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INFLUENCE OF PUNCH GEOMETRY AND HOLE EXPANSION RATIO ON THE HOLE FLANGING PROCESS: A FINITE ELEMENT ANALYSIS

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Abstract: *This study investigates the effect of punch geometry and hole expansion ratio (HER) on the hole flanging process through finite element analysis (FEA). Three punch shapes – cylindrical, conical, and spherical – were analyzed at varying HER levels (122%, 100%, and 82%) to assess their influence on strain distribution, thickness reduction, and forming force. The results indicate that higher HER values lead to increased strain and thinning, while punch geometry significantly affects formability. The cylindrical punch exhibits the highest deformation and force requirements, while the spherical punch minimizes these effects.*
Keywords: *hole-flanging; finite element analysis; sheet metal forming; hole expansion ratio; thickness reduction; strain distribution; forming force*

1. INTRODUCTION

Hole-flanging is a sheet metal forming process used to create flanges around pre-cut holes, enhancing structural integrity and providing functional features such as fastening points. The process involves expanding a hole using a punch, leading to material deformation and thinning, which must be carefully controlled to prevent failure.

Key process parameters influencing hole-flanging include the punch shape and the hole-expansion ratio (HER). The hole-expansion ratio is defined as:

$$\mathrm{HER} = \left(\frac{\text{final diameter}}{\text{initial diameter}} - 1\right) \text{x } 100\% \,. \quad (1)$$

It determines the degree of hole expansion and material stretching. A higher HER generally results in greater deformation and potential thinning of the material.

The choice of punch shape significantly impacts strain distribution, thickness reduction, and the forming force required. Cylindrical punches ensure uniform expansion but may induce higher stress concentrations. Conical punches provide a gradual expansion, reducing peak forces but potentially leading to non-uniform deformation. Spherical punches distribute stress more evenly but can cause excessive thinning.

Among previous studies focusing on the conventional hole-flanging process, in terms of punch geometry used, the conical, spherical, and cylindrical punch shapes are the most commonly examined. Among these, the conical punch has been the most widely utilized, followed by hemispherical and cylindrical shapes. While the majority of studies investigate a single punch geometry, one notable study [1, 2] conducts a comparative analysis of all three shapes, specifically examining their effect on the hole expansion ratio in deep-drawing steel sheets. The findings indicate that the maximum achievable hole expansion is strongly dependent on punch geometry, with the conical punch yielding the highest hole expansion ratio, while the cylindrical punch exhibits the lowest. Additionally, wall thinning is significantly reduced when using conical and spherical punches compared to the cylindrical counterpart. Furthermore, strain distribution analysis suggests that the conical punch provides the most favorable strain state.

The hole expansion ratio has also been studied in the context of different hole-flanging techniques, with conflicting conclusions regarding the comparative performance of conventional and incremental approaches. While some studies [3] suggest that incremental hole flanging results in larger HERs than the conventional method, others [4] report the opposite, indicating that HER values in incremental hole flanging can be lower. Additionally, investigations into single-stage versus multi-stage hole-flanging strategies [5] reveal that increasing the number of forming stages does not necessarily lead to higher HERs. A noteworthy study [6] demonstrated a remarkable 130% increase in HER by employing a specialized incremental featured tool compared to a conventional incremental ball-nose tool. This finding further underscores the strong correlation between HER and punch geometry.

Despite the current research on hole flanging, extremely few studies have systematically analyzed the influence of varying punch geometries on the hole expansion ratio (HER) within the process. While existing literature provides insights into the effects of punch shape on factors such as strain distribution, thinning, and limit expansion, most studies focus on individual punch geometries rather than comparative analyses. Furthermore, conflicting findings regarding HER variations in different flanging techniques highlight the complexity of the process and the need for a deeper understanding of the underlying mechanics.

Given this gap, the present study employs numerical simulations with the aim of further investigating the effect of the punch geometry and hole expansion ratio on key output parameters, namely the major strain, minor strain, thickness reduction and forming force.

