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THE DEVELOPMENT OF AN INTEGRATED PLATFORM (CAD/FEA/CAM) FOR THE DEEP DRAWING PROCESS

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ABSTRACT

The main objective of this research is to develop an integrated platform for a computer aided design, finite element analysis, and computer aided manufacturing modules (CAD /FEA/CAM) of the deep drawing process for cylindrical cups. The integrated platform was done through the use of programs (VB6), UGS-NX9, and ABAQUS on a personal computer. In this paper, these modules are constructed to facilitate several industrial applications in the process of sheet metal die design and manufacturing. Finally, CAD /FEA/CAM results for a case study are applied experimentally to validate the developed integrated platform. Simulation results provide useful information to address the feasibility of the actual production process.

Keywords: CAD, FEA, CAM, deep drawing, tool path simulation, validation.

1. INTRODUCTION

Many engineers create tools of the same geometry as those used in process modeling or simulated manufacturing using computer-aided design (CAD) programs. Manufacturers can model their manufacturing process in a virtual environment to save money and time spent on real-world pilot development or realistic testing during the evaluation phase. Furthermore, simulation findings provide useful information for determining the feasibility of a real production process. The quality of the product will also be improved. The complexities of redesigning and upgrading tools are minimized.

The current manufacturing environment can be categorized by the paradigm of providing products of increasing diversity, minor batches, and better quality in the context of growing global competition. Industries cannot continue worldwide competition unless they present new products with higher quality, at lower costs, and with smaller lead-time. There are intense international competition and reduced availability of skilled labor. With affected variations in computing power and extensive obtainability of software tools for design and manufacture, engineers are now utilizing Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), and Finite Element Analysis (FEA) systems to computerize their design and manufacture processes. These technologies are now utilized every day for varieties of diverse engineering problems.

Commercially available CAD/CAM systems offer some help in drafting and analysis in the die design process, but human knowledge is still required to reach the final design [1]. Also, these systems are general-purpose and involve high setup costs. Many systems, such as Case-Based Reasoning, Blackboard Architecture systems, Hybrid Systems, Artificial Neural Network, Graph Theory, and Knowledge-Based System, are being used worldwide to solve challenging problems in the design and manufacturing fields as artificial intelligence develops.

Amongst the methods of sheet metal forming, deep drawing is the most commonly used. However, the old process design of deep drawing is done by human experiences with their experimental knowledge. In the latest years, some computer-aided process and die design systems based on the experimental knowledge of the field specialists have been technologically progressive for axisymmetric deep drawing products.

The Automatic Generation of Forming Process Outlines (AGFPO) method was developed by Eshel *et al.* [2] for axisymmetric components produced by the deep drawing process. They suggested the G&TR (Generate, Test, and Rectify) approach for the process planning of axisymmetric deep drawing products. The system depends only on experience-based die-design rules for its process-sequence design.

Thus a knowledge-based system that joins the experimental database, production guidelines, and inference machine, looks like to overcome the difficulty of design for different forming processes [3]. In the field of the deep drawing process, Eshel *et al.* [4] are the leaders of the expert method. They contributed to establishing the fundamental metal flow pattern and mathematical formalization for the deep drawing process and complete the experimental system known as automatic generation of forming process outlines (AGFPO) dependent on the C-Prolog and UNIX operating system. They also proposed to a reasonable tactic for rule-based automatic reasoning called as generate and test and rectify (G&TR).

Tisza's work [5] defines a modular CAD/CAM system, for developing deep drawing process arrangements and designing tools for the fabrication of sheet metal products having axisymmetric and rectangular cross-sections. Sitaraman *et al.* [6]developed a hybrid computer-aided engineering (CAE) framework for the automated design of axisymmetric sheet metal component process arrangements. A knowledge-based system (KBS) or expert system module, as well as a process modeling evaluation module, are the two key products of the hybrid CAE system. In designing axisymmetric deep drawing elements, Xiao *et al.* [7] developed the expert model. The model can be used for general drawing process planning as well as axisymmetric part strip progressive drawing. Tisza *et al*. [8] built an expert framework for axisymmetric deep drawing product process planning.

Doege and Boinski [9], at the Institute for Metal Forming and Metal Forming Machines at the University of Hannover, developed a computer-aided design system for the design of deep-drawn products in the framework of research projects. The system depends on elementary calculation techniques, experimentally defined parameters, and technological expert knowledge. By resources of the program system established at the Institute for Metal Forming and Metal Forming Machines and based on the geometry of the finished part, a rough design of the forming phases is done with the aid of process-specific parameters and empirical values. Based on these rough geometries, the number of phases and the geometry of the individual phases are enhanced by finding the part-specific limits of failure. This technique is mainly utilized to check the finished design strategies.

Tisza [10], [11] developed a deep drawing expert framework built on the Linux operating system and used Motif and OpenGL. Based on G&TR, the system, he adopted the scheme where a geometrically feasible process plan was rectified by technological constraints.

Esche *et al.* [12] established the Axisymmetric Sequence Forming Expert System (ASFEX) for axisymmetric parts, produced by deep drawing. The process design systems (Eshel [2], Sitaraman [6], Xiao [7], Zhu [8], Tisza [11], and Esche [12]) were developed utilizing the G&TR strategy that was suggested by Eshel *et al*. [2], and the tool design and forming analysis were done.

A CAD/CAM platform for axisymmetric deep drawing processes was constructed by Park *et al.* [13]. Where the Pro–Deep system produces the inputs for this CAD/CAM platform. The system, Pro–Deep program, is the process design of a deep drawing system for axisymmetric products; Doege *et al.* [14]. A knowledge-based technique is used for the system under the environment of CAD/CAM software of a personal designer. The geometry of the intermediate and the final product in deep drawing processes, with process parameters, is the input for the CAD/ CAM arrangement. The input information can be found from the outcomes of the Pro–Deep program. The part drawings of die sets for each process are produced in the tool design module of the CAD/CAM system. Additionally, die construction drawings could be acquired. NC commands for the fabrication of the part could be generated in the designed CAD/CAM system. The system can be useful to a blanking die set and deep drawing in a simple action press.

