results of Thiruvarudchelvan et al [4]. Figs. 5 and 6 indicate good agreement between the predicted punch force (PF) and BHF scheme and those obtained experimentally [4]. Fig. 7 indicates excellent agreement between the FEM predicted strains distributions and those obtained experimentally [4].

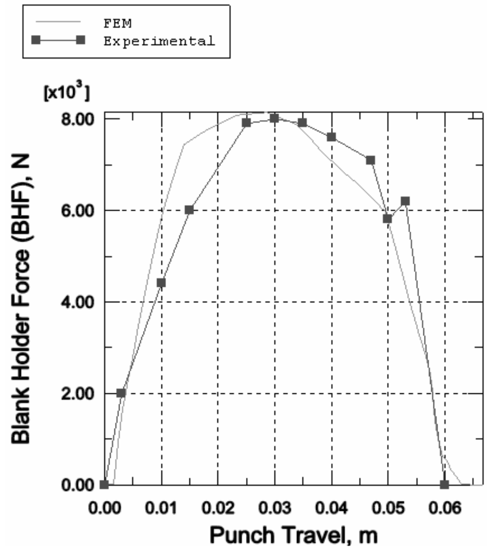


Fig. 5. Finite element predicted BHF compared to the experimental one [4]

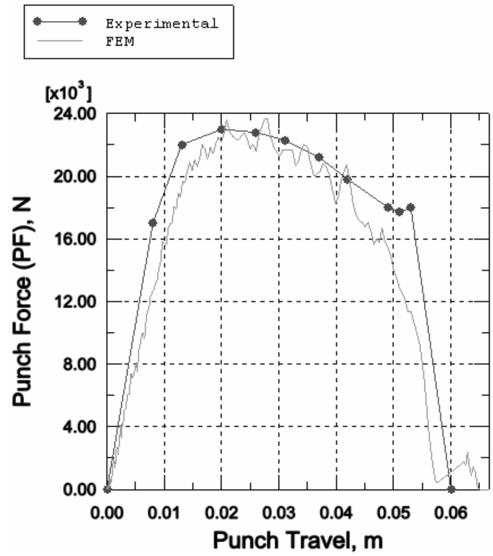


Fig. 6. Finite element predicted PF compared to the experimental one [4]

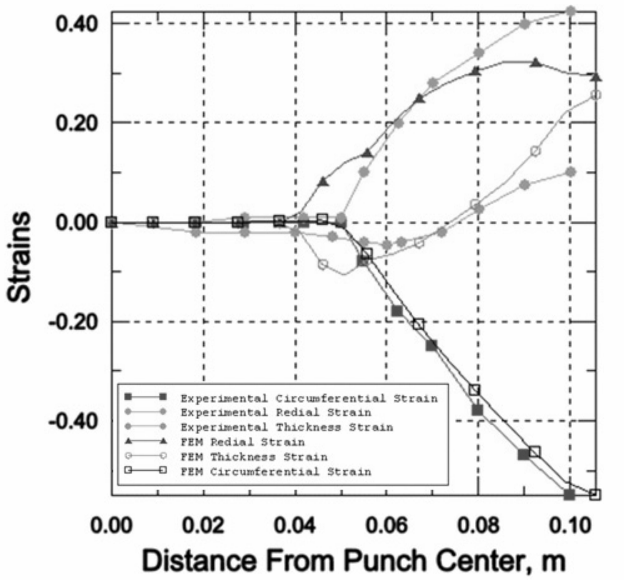


Fig. 7. Predicted strain distributions as compared to experimental ones [4]

Effect of pad clearance

Clearance between the pad and blank-holder should be carefully selected. In the validation study a clearance of 0.1 mm was used. Excessive clearance could be detrimental. Numerical experimentation revealed that the maximum clearance for the problem under consideration is 0.5 mm. Excessive wrinkling will be triggered for larger clearances, as depicted in Fig.8. In fact, excessive clearance would cause a delay in the application of the BHF and the early phase of the cup forming is unsupported which enhances wrinkling conditions, Fig. 9. Increasing the pad height with excessive clearance was found to be ineffective in suppressing wrinkling by the application of larger, but delayed, BHF. The clearance between the pad and the blank-holder is a very sensitive parameter, as it decides when the BHF come into action in the process. The delaying in the BHF at the beginning of the process leads to a very fast initial blank wrinkling.