2. MATERIALS AND METHODS

In this study, numerical simulations of the hole flanging process were conducted using finite element analysis (FEA). The simulations were performed with the Thin Shell 163 element type. Shell elements, in contrast to solid elements, are particularly advantageous in capturing the deformation characteristics of thin-walled structured, allowing for accurate measurement of thinning, which is a key parameter in evaluating formability and failure in sheet metal forming.

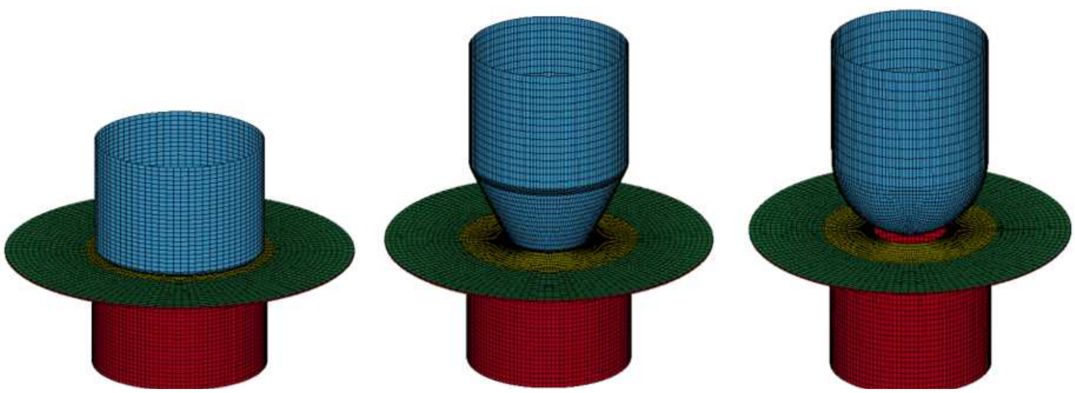

Fig. 1. Punch shapes

The material selected for this study is DC05 steel, a deep-drawing steel grade commonly used in industrial applications due to its good formability and ductility properties. DC05 is a low-carbon steel with enhanced mechanical properties, making it particularly suitable for forming operations such as hole flanging. The key mechanical properties of DC05 steel are presented in Table 1.

Table 1.

DC05 material properties

DC05 Steel – Property	Value
Young’s Modulus	220 GPa
Density	7870 kg/m3
Poisson’s ratio	0.3
Yield Strength	180 MPa
Ultimate Tensile Strength	300 MPa

To evaluate the influence of punch geometry on the hole flanging process, three distinct punch shapes were considered: cylindrical, conical, and spherical. Each punch geometry induces a different strain distribution and material flow during hole expansion, which in turn affects the hole expansion ratio (HER) and overall formability of the material. The punch shapes used in the numerical simulations are presented in Figure 1.

A structured Design of Experiments (DoE) approach was employed to systematically investigate the effects of punch shape and HER on the hole flanging process.

In this study, two key parameters were considered: the punch geometry and the hole expansion ratio (HER). These parameters were varied at three levels each, namely a cylindrical, conical and spherical punch shape, and a HER of 122%, 100%, and 82%, respectively.

The combination of these factors resulted in a total of nine simulation cases, summarized in Table 2.

Table 2.

Design of experiments

No.	Punch geometry	Hole Expansion Ratio (HER)
1	cylindrical	122%
2	cylindrical	100%
3	cylindrical	82%
4	conical	122%
5	conical	100%
6	conical	82%
7	spherical	122%
8	spherical	100%
9	spherical	82%

3. RESULTS

The analysis of the hole flanging process was primarily focused on four key output parameters: major strain, minor strain, thickness reduction, and maximum forming force.