The Virtual Design System (VDS) was developed by Hindman and Ousterhout [15], and it involves an expert system, manufacturing process models, and real-time fabrication. Where in an innovative method, the VDS for sheet metal shaping is used. The World Wide Web is utilized as the platform for the VDS, and it provides many benefits to the traditional stand-alone method. The VDS assists by rapidly producing the required data for the development of a successful component and can operate simple simulations of actual production processes. In addition, it does not need the user to have a special processing platform or to be positioned in a special geographic area. Completed designs can be moved to the production facility rapidly to begin manufacturing. File protection and precision are addressed as possible disadvantages to this process. Real-world implementation of this system is becoming carried out.

Singh and Sekhon [16] established a professional technique to help the sheet metal planner in making an informed selection of the press machine for a given deep drawing sheet metal process from the alternative machines available on a given shop floor.

Kim *et al*. [17] proposed an expert development system based on a 3D CAD system customized for the design of drawing die for automotive parts. The suggested system facilitates the die design process professionally and systematically by employing standard data and design information. The standard data and design information of draw die have been gathered and accumulated through the meeting with design professionals employed in the Korean motor company. Parametric design utilizing an information base and standard database are presented for dealing with different and complex design information easily.

Potocnik *et al.* [18] suggested a smart system for the automatic computation of stamping parameters to design a stamping die for manufacturing a hollow cup with flange. This system runs on the basis of incorporated information that is inserted in a CATIA V5 utilizing user parameters and programmable recognized relationships among them.

Liu *et al*. [19], suggested a comprehensive strategy with two developed analytical models for multi-stage deformation pass design. The models are matched with finite element analysis and experimental works for assessing the process formability of the final product and thickness strain distributions. Two open-loop analytical models have been created and tested, utilizing the assumption of shear deformation, provided the expected thickness strain of the final product as the major parameter. Utilizing the same technique as in Li *et al*. [20], based on the design factors, the formed shaping phases can be predictable first (total thinning and average thinning rate). In order to identify the equivalent deformation pass, the minimum thickness strains in the intermediate forming stages are developed to determine the expected thickness strains in each forming stage. A case study is presented to show the design system.

Through the last two decades, the incorporation of structural design and performance analysis perform an important part in complicated product design. The objective of this integration is to get significantly better efficiency, higher consistency, and smaller improvement phases [21]. Nevertheless, a crucial difference between CAD and CAE requires tiresome repeated interactions between CAD and the finite element model (FEM). When a complicated product design is included, tiresome repeated interactions are predicted to expense over 80% of the expense of the whole analysis, and the final product is probably not competent [22]. At the present time, several created optimization techniques have enhanced the performance of dealing with this powerful module of CAD/CAE integration. The majority of these techniques could be classified into two categories. One is interface depending on data exchange and environment of CAD/CAE software, which is commonly utilized to integrate varied systems [21]. Matin *et al.* [23] introduced a knowledge-based, parametric, modular, and feature-based incorporated CAD and CAE system for the design of the mold. Liu and Ma [24] suggested a novel CACD/CAD/CAE incorporated platform for design, modeling, and optimization of fiber-reinforced plastic parts, which can greatly improve the modern design process by recognizing partial automation and multi-stage optimization. Based on Matin *et al*. [23] and Liu *et al.* [24], Wang and Niu [25] suggested a CAD/CAE incorporation technique in the design and optimization of a machine tool structure and utilized a knowledge-based design and multi-stage optimization method to preserve incorporation between CAD and FEA modules.

Wang and Hu [26] introduced an open and integrated platform that carries out the structural design optimization through connecting the enhanced sequential approximation optimization (SAO) algorithm along with the CAD/CAE framework. Hamir *et al*. [27] suggested a new software environment for CAD/CAE integration dependent on the combined representation which is managed on the same High Level Topology (HLT). Nagashima [28] presented a node by node meshless method (NBNM) which is able to employ CAD data simply and carrying out efficient adaptation analysis.

Saric *et al.* [29] established an integrated intelligent CAD system for designing mechanical power transmitting mechanisms. Saric and his team used the C# program to develop this system. Their system is contained modules for the calculation of geometrical and design features of mechanical power transmitting mechanisms. 3D geometrical parameter modeling was performed for mechanical power transmitting mechanisms in CAD/CAM/CAE system CATIA V5 software.

Kirkwood and Sherwood [30] suggested virtual persistent identifiers (VPI) which provide continuous integration between the FE model and introduced neutral format CAD models. Saric and Muminovic [31] developed an integrated intelligent CAD system for the design of pressure vessels. This system will assist engineers by providing rapid computations of design factors, automatic generations of a 3D geometrical model, and automatic transference of numerical analysis for stress and deformation for pressure vessels.

Yin *et al.* [32] developed a CAD/CAE framework that included a quick-redesign vibration analysis system as well as a unified data architecture for traveling-wave tubes. Traveling wave tubes (TWTs) are commonly utilized as a microwave power amplifier in civil and military applications. There are four modules in this system: CAD/CAE integrated design environment, parametric modeling, simple finite element free vibration analysis solver, and fast finite element random vibration analysis solver.

In the last decade, researchers are still trying to develop integrated platforms to facilitate the design and manufacturing process in several fields, including the design and manufacture of deep drawing dies [29]–[35]. Consequently, the ultimate aim of the present work is to develop an integrated platform for CAD/FEA/CAM of sheet metal dies for automatic process sequence design, FEA simulation, and manufacture tools for the sheet metal deep drawing process of cylindrical cups.

2. CAD/FEA/CAM SYSTEM FOR THE DEEP DRAWING PROCESS OF CYLINDRICAL CUPS

The overall objective of this research is to develop an integrated platform for CAD/FEA/CAM of sheet metal dies in the deep drawing process for cylindrical cups. The integrated platform is created by writing in VISUAL BASIC codes and by using UGS-NX9 and ABAQUS programs through the codes of VISUAL BASIC programming language with a personal computer.

