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CAD INTEGRATED DESIGN AND ANALYSIS OF COMPOUND DIE

Ahmad T. A. JUNDI

Master's Thesis

Supervisor

Asst. Prof. Dr. Yaser ALAIWI

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The thesis titled CAD INTEGRATED DESIGN AND ANALYSIS OF COMPOUND DIE prepared by AHMAD T. A. JUNDI and submitted on 08/08/2023 has been **accepted unanimously** for the degree of Master of Science in Mechanical Engineering.

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Ahmad T. A. JUNDI

Signature

DEDICATION

I dedicate this to the able Asst. Prof. Dr. Yaser Alaiwi who is my supervisor, who guided me every step of the way until the completion of this work. I also dedicate it to my family, who provided all the support and care for me.

ABSTRACT

CAD INTEGRATED DESIGN AND ANALYSIS OF COMPOUND DIE

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Sheet metal is an extensively utilized material in various daily applications due to its versatility. Researchers have demonstrated a keen interest in exploring different aspects of metal sheets, including bending, and cutting techniques. The objective of this research is to conduct a comprehensive design and analysis of a compound die, which is widely used in the sheet metal manufacturing industry. The study will involve selecting a specific product from the market with defined specifications, followed by creating a detailed SOLIDWORKS drawing of the chosen product. Mathematical equations will then be utilized to design the die, determining the optimal thickness for each component while considering the impact of cutting forces on die parts. The function of each die component will also be elucidated. Subsequently, the complete die design will be realized using SOLIDWORKS software, and a finite element analysis will be performed using the ANSYS Workbench software to ensure its structural integrity, where the maximum stresses will be calculated on it, as well as total deformations, safety factor, and maximum elastic strain, as well as its life.

Keywords: Sheet Metal, Compound Die, Finite Element Method, Manufacture Products, CAD, CAE

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ABBREVIATIONS

CAD	:	Computer Aided Design
CAE	:	Computer Aided Engineering
CAM	:	Computer Aided Manufacturing
FEM	:	Finite Element Method
FEA	:	Finite Element Analysis
MPF	:	Multipoint Forming
KBS	:	Knowledge-Based System
ANN	:	Artificial Neural Network
AISI O1	:	Oil-Hardening Tool Steel
MATLAB	:	Matrix Laboratory Software
AISI D2	:	Air Hardening Tool Steel

LIST OF SYMBOLS

F_{Bl}	:	Blanking Force
L_{Bl}	:	Blanking Perimeter
t	:	Sheet Metal Thickness
S	:	Shear Strength
F_{pr}	:	Piercing Force
S_{ut}	:	Ultimate Strength
D_{bp}	:	Blanking Punch Diameter
D_b	:	Blank diameter
c	:	Clearance
D_h	:	Hole punch Diameter
L_{bl}	:	Blanking Punch Face Length
w_{bl}	:	Blanking Punch Face Width
F_{st}	:	Stripper Force
E	:	Total Cutting Energy
D_{sd}	:	Sheard Depth
K	:	Coefficient
F	:	Deformation Force
L_{pmax}	:	Maximum Punch Length
E	:	Modulus of Elasticity
d	:	Punch Diameter

σ_{comp} : Maximum Compressive Stress

σ : Maximum Stress

σ_{db} : Die Block Stress

σ_{st} : Stripper Plate Stress

σ_{hold} : Holder Plate Stress

F_{cr} : Critical Force

I_{min} : Minimal Moment of Inertia

H : Die Block Thickness

h : Die Opening Height

α : Angular Clearance

a_1 : Workpiece Length on Die Opening

b_1 : Workpiece Width on Die Opening

a : Workpiece Length with Clearance on Die Opening

b : Workpiece Width with Clearance on Die Opening

e : Wall Thickness

A : Die Block Total Length

B : Die Block Total Width

t_{st} : Stripper Plate Thickness

T_{hold} : Holder Plate Thickness

T_{top}	:	Top Base Plate Thickness
T_{Bottom}	:	Bottom Base Plate Thickness
y_{st}	:	Stripper Plate Deflection
C_{min}	:	Spring Minimum Clearance
ID	:	Spring Inner Diameter
OD	:	Spring Outer Diameter
D_m	:	Spring Mean Diameter
l_s	:	Spring Solid Length
l_o	:	Spring Free Length