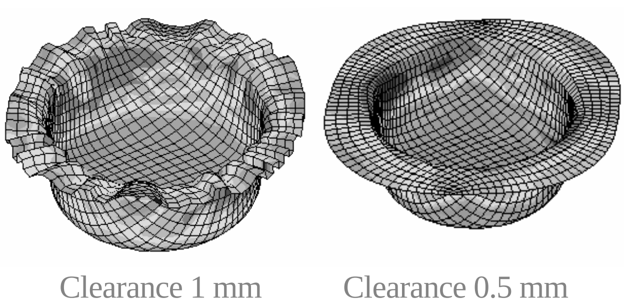


Fig. 8. Effect of excessive clearance on wrinkling

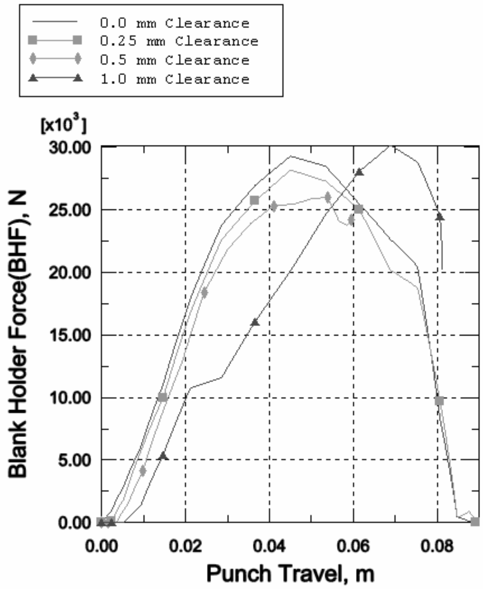


Fig. 9. Effect of clearance on BHF

Effect of pad height

Different pad heights are investigated keeping a pad thickness of 15 mm. As expected, results showed that the BHF is directly proportional to the pad height .At punch stroke of 35 mm the blank-holder forces were 25.5, 34.2 and 36.4 KN for the pad heights of 40, 50 and 60 mm respectively. This seems reasonable as the frictional force effect on the inner surface of the blank-holder increases with the increase of the area of pad surface in contact with the blank holder. It should be noticed that the punch force (PF) also increases with the pad height. The BHF is roughly proportional to the PF; however, the ratio of the BHF/PF is not in direct correlation to the pad height, Fig. 10.

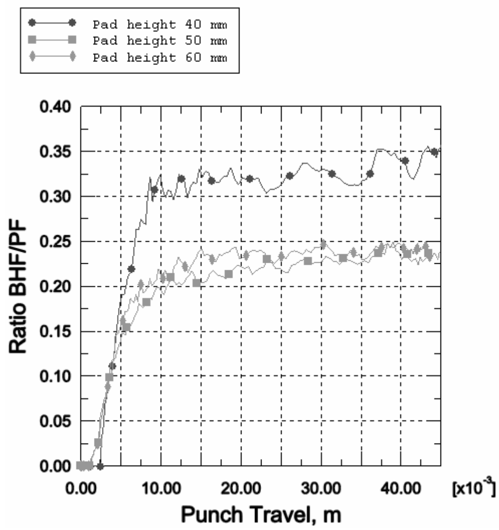
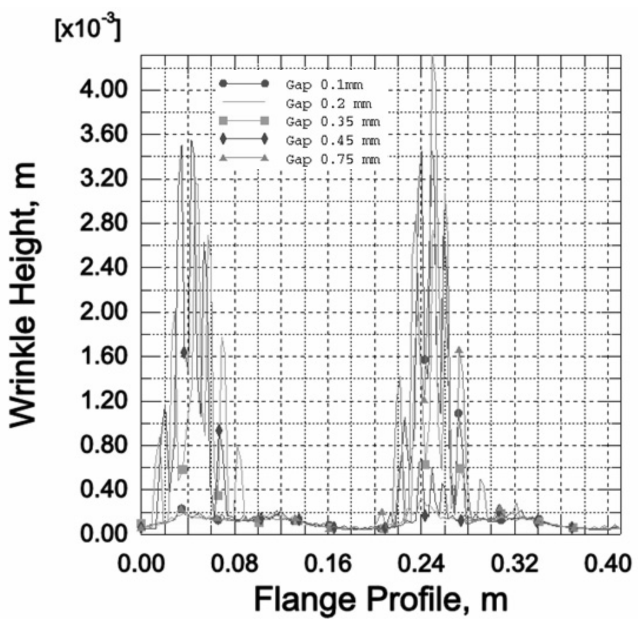
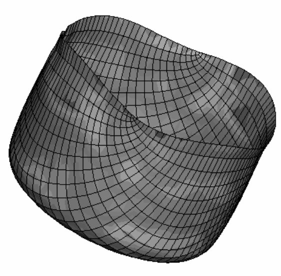