The major strain provides insight into the extent of elongation experienced by the sheet metal, while the minor strain represents the contraction or expansion of the material perpendicular to the direction of major strain. Excessive strain values can lead to localized thinning and potential fracture. High levels of thickness reduction may result in weakened structural integrity. The maximum forming force refers to the peak force required to complete the hole expansion process and it determines the energy input needed for manufacturing.

The resulting data are presented in the series of Figures 2-5 for case 9, and summarized in Tables 3 and 4, which provides a comparative overview of the major and minor strain, thickness reduction, and maximum force for each case.

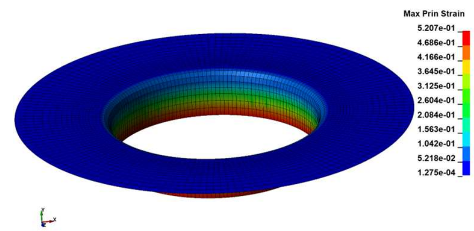

Fig. 2. Major strain distribution in case 3 (spherical punch, HER = 82%)

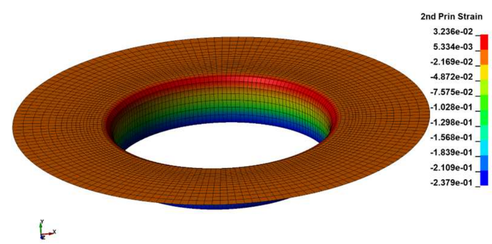

Fig. 3. Minor strain distribution in case 3 (spherical punch, HER = 82%)

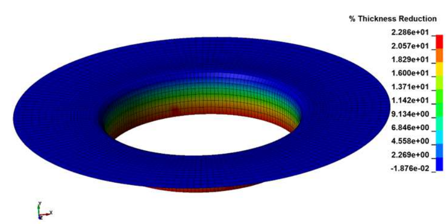

Fig. 4. Thickness reduction in case 3 (spherical punch, HER = 82%)

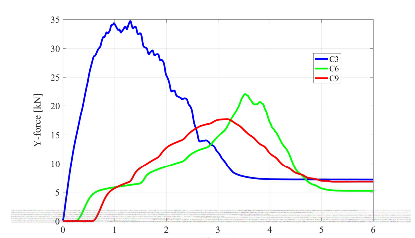

Fig. 5. Forming force in cases 3 (cylindrical punch), 6 (conical punch) and 9 (spherical punch, HER = 82%)

When analyzing the major strain, minor strain, and thickness reduction distributions, a common pattern was observed across all cases. The highest values for all three parameters consistently appear in the cylindrical wall of the formed flange, particularly at its lowest section. This region undergoes the most severe deformation due to the combined effects of stretching and material flow constraints. During the forming process, the major strain increases steadily as the material is stretched radially outward to form the flange, especially around the lower section of the cylindrical wall. At the same time, the minor strain becomes more negative due to thinning in the circumferential direction. This combination of stretching and thinning leads to localized deformation, with the highest strain concentrations occurring where the material flow is most restricted.

Table 3.

Results (Part ½)

No.	Major strain [mm/mm]	Minor strain [mm/mm]
1	0.7072	-0.3223
2	0.6017	-0.2810
3	0.5191	-0.2426
4	0.7218	-0.3346
5	0.6215	-0.2944
6	0.5409	-0.2531
7	0.7000	-0.3237
8	0.6050	-0.2855
9	0.5207	-0.2379

Table 4.

Results (Part 2/2)

No.	Thickness reduction [%]	Force [kN]
1	31.16	46.29
2	27.02	40.43
3	23.53	34.69
4	30.11	25.82
5	26.12	22.73
6	22.88	22.02
7	30.17	22.59
8	26.37	19.29
9	22.86	17.69

To better visualize and interpret the dependencies between the input parameters and the output results, a series of 3D surface plots are also provided below. These graphs illustrate how the major strain, minor strain, thickness reduction, and forming force vary as functions of the punch geometry and HER.