1. INTRODUCTION

1.1 GENERAL OVERVIEW ABOUT SHEET METAL

Sheet metal is a versatile construction material with a lot of applications. From utilitarian structures like storage sheds to intricate components such as airplane wings, it finds extensive use in various industries. Sheet metal encompasses a diverse range of materials, each possessing its own unique set of advantages and limitations. This article will delve into the different types of sheet metal and their respective applications. Sheet metal is typically composed of an alloy that combines iron with small quantities of other metals such as copper, nickel, manganese, or chromium. This amalgamation imparts specific physical properties to the sheet metal, catering to different requirements. For instance, stainless steel, known for its exceptional corrosion resistance, is an ideal choice when durability is paramount. On the other hand, aluminium, despite being less robust than other metals, offers the advantage of reduced weight, making it desirable for applications where weight reduction is crucial. The applications of sheet metal are incredibly diverse. It can be employed in the fabrication of a wide range of products, from simple signage to complex automotive components. In the automotive industry, sheet metal is utilized to manufacture body panels, chassis parts, and structural elements. Its malleability allows for intricate shaping and forming, resulting in precise and visually appealing designs. Furthermore, sheet metal is indispensable in the construction sector, where it is used for roofing, cladding, and architectural embellishments, offering both functionality and aesthetic appeal. Sheet metal also finds extensive use in the manufacturing of appliances, electronic enclosures, and various consumer goods. Its ability to be easily fabricated and formed into desired shapes makes it an excellent choice for creating intricate designs and precise components. Additionally, the medical industry relies on sheet metal to produce equipment, surgical instruments, and medical device components. Its biocompatibility, ease of sterilization, and adherence to strict quality standards make it an ideal material in this field [1].The figure below shows the mild steel which is one of the common sheet metals.

Figure 1.1: Mild Steel Sheet Metal [2].

Figure 1.2: Car body made from Sheet Metal [3].

Sheet metal forming is a pivotal technology in the industrial sector, experiencing significant growth due to advancements in modern industries. The increasing demand for sheet metal parts with diverse shapes and properties has propelled the development of various techniques for forming challenging materials with high strength and low plasticity, as well as complex-shaped components. In the manufacturing industry, four primary conventional methods are employed to fabricate metallic products: casting, cutting, joining, and metal forming [4].

The process of metal casting entails the pouring of molten metal into a specially designed mould, resulting in the creation of a three-dimensional metal component. Within the mould, there exists a hollow cavity that corresponds to the desired geometric shape of the final product. Subsequently, the molten metal is left to cool and solidify, ultimately forming the desired solid part [5].

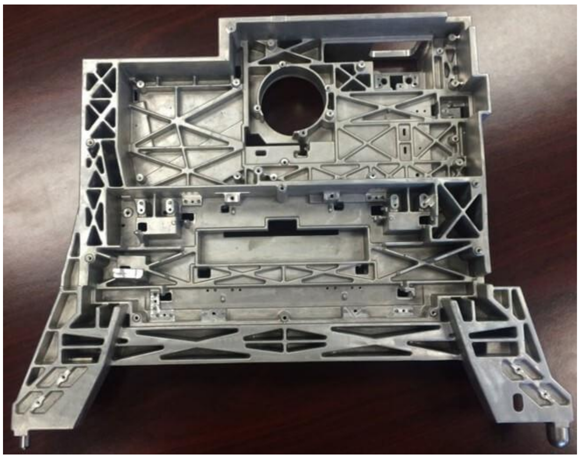


Figure 1.3: Frame Plaster mould made from Aluminium Sheet Metal by Casting [5].