An integrated platform is developed to connect the three systems (CAD, Parametric model of FEA, and CAM) for the deep drawing process of cylindrical cups. Figure-1 shows the window of the integrated platform (CAD/FEA/CAM), whilst Figure-2 describes the flow chart of the sequence of the solution in this integrated platform for the deep drawing process of cylindrical cups.

In the proposed integrated platform, the user can utilize the CAD module to calculate the processes parameters (forces, press capacity, die and punch dimensions) and can get complete parametric drafting drawing for the die set (punch, blank holder, and die). Furthermore, the user can employ the FAE module to get the 3-D numerical simulation of sheet metal deep drawing process for cylindrical cups (Parametric Model) by using ABAQUS/EXPLICIT finite element analysis (FEA) software with anisotropic material properties and simplified boundary conditions to check failure in the drawn cup. This will be done by linking the integrated platform of CAD/FEA/CAM with the ABAQUS/EXPLICIT FEA software. Figure-3 illustrates the important dimensions of the die set assembly (punch, blank holder, and die) for the deep drawing process [36].

To minimize processing time, the numerical analysis of the deep-drawing process was conducted using just one-quarter of the 3D numerical model due to the symmetry. Figure-4 [36] demonstrates the 3D FEA model. The punch, die, and holder were all modeled using the distinct rigid form, and their motion was controlled by the motion of a single node called the rigid body reference node. R3D4 elements mesh type is utilized with the die, punch, and blank holder. With a planar shell base and meshed with reduced integration S4R shell-type element, only the blank sheet metal was made deformable [37]. Inside the simulation software (ABAQUS/EXPLICIT), the material is modeled as an elastic-plastic material with isotropic elasticity, with the Hill anisotropic yield criteria for plasticity used to characterize the anisotropic characteristics of the sheet metal.

Finally, the user can use the CAM module to get tool path simulation and generate CNC machining commands (G-Codes) for the die set manufacturing processes. This will be done by connected the integrated platform of CAD/FEA/CAM with the UGS-NX9 program.

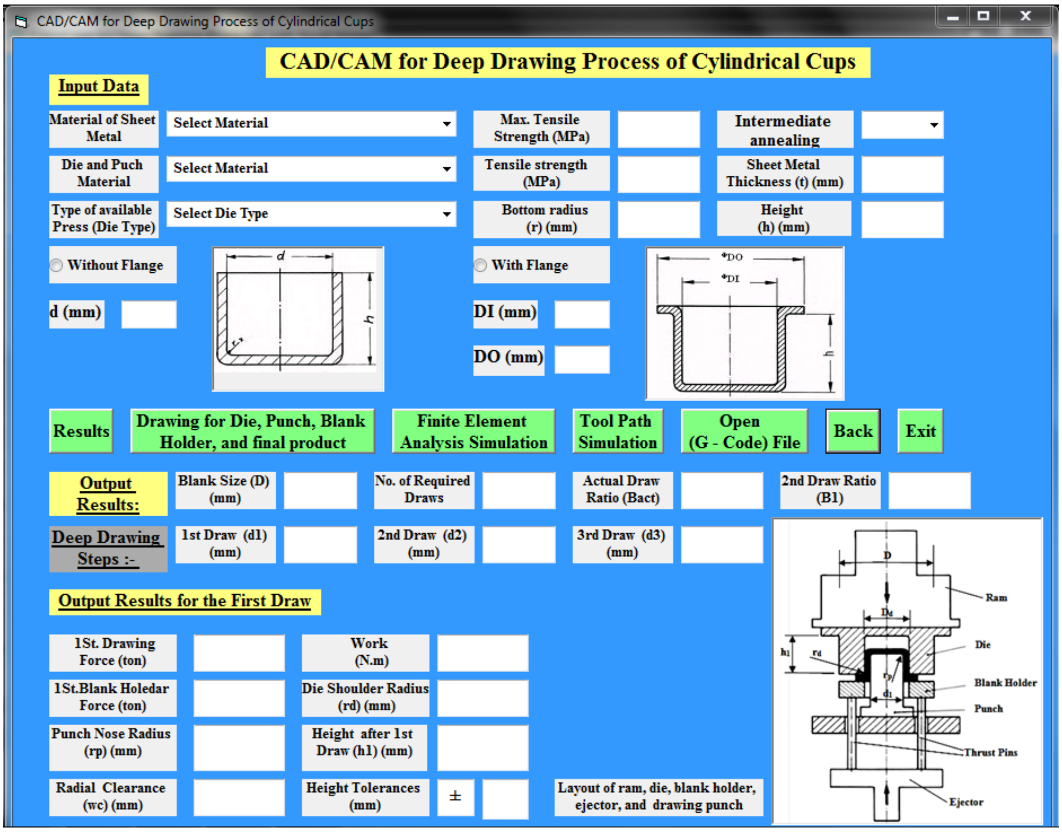


Figure-1. The integrated platform (CAD/FEA/CAM) for deep drawing processes of cylindrical cups.

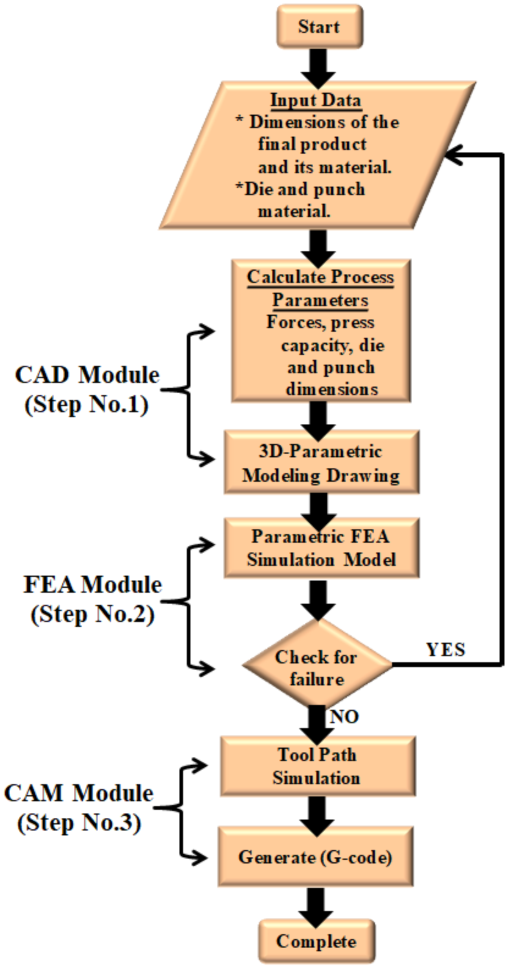


Figure-2. Flow chart of the sequence of the solution in the integrated platform of (CAD/FEA/CAM) for the deep drawing process of cylindrical cups.