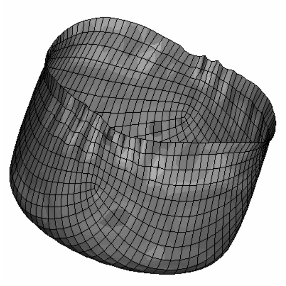
Fig. 10. Variation of the BHF/PF ratio with pad height

3.2. Elastic blank holder

Many parameters could affect the performance of the elastic or pliable blank-holder ring. This includes the gap height, elastic plate radius and thickness, and the diameter of pressurized zone of the elastic ring. Fig. 11 shows clearly the role of the gap between elastic ring blank-holder and the blank. A gap in excess of 0.2 mm was found to aggravate wrinkling- height dramatically. Here,a BH pressure of 1.44 MPa was applied, and the outer elastic ring diameter was taken equal to twice that of the blank diameter. This could be attributed to the difficulty of having suitable conformity between the elastic ring and the flange when the gap is enlarged. The gap height seemed to be crucial in suppressing wrinkling. In this model, for gap heights less than 0.2 mm the elastic BH was effective in suppressing wrinkling; however, no such improvement was noticed in the severity. The effects of elastic ring diameter and thickness were found to be insignificant on wrinkling.







Gap of 0.2 mm Gap of 0.35 mm

Fig. 11. Effect of gap height on the wrinkling of elastic BH

3.3. Pulsating blank holder

A pulsating BHF scheme is considered. Two main parameters may affect the performance of this scheme, namely the pulsation amplitude and frequency, for a given maximum value of the BHF. The pulsation frequency was changed between 2.5 to 100 cycle/stroke, and the amplitude was changed from 2.5 to 20 KN. Various numerical experimentations suggested that the frequency has no decisive role in improving the severity of deformation under the given conditions. Improvement in wrinkling height was observed as the frequency increased up to a certain limit after which no further improvement was noticed, and there was insignificant effect of the pulsation frequency on the wrinkling, Fig. 12.

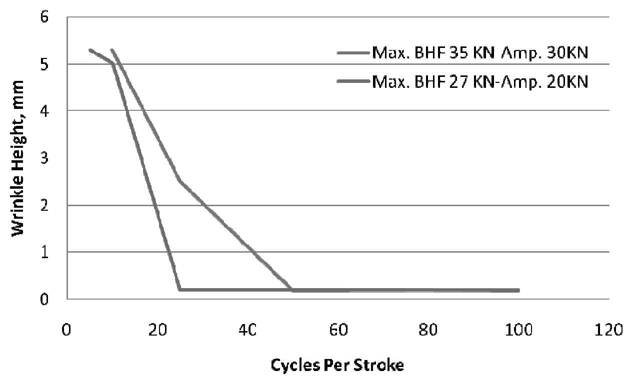


Fig. 12. Effect of the BHF frequency on wrinkling

On the other hand, pulsation amplitude of the BHF seemed to play a decisive role in the performance of pulsating BHF schemes. Increasing the pulsation amplitude was found to decrease the friction force between the blank and the blank-holder, Fig. 13. Consequently, increasing the pulsation amplitude improved also the FLD severity and the sheet metal thinning as shown in Fig. 14 and Fig. 15.