Sheet metal cutting encompasses various pressworking operations aimed at removing specific sections of sheet metal material. The primary objective of sheet metal cutting is to eliminate portions of the sheet metal by applying considerable force to the material through cutting edges. one of the famous methods in cutting sheet metal is the laser cutting as in the figure below [6].

Figure 1.4: Laser Cutting of a Sheet Metal [7].

Manufacturing processes can also utilize joining techniques like welding and brazing. Joining involves bringing two or more surfaces together to establish continuity in the final product. However, this method may not be applicable to all material types, and complex failure modes can occur in the joined components [4].

Sheet forming involves the deformation of a metal blank using tools or dies, primarily through the application of tensile stresses. The design and control of these processes are influenced by factors such as the material characteristics of the workpiece, the conditions at the interface between the tool and workpiece, the mechanics of plastic deformation (metal flow), the equipment utilized, and the requirements for the final product. These factors guide the selection of tool geometry and material, as well as processing conditions including workpiece and tooling temperatures, lubrication, and more. Due to the intricacy of many sheet-forming operations, models of various types, such as analytic, physical, or numerical models, are commonly employed to aid in the design of such processes [8].

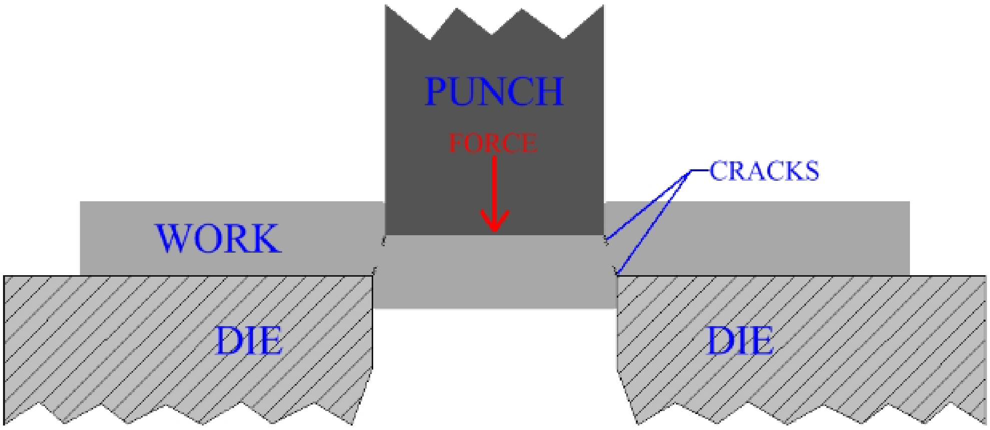


Figure 1.5: Sheet Metal Forming using Simple Die [9].

1.2 THESIS OVERVIEW

In this thesis, a design will be made for a compound die that performs 4 cutting processes for a sheet of metal in one stroke, where it will perform an outer shape cutting process (blanking) and 3 cutting operations for holes (piercing). After that, appropriate analyses will be made for the important parts in this die to ensure that it performs its function without failure an introduction to the importance of sheet metal, its applications and manufacturing methods is given in Chapter 1.

In Chapter 2, many reference studies related to sheet metal dies in general and compound dies will be reviewed. Where it will talk about the method of work in each research with the results and conclusions that have been reached.

In Chapter 3, there will be talk first about the types of dies used in the manufacture of metal sheets and the processes they carry out, after that a detailed explanation will be made of the theoretical material and the mathematical equations used in force calculations and die design in general, and more focus will be made on the equations related to cutting operations, and then it will be used Theoretical article on designing a die to manufacture a product in the shape of L with 3 holes, where all parts of the die will be designed and assembled using the SOLIDWORKS software, and then the analysis process will begin for some important parts of the die using the ANSYS Workbench.