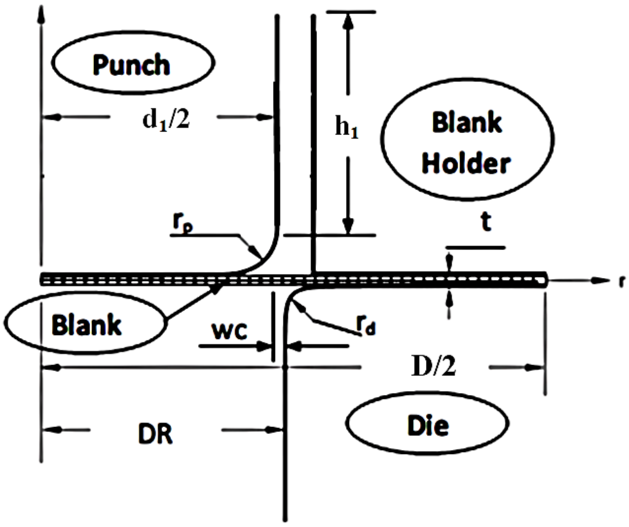


Figure-3. Dimensions of the deep drawing die set assembly.

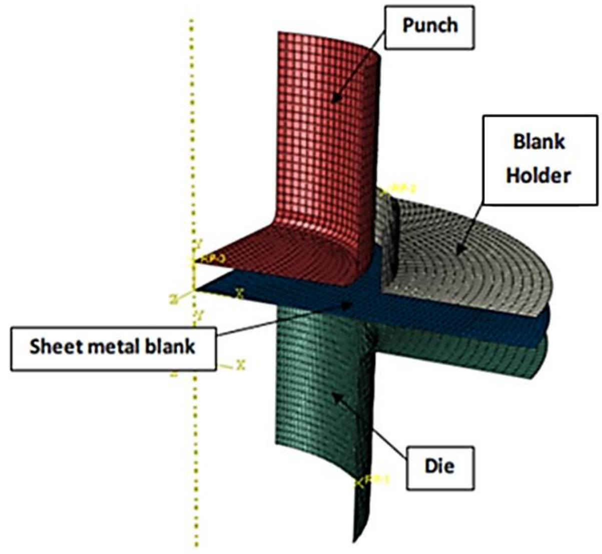


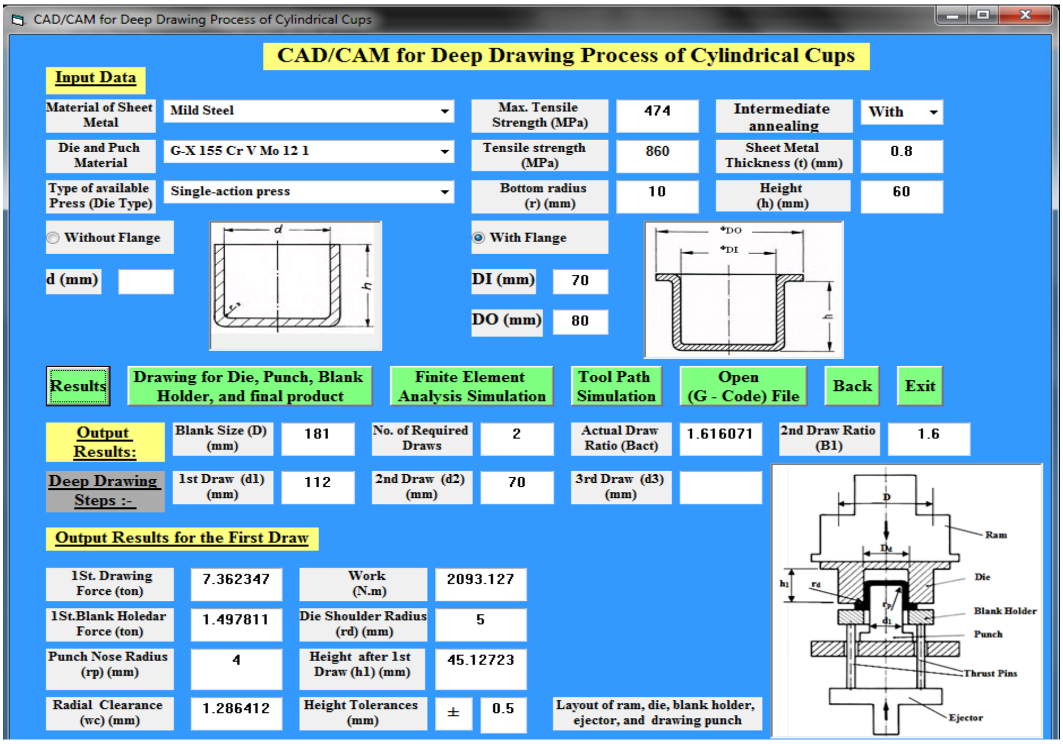
Figure-4. The model assembly scheme in FEM.

3. RESULTS AND DISCUSSIONS

The aim is to manufacture sheet cylindrical cups on a single-action drawing press (for the first draw). The material of the sheet metal of the presented case study is mild steel with an ultimate tensile strength equal to 474 MPa and sheet metal thickness equal to 0.8 mm. Also, the design of the die set (punch, blank holder, and die) is required. The material of the die, the punch, and the blank holder is steel (H13). Figure-5 shows the sequence of the solution (Input Data, and Output Results) by using the first module. Figure-6 displays 3D modeling for the die and the die set assembly by utilizing the first module which is obtained by pressing on drawing button in Figure-5.