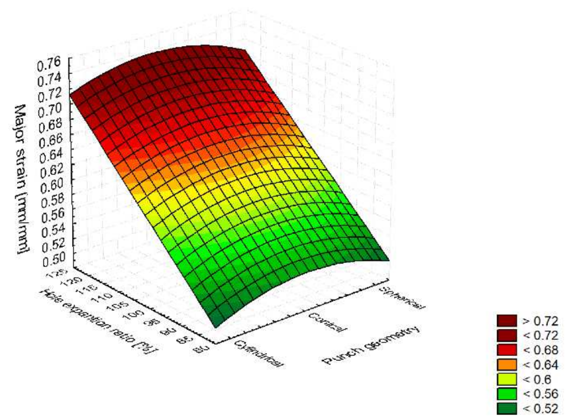

Fig. 6. Variation of major strain with HER and punch geometry

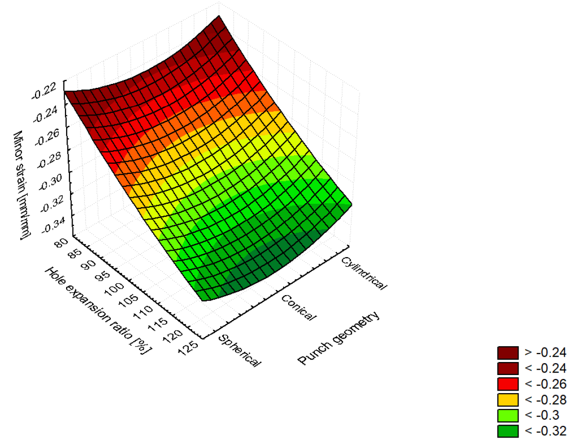

Fig. 7. Variation of minor strain with HER and punch geometry

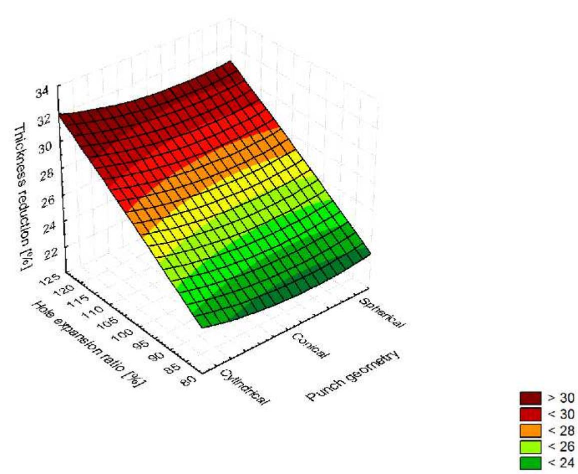

Fig. 8. Variation of thickness reduction with HER and punch geometry

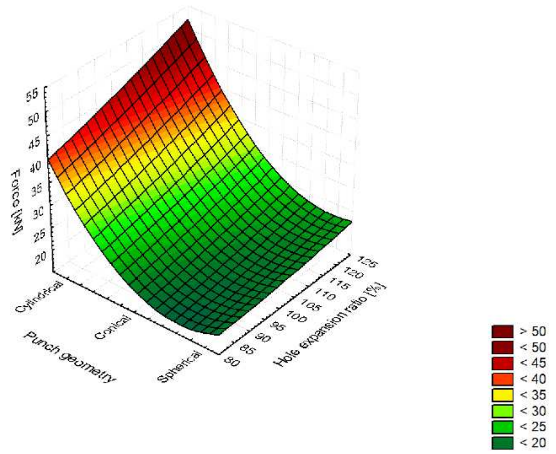

Fig. 9. Variation of forming force with HER and punch geometry

The key observations for each output parameter, as deducted from the variation graphs presented in Figures 6-9, are described in the following sub-chapters.

3.1 Major strain

The major strain increases with increasing HER across all punch shapes. Conical punches exhibit the highest major strain values, but not significantly higher than those obtained with the other punch shapes. The major strain values for cylindrical and spherical shapes are very similar. The highest major strain is found at the combination of highest HER (122%) and conical punch. The lowest major strain occurs at the combination of lowest HER (82%) and cylindrical punch.