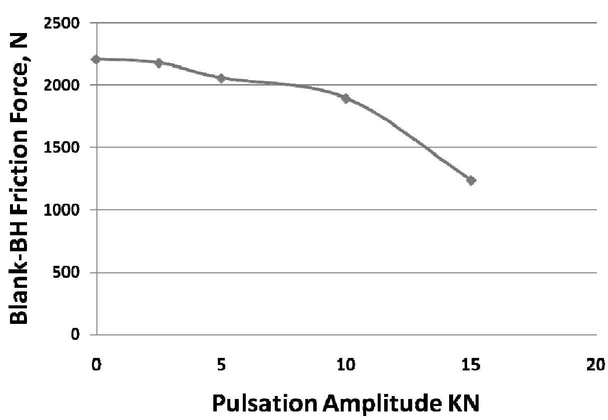


Fig. 13. Effect of the BHF pulsation amplitude on friction force

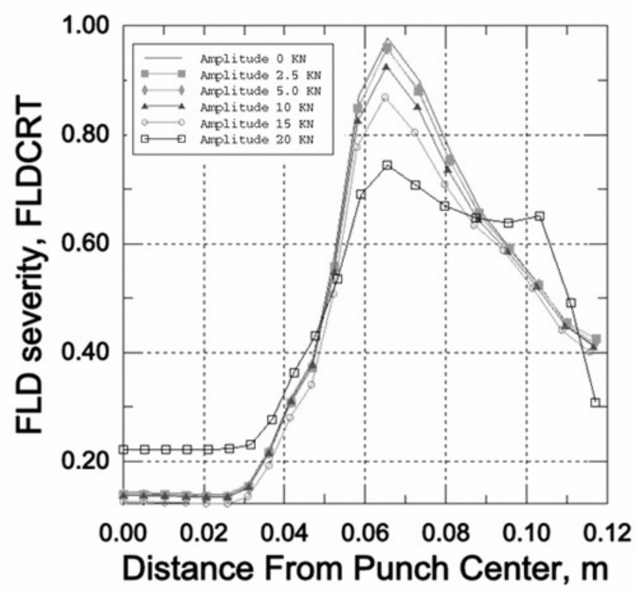


Fig. 14. Effect of BHF pulsation amplitude on deformation severity

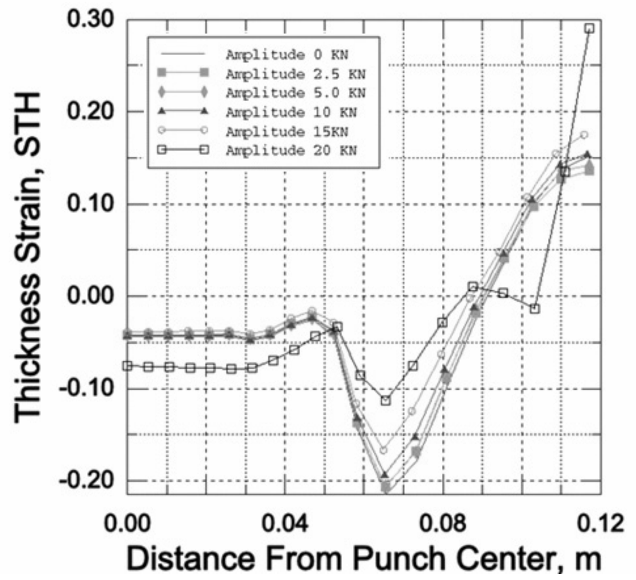


Fig. 15. Effect of BHF pulsation amplitude on thickness strain

However, large BHF amplitude could aggravate wrinkling conditions. For instance, as indicated in Fig. 16, for a maximum BHF of 27 kN and increasing the amplitude to more than 15 kN at a frequency of 10 Hz caused excessive detrimental wrinkling. Changing the frequency from 10 to 25 Hz decreased the wrinkling height drastically. This suggests that certain combination of frequency and amplitude could lead to favorable forming conditions. It seems that one should be a bit conservative in adopting the conclusion made by Siegert and Ziegler [11] suggesting that the working window gets wider with the increase of BHF amplitude. In fact, the LDR does not increase monotonically with the BHF amplitude; rather it peaks up and then drastically decreases as the BHF amplitude increases, Fig. 17.