For the FEA module ($2^{nd.}$ step); as seen in Figure-5, by pressing on the finite element analysis simulation button, the integrated platform will assist in identifying any design issues before they are produced. In this module, the FE model for the 3D numerical simulation of the sheet metal deep drawing process (Parametric Model) was developed by applying anisotropic material properties and simpler boundary conditions as presented in the previous section.

Many damage initiation criteria for ductile materials are available in ABAQUS, each of which is synonymous with different shapes of material fracture. One of these criteria is the sheet metal necking instability damage initiation criterion. This includes forming limit stress diagram (FLSD) intended to assess the formability of sheet metal and to numerically predict necking instability in sheet metal taking into account the deformation history. An (FLSDCRT) value of 1.0 or higher indicates that the initiation criterion has been met [38].



CAD/CAM for Deep Drawing Process of Cylindrical Cups

CAD/CAM for Deep Drawing Process of Cylindrical Cups

Input Data

Material of Sheet Metal: Mild Steel
Die and Puch Material: G-X 155 Cr V Mo 12 1
Type of available Press (Die Type): Single-action press
Max. Tensile Strength (MPa): 474
Tensile strength (MPa): 860
Bottom radius (r) (mm): 10
Intermediate annealing: With
Sheet Metal Thickness (t) (mm): 0.8
Height (h) (mm): 60
○ Without Flange
d (mm):
● With Flange
DI (mm): 70
DO (mm): 80

Output Results:
Blank Size (D) (mm): 181
No. of Required Draws: 2
Actual Draw Ratio (Bact): 1.616071
2nd Draw Ratio (B1): 1.6

Deep Drawing Steps :-
1st Draw (d1) (mm): 112
2nd Draw (d2) (mm): 70
3rd Draw (d3) (mm):

Output Results for the First Draw
1St. Drawing Force (ton): 7.362347
1St.Blank Holedar Force (ton): 1.497811
Punch Nose Radius (rp) (mm): 4
Radial Clearance (wc) (mm): 1.286412
Work (N.m): 2093.127
Die Shoulder Radius (rd) (mm): 5
Height after 1st Draw (h1) (mm): 45.12723
Height Tolerances (mm): ± 0.5

Layout of ram, die, blank holder, ejector, and drawing punch

Figure-5. The integrated platform for $1^{st.}$ Module (Insert input data, and Getting Output Results for 1st. Deep Drawing).

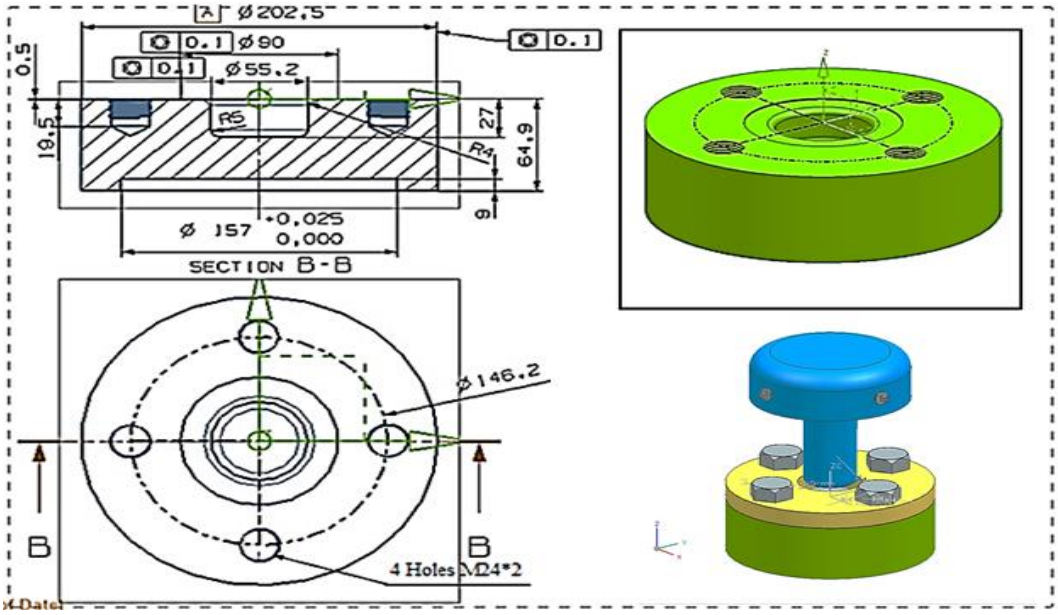


Figure-6. $1^{st.}$ Module (3D Modelling for Die and die set assembly).

The geometry of the die (die shoulder radius, punch nose radius, and radial clearance) affects the thickness distribution and thinning of the sheet metal blank in the deep drawing processes. Figure-7 shows the values of forming limit stress diagram (FLSD) damage initiation criterion (FLSDCRT) at different values of die shoulder radius (r_d). Figure-8 demonstrates the values of forming limit stress diagram (FLSD) damage initiation criterion (FLSDCRT) at various values of the punch nose radius (r_p). Where the radial clearance is formulated as the difference between die radius and punch radius; as shown in Figure-3. Figure-9 displays the values of forming limit stress diagram (FLSD) damage initiation criterion (FLSDCRT) at diverse values of radial clearance (wc) by using damage initiation criteria in ABAQUS for FLSD of mild steel material of the sheet metal.