In Chapter 4, the results that have been reached, whether theoretical or results obtained from the ANSYS software, will be reviewed, and they will be commented on and discussed, as 3 common materials will be used during the analysis process which are AISI D2, AISI O1 and AISI A2.

In Chapter 5, which is the last, the final conclusions from this thesis will be discussed in detail, and future work will be proposed to develop this type of analysis or to complete the works that have remained incomplete.

1.3 THESIS CONTRIBUTIONS

This thesis contributes to many important matters related to the manufacture of metal sheets or the analysis of dies, including:

a. All factors and parameters related to the metal cutting process using dies are shown in detail.

b. Design compounds die for outer shape cut and 3 holes cut in detail and accuracy, using theoretical material with strong references.

c. Demonstrating that compound dies can perform more than 3 cutting operations at the same moment on a product whose thickness is more than 5 mm (the product in this thesis is 6 mm).

d. Demonstrating the CAD integrated design by transferring the design parts of the SOLIDWORKS software to Ansys to complete the rest of the analysis operations in detail.

2. LITERATURE REVIEW

The following research discussed the importance of using CAD /CAM in die design and was the importance of utilizing CAD/CAM in die design was discussed in the research. The Auto-troll formed package was employed for progressive die design, aiming to streamline the practical design process and reduce time and effort. The study also investigated the minimum bending radius and bending forces. Based on experiments conducted on both the software and practical parts, it was concluded that the implementation of CAD/CAM techniques accelerates the progressive die workflow. The utilization of stored expert data and standard libraries of parts significantly expedites the design process. However, it was also noted that many experienced designers are necessary to achieve the desired metal formation [10].

The previous research focused on the discussion of MPF (Multipoint forming), a control system designed to enhance the flexibility of sheet metal part formation. Sets of reconfigurable pins were utilized in this study, functioning similarly to stamping dies in shaping the metal sheet. Designing the pin shape and calculating errors were facilitated using CAD/CAM techniques. The research also delved into the control subsystem of the tool, which is a computer-based system operated via an Industrial field bus. This system allowed for the adjustment of hundreds of pins to the required height based on data and information received from the host computer. Following the establishment of the MPF system, various forming experiments were conducted. A non-parametric model was developed by utilizing the spatial forms of input and feedback, which were then employed for online identification to mitigate spring back during the forming process. Additionally, the prediction of pin group shapes for forming purposes was successfully achieved [11].

Alternative methods for manufacturing stamping tools to achieve a lightweight design by enhancing the stiffness of the structure while reducing the tool weight were discussed in previous thesis. The die tool is influenced by two different loads, one during the operation case and the other during transportation. A simulation of the forming process was conducted using LS Dyna software, which allowed the observation of the force's impact on the die during operation, as well as the loads experienced during transportation. Subsequently, the structure of the die was enhanced using the Opti-Struct software, and a comparison was made between the modified die and the original die. It was observed that the weight of the diewas successfully reduced by 20%, along with a 30% decrease in displacement [12].

In previous research, the work of a knowledge-based system (KBS) whose objective is the selection of progressive die components in stamping industries was explained through the automation of the design process. The KBS system was built using artificial intelligence. The KBS system was organized into seven modules and designed to be loaded into AutoCAD. The knowledge-based system was designed in a way that expert tips and skills were stored. The seven modules mentioned contained all the details of the die, including dimensions, fasteners, back and front plate, punch, block of die, and other components. The stored data files could be extensively used for automatic modeling of the assembly of die components and dies. It was also discussed that one of the advantages of this system is its ability to be used on AutoCAD, resulting in lower costs, and facilitating its adoption in medium and small stamping industries [13].