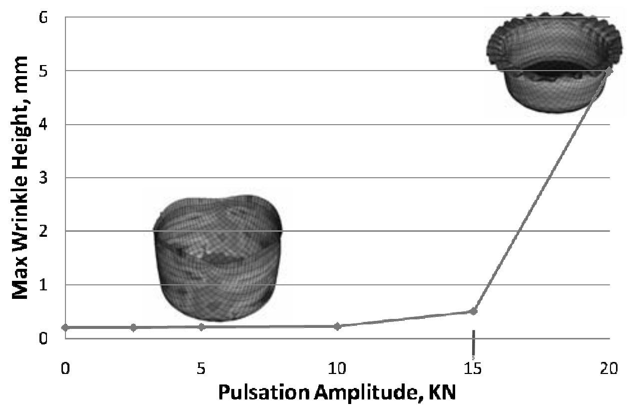


Fig. 16. Effect of BHF pulsation amplitude on wrinkling height

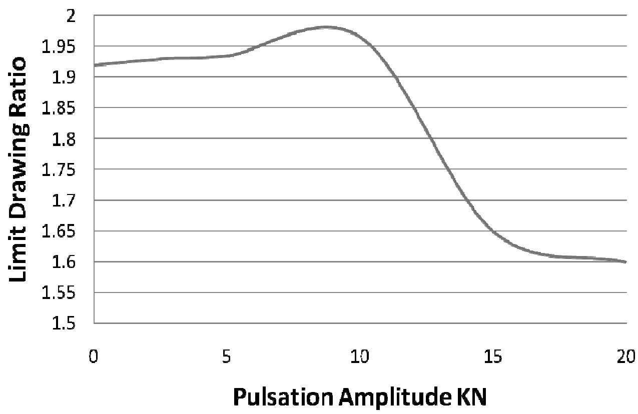


Fig. 17. Variation of the LDR with the BHF amplitude

3.4. Comparative study

In the previous sections emphasis was put on the determination of the conditions leading to successful cups, using various blank-holders. It is of interest now to compare the best results obtained for the 3 non-conventional BH used in this study. Fig. 18 indicates that for a drawing ratio of 1.92 (which is the optimum fixed BHF value), all non-conventional BH improved severity. The elastic ring blank-holder resulted in the least forming severity (lowest maximum FLDCRT). This blank-holder also produced the least wrinkling height, Table 1. However, it was noticed that this BH leads to the largest waviness among all blank-holders. It was noticed also that the location of maximum severity was in the cup wall, near to the punch nose in all cases considered.

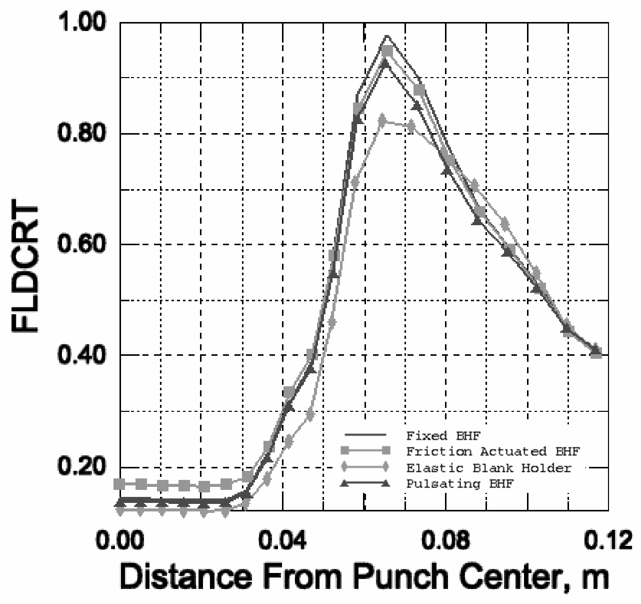


Fig. 18. FLDCRT for various BHF schemes

Table 1.
Comparison between various BHF schemes

	FLDCRT	Thickness Strain	Wrinkle height
Fixed Stiff BHF	0.9906	-0.2212	0.2
FA BHF	0.9621	-0.2044	0.19
Pulsating BHF	0.943	-0.1974	0.18
Elastic BH	0.8643	-0.1648	0.05

4. Concluding remarks

This study has indicated the complexity and interactive nature of the parameters affecting the performance of various blank-holding techniques. It has been demonstrated that certain combinations of such parameters would lead to the most favourable working conditions leading to a successful cup drawing. Efforts should be made to develop effective optimization techniques to control these parameters and optimize the BHF schemes. Experience suggests that using the finite element method as an evaluation engine of the objective function used in optimization is very powerful, but unfortunately very time consuming.

No claim is made here that the presented work is complete. The complexity of the problem calls for further studies taking the peculiarities of different materials formability limits and the complexity of part geometry. Here, the finite element method lends itself as a valuable tool for the assessment studies of the performance of various blank-holding techniques. The present work is part of a research work that is currently in progress under the supervision of the senior author on the assessment and search for optimized BHF schemes in deep drawing processes.

Development of blank-holding schemes continues to raise much interest. Combining ideas and concepts of different non-conventional techniques (see e,g. [7]) seems to be promising and is worth considering for finite element-based assessment.

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