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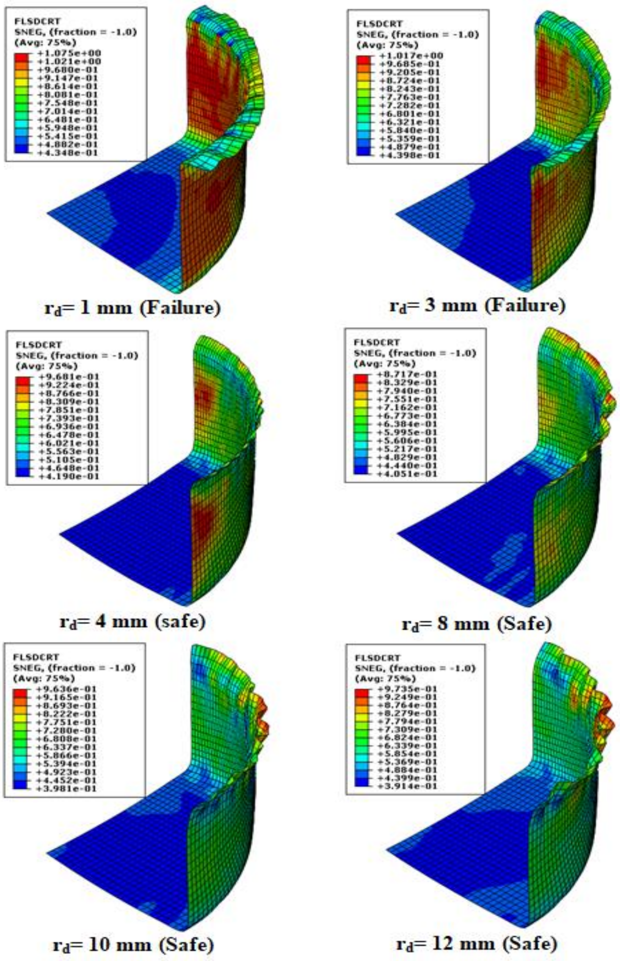
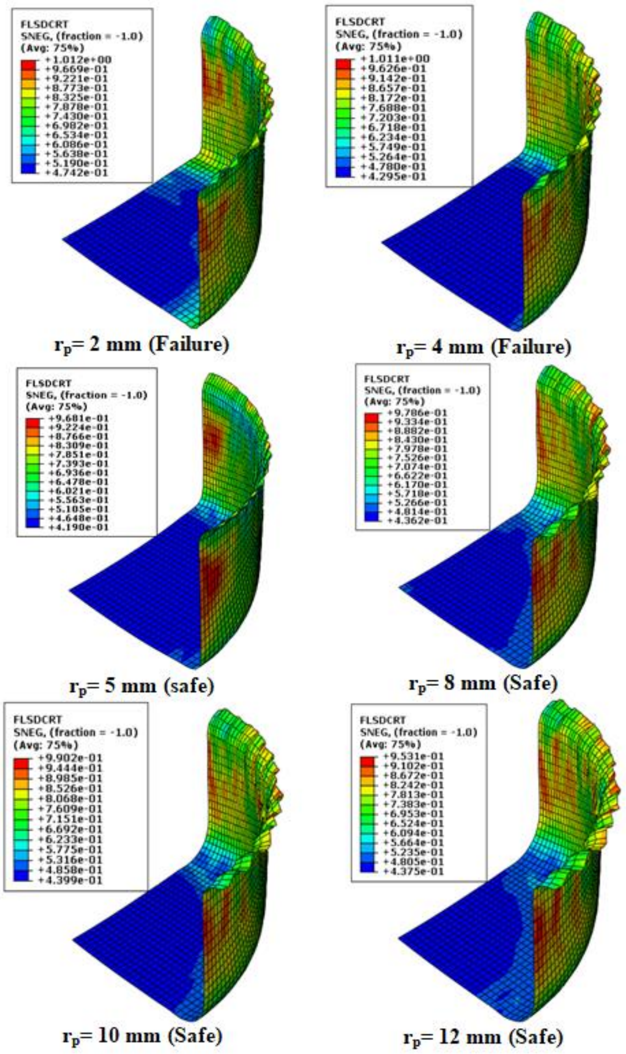


r_d= 1 mm (Failure) r_d= 3 mm (Failure)

r_d= 4 mm (safe) r_d= 8 mm (Safe)

r_d= 10 mm (Safe) r_d= 12 mm (Safe)

Figure-7. Check failures at different values of die shoulder radius (r_d) by using damage initiation criteria in ABAQUS for FLSD of mild steel material of the sheet metal.



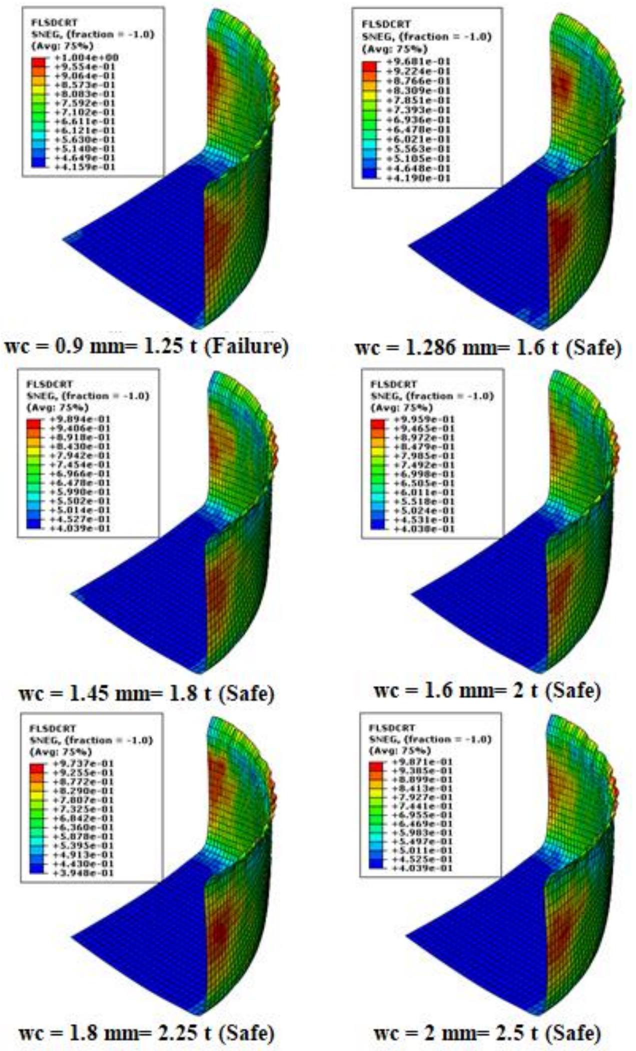
r_p= 2 mm (Failure) r_p= 4 mm (Failure)

r_p= 5 mm (safe) r_p= 8 mm (Safe)

r_p= 10 mm (Safe) r_p= 12 mm (Safe)

Figure-8. Check failures at diverse values of the punch nose radius (r_p) by using damage initiation criteria in ABAQUS for FLSD of mild steel material of the sheet metal.