An overview of the development in die design and computer-aided process planning was initially given in a previous study. Analysis, simulation, and die design were then performed using the developed techniques at Miskolc University to satisfy the aim of the research, which is the increase of global competitiveness in the field of sheet metal forming. After the simulation and design were conducted, it was concluded that the application of CAE (Computer Aided Engineering) technology leads to important developments. The workshop based on the principle of experiment and error, which often incurs high costs, was replaced by an integrated system using the computer or the finite element method. A better-quality product was obtained in a much shorter time and with fewer errors. This contributed to increasing production with high efficiency and effectiveness [14].

In this research, the development of an expert system to assist designers and experts in designing blanking dies for sheet metal operations was discussed. The system, named INTBDIE, was organized into twelve units and coded in the AutoLISP language. It was designed to be loaded into the AutoCAD software, enabling automatic modeling of the die components based on the stored tips and experiences in various output data files. The system's compatibility with AutoCAD allows for a low-cost implementation, making it highly suitable for small and medium industries. Tests were conducted on various metal sheets, and the results obtained closely aligned with those utilized in the metallic sheet industries [15].

In this research, the compound and progressive dies were utilized together in one die to conduct an experiment and analysis of a U-shaped part. The die was designed to perform cutting, punching, bending, and lancing simultaneously in one process. The working principles and essential design considerations of the die were explained. Tests conducted on production confirmed improvements in production quality, efficiency, and economic viability across various levels [16].

In other research, an offer was made to create a compound die that not only performs the blanking and drawing process but also carries out the trimming process. This offer was made due to their observation that the part after blanking and drawing in some metals is uneven from the upper sides. Additionally, creating a separate die solely for trimming after the drawing and blanking process could incur significant costs. Therefore, in their research, a compound die was developed that has a constant pressure of blank holder and performs the three mentioned operations. It was concluded that the implementation of this type of dies results in a reduction in production costs and an increase in production efficiency and improvement. Hence, the requirements of production are met [17].

In previus study, the punching force of the combination die during the process of forming a U-shaped piece, known as U-Clamps, was analyzed. The combination die was designed and manufactured by them to produce the U clamps. The sheets used in their research were made of aluminum and Mild steel. It was concluded from their research that there is no difference between the theoretical punch force and the actual one [18].

The research on making a punching die for a thick plate of steel was conducted before. The design and manufacturing technology features of the die were clarified, explained, and described. The clearance value between the core plate and the Cavite plate was chosen by them based on the production of the blanking die for the thick steel plate [19].

In previous research, the design of a compound dies to be used in drawing the parts containing the holes in the flange was discussed. The part on which the die would be built required five operations in the same stroke: drawing, blanking, flange hole piercing, bottom hole piercing, and trimming in one stage. It was confirmed through production tests that there were improvements in product efficiency, production quality, and economy [20].

In the previous research, a new methodology was proposed by them to develop a system capable of automatically re-modeling the cutting components of the compound washer dies. The methodology is based on the integration of CATIA V5 software modules with the design and assembly of parts, knowledge advisor, as well as the mechanism of publication and design knowledge of compound cutting die. The system developed in this methodology consists of two parts, the first being GAJA1 and the second being GAJA2. The problem of die design regarding the dimensions, shape, and materials intended for the stamping part is specialized by GAJA1. It transfers design parameters and features to GAJA2, which in turn interprets the values of the parameters and works on automatically modeling them to the components of cutting die [21].

In other paper, the creation of a knowledge-based system was also discussed. The system is designed specifically for symmetrical parts on the axis of the deep drawing dies. In their research, it was determined that this system would consist of 27 modules and be coded in AutoLISP language. The Visual Basic software, with the help of AutoCAD, will be used to create the user interface. One of the advantages of this system highlighted in the research is its ability to automate all the main activities of die design, including designing the strip layout, evaluating the manufacturability of deeply drawn parts, selecting die components, process planning, assembling dies, and modeling their components. additionally, also the user-friendly, and cost-effective emphasized. The conclusion drawn was that the system has been successfully developed, capable of completing tasks in a short period of time and is cost-effective [22].