3.2 Minor strain

Similar to the major strain, the minor strain (on absolute value) increases with increasing HER across all punch shapes. Also, the spherical punch gives the lowest values of the minor strain. The highest minor strain (on absolute value) is found at the combination of highest HER (122%) and conical punch. The lowest minor strain (on absolute value) is found at the combination of lowest HER (82%) and spherical punch.

3.3 Thickness reduction

Again, thickness reduction increases with increasing HER across all punch shapes. The cylindrical punch causes the highest thinning, while the conical and spherical punches give very similar results, just slightly lower than the cylindrical punch. The highest thinning is found at the combination of highest HER (122%) and cylindrical punch. The lowest thinning is found at the combination of lowest HER (82%) and spherical punch.

3.4 Forming force

The maximum force also increases with increasing HER across all punch shapes. The cylindrical punch requires the highest force, approximately twice as high as that required by the other two punch shapes, while the spherical punch requires the lowest force. The conical punch shows a slower rate of decrease in minor strain as HER decreases. The highest force is found at the combination of highest HER (122%) and cylindrical punch. The lowest force is found at the combination of lowest HER (82%) and spherical punch.

The relationship between parameters reveals a consistent trend. The major strain, minor strain, thickness reduction, and maximum forming force all increase with increasing hole expansion ratio. Similarly, the punch geometry significantly influences the results, with the cylindrical punch almost consistently producing the highest values for all parameters, while the spherical punch results in the lowest values. This suggests that more gradual punch geometries, such as the spherical shape, lead to reduced deformation and thinning, whereas the cylindrical punch induces the most severe strain and force requirements.

4. CONCLUSIONS AND DISCUSSION

The study indicates that the punch shape and hole expansion ratio significantly affect the forming process. The results suggest a decreasing trend in forces, thickness reduction, and strains as HER decreases, suggesting a clear dependency between these parameters. While the exact mathematical relationship would require further regression analysis, the trend suggests a near-linear decrease. Similarly, these output parameters decrease progressively from cylindrical to conical to spherical punches in almost all cases.

Therefore, cylindrical punches demand the highest forming force, which could lead to increased tool wear and energy consumption. Spherical punches, on the other hand, require the lowest force, making them advantageous for applications where reduced energy input is critical.

Thinning is more severe in cylindrical punches, which may lead to structural weaknesses. Conical punches offer a balance by moderating force requirements while minimizing excessive thinning. Spherical punches provide the most uniform strain distribution, ensuring better material utilization and improved durability of the formed flange.

Among all cases, the spherical punch together with a HER as small as possible presents the most favorable outcome, combining low forming force with minimized thinning, thereby ensuring efficiency and part integrity.

However, additional validation, including experimental trials, is recommended to verify numerical results and further refine process parameters for specific applications.

This study provides valuable insights into the hole-flanging process, aiding in the selection of optimal punch geometry and forming conditions for improved efficiency and material integrity.

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Influența geometriei poansoanului și a coeficientului de răsfrângere asupra procedeului de răsfrângere a marginilor: analiză cu elemente finite

Acest studiu investighează efectul geometriei poansonului și al coeficientului de răsfrângere (HER) asupra procedeului de răsfrângere a marginilor prin analiza cu elemente finite (FEA). Trei forme ale poansonului - cilindrică, conică și sferică - au fost analizate la diferite niveluri HER (122%, 100% și 82%) pentru a evalua influența acestora asupra distribuției deformațiilor, reducerii grosimii și forței de deformare. Rezultatele indică faptul că valorile HER mai mari conduc la creșterea deformării și a subțierii, în timp ce geometria poansonului afectează semnificativ deformabilitatea. Poansonul cilindric conduce la cele mai mari deformații și forțe, în timp ce poansonul sferic minimizează aceste efecte.

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