These results show that for the die shoulder radius (r_d) that is equal to or less than three times the thickness of the blank (t), the cup fails (tearing in the cup wall or fracture at corners) due to increasing the deep drawing force which causes an increase in thinning, whilst for (r_d) greater than (10t), thinning is stable.



wc = 0.9 mm= 1.25 t (Failure)

wc = 1.286 mm= 1.6 t (Safe)

wc = 1.45 mm= 1.8 t (Safe)

wc = 1.6 mm= 2 t (Safe)

wc = 1.8 mm= 2.25 t (Safe)

wc = 2 mm= 2.5 t (Safe)

Figure-9. Check failures at diverse values of radial clearance (wc) by using damage initiation criteria in ABAQUS for FLSD of mild steel material of the sheet metal.

In addition, the punch nose radius (r_p) that is equal to or less than four times the thickness of the blank (t), the cup fails (tearing at the bottom cup corners) due to raising the deep drawing force which causes an increase in thinning, whilst for (r_P) greater than (8t), the wrinkling is increased in the tips of the cup. Also, from the above results, for the radial clearance (wc) that is equal (1.1) of the sheet thickness (t), the cup fails due to an increase in the deep drawing force.

The manufacturing module ($3^{rd.}$ step) can help to get a tool path simulation and generate CNC commands (G - Codes) for die manufacturing processes. This will be completed by pressing on tool path simulation and open (G_codes) file buttons. Figure-10 (a) to Figure-10 (d) present the tool path simulation for the die manufacturing process. Finally, Figure-11 explains the generated file for CNC machining commands (G - Codes) for the machining process of the die.

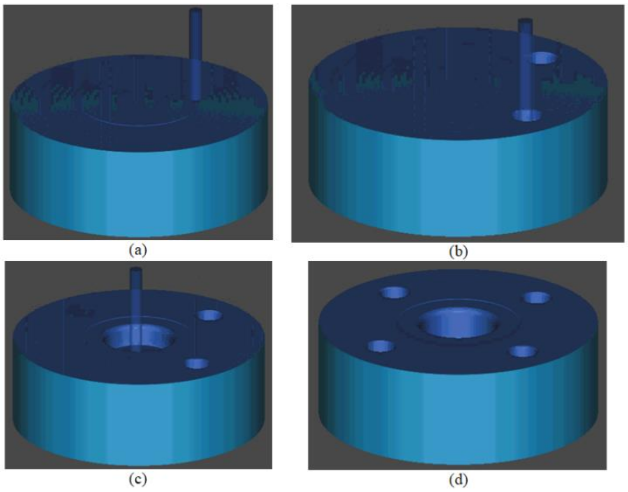
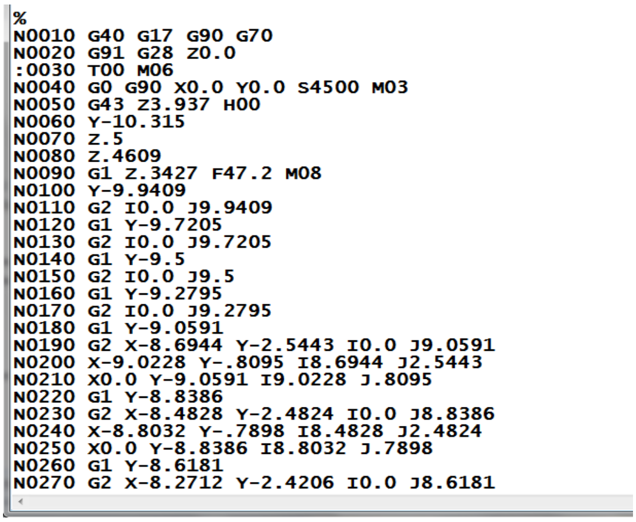

(a) (b) (c) (d)

Figure-10. From (a) to (d) Tool path simulation for the die manufacturing process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%
N0010 G40 G17 G90 G70
N0020 G91 G28 Z0.0
:0030 T00 M06
N0040 G0 G90 X0.0 Y0.0 S4500 M03
N0050 G43 Z3.937 H00
N0060 Y-10.315
N0070 Z.5
N0080 Z.4609
N0090 G1 Z.3427 F47.2 M08
N0100 Y-9.9409
N0110 G2 I0.0 J9.9409
N0120 G1 Y-9.7205
N0130 G2 I0.0 J9.7205
N0140 G1 Y-9.5
N0150 G2 I0.0 J9.5
N0160 G1 Y-9.2795
N0170 G2 I0.0 J9.2795
N0180 G1 Y-9.0591
N0190 G2 X-8.6944 Y-2.5443 I0.0 J9.0591
N0200 X-9.0228 Y-.8095 I8.6944 J2.5443
N0210 X0.0 Y-9.0591 I9.0228 J.8095
N0220 G1 Y-8.8386
N0230 G2 X-8.4828 Y-2.4824 I0.0 J8.8386
N0240 X-8.8032 Y-.7898 I8.4828 J2.4824
N0250 X0.0 Y-8.8386 I8.8032 J.7898
N0260 G1 Y-8.6181
N0270 G2 X-8.2712 Y-2.4206 I0.0 J8.6181
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Figure-11. The Generated CNC commands (G - Codes) for Die Manufacturing Process.

4. VALIDATION OF THE INTEGRATED PLATFORM (CAD/FEA/CAM)

The integrated platform of (CAD/FEA/CAM) is validated by designing and generating CNC machining commands (G - Codes) files for the manufacturing process of the die set (punch, blank holder, and die) for the deep drawing process; as shown in Figure-12. This die set is utilized for educational purposes in the mechanical engineering workshop of Engineering College at Qassim University.

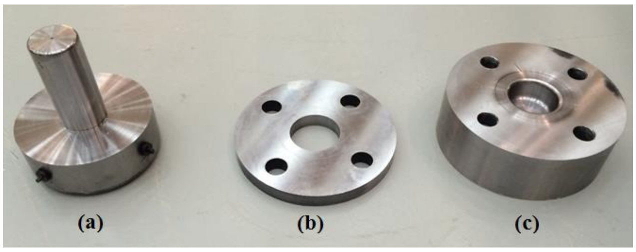

Figure-12. The manufactured die set for the deep drawing process: (a) Punch, (b) Blank Holder, and (c) Die.

The deep drawing process is performed by using the above die set. Starting with the installation of the die at the bottom of the MTS advanced servo-hydraulic universal testing machine. While the bench is installed in the upper part of the MTS universal testing machine; as demonstrated in Figure-13. Then the sheet metal blank was placed above the cavity of the die. After that, the blank holder is placed on top of this blank. At that time, the blank holder is adjusted according to the calculated value which is gotten from the output results as shown in Figure-5. This adjustment is done through the tightening of four springs to a certain length according to the spring stiffness of these springs; as displayed in Figure-14. The required displacement (the tightening distance) for each spring is determined from the following equation:

$$F_S = K\ \delta$$

Where:

$F_S =$ The blank holder force per spring (N).
$K =$ The spring stiffness (N/mm).
$\delta =$ The required displacement (the tightening distance) for each spring to get the required blank holder force per spring (mm).

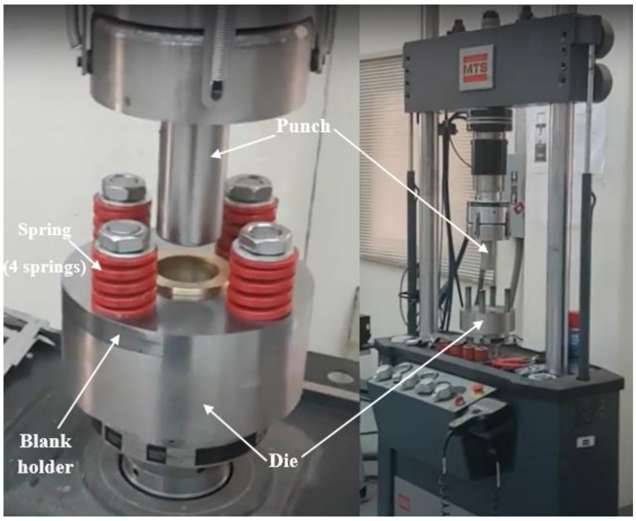

Figure-13. The deep drawing process setup

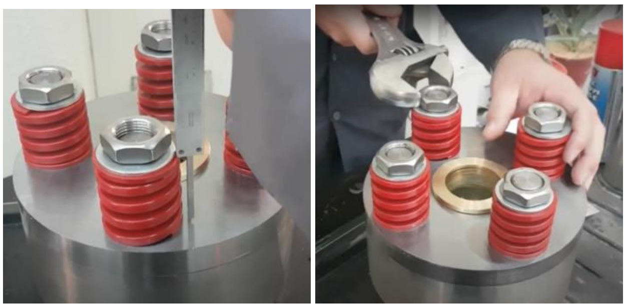

Figure-14. The tightening process of the four springs.

Figure-15 illustrates the stages of the deep drawing process. As a final result, Figure-16 displays the produced cups by using the fabricated die set which is free from any defects for different materials of sheet metal (brass, aluminum, and steel).

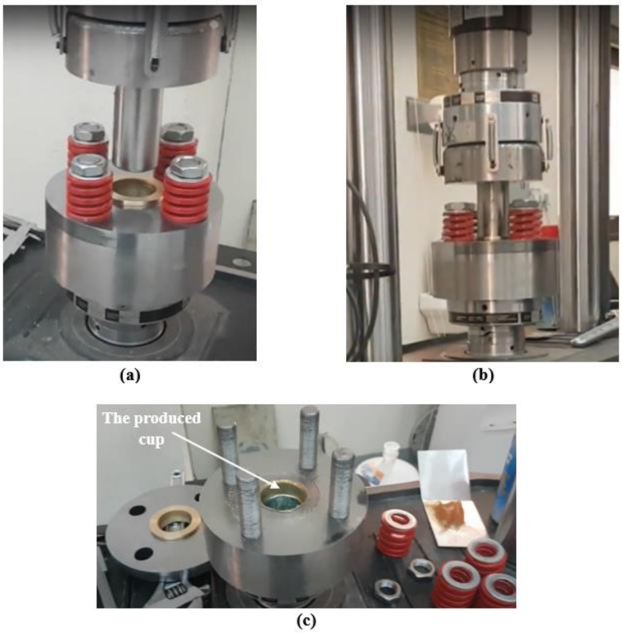

Figure-15. The stages of the deep drawing process: (a) before the process, and (b) during the process, and (c) after the process.

Figure-16. The produced cups (brass, aluminum, and steel).

5. CONCLUSIONS

A number of conclusions can be drawn from the different outcomes of this research:

- In this paper, a computerized handling system has been developed to connect the three modules (CAD, Parametric model of FEA, and CAM) for the deep drawing process of cylindrical cups, which makes it development in accessing the FEA from within a CAD Package.
- The integrated platform (CAD/FEA/CAM) is developed to assist sheet metal design engineers to create tools with the same geometry as those used in the process simulation or virtual manufacturing.
- The simulation findings provide useful information to address the feasibility of the actual production process. Also, it helps to enhance the product quality. Moreover, the riskiness of redesigning and upgrading tools is minimized.

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