The life prediction of the compound die was studied in a previous study, which is a crucial aspect, particularly for experienced die designers. The life of the compound die was predicted using an artificial neural network (ANN), incorporating the finite element method (FEM) for analysis to identify variables affecting the die's life and determine critical points with the highest stress. The neural network was constructed using MATLAB software. The system (ANN) and FEM results were used together by training the network with selected values from the FEM analysis results, and then testing the network with additional values to achieve minimum error. The results were presented accordingly. The conclusion reached was that the model test was successful after conducting tests on several metal plates using the compound die [23].

The necessity of adjusting the gap between the dies was presented by the researcher, as it is known to impact the product quality and the life of the die. Emphasis was placed on ensuring a consistent gap between the terrace and the sunken die. The mention of finding a positive gap was also made, and a list of various methods was provided, including the acid corrosion method, coppering method, gasket method, through light method, measurement method, and trial cut method. The conclusion was drawn that the production process and appropriate assembly methods should be employed to ensure product quality, errors are minimized, production costs are reduced, and economic efficiency is improved [24].

A study was conducted on the design of a combination die and its impact on the forming process in sheet metal to enhance production and productivity. The manufacturing method was examined and analyzed in terms of its effect on productivity. To demonstrate this, a piece of U clamp was obtained, and an experiment was performed using the combination die. It was concluded that the combination die enables the execution of three shaping operations (trimming, bending, and piercing) in a single strike, utilizing only one die instead of three, resulting in significant improvements in productivity [25].

A compound die was created in previous research, assisted by computer-aided design (CAD), to carry out the punching, blanking, and drawing process for obtaining the desired part, specifically the housing of Downlight. A comparison was made between the results obtained from computer-aided design and manually conducted design. The conclusion drawn was that the computer-aided design yielded results closely aligned with the manual results, providing greater accuracy in less time [26].

The warm forming of an aluminum alloy, specifically 5083 H111, was studied in other research using a progressive die. The temperature range between 180 and 220 was chosen, achieved by heating the aluminum alloy using a conduction heater. The selection of the progressive die aimed to ensure good geometric control of the piece, which would take the shape of an omega. The results demonstrated the significance and advantage of reducing the radius of the die and the punch in warm drawing to better observe the effect of temperature on the piece's geometry. Several conclusions were drawn, including the appropriateness of choosing the omega shape for the analyzed piece to showcase the positive impact of warm forming on reducing spring back. The tool underwent successful testing, operating at a rate of 30 strokes per minute on the test press [27].

An expert system, named CDPUN, based on expert advice for selecting a punch for a compound die was discussed in this research. Technical knowledge was acquired from various sources and represented using IF-THEN production rules. The rules were coded in AutoLISP, and the user interface was created using Visual Basic software. The system facilitated the transfer of expert advice to the lower and upper punches, punch plate selection, determination of punch size and type, as well as advice on clearance between the die block and the punch. The system boasted a low cost, requiring only a computer with Visual Basic and AutoCAD software, making it suitable for medium and small stamping industries. An experiment was conducted using the system on three sheet metal plates, and it was concluded that its implementation was cost-effective, with the knowledge base modifiable according to workshop capabilities [28].

A research paper presented the introduction of a new system based on experts in the sheet blanking die, constructed using CATIA software and Visual Basic. The system comprised 14 sub-modules, further divided into 18 main sub-modules, with each sub-module dedicated to a specific die plate or component [29].

The development of the CAD system in the field of automatic modeling of compound die used in sheet metal industries was discussed in previous study. The proposed system, consisting of 9 units, was coded by AutoLISP language, and a user interface was created using Visual Basic in addition to AutoCAD. Drawings, whether 2D or 3D, can be created automatically for all the main components of the compound die in the drawing editor inside the AutoCAD software by the system proposed. The test was passed successfully after conducting experiments on a group of metal sheets used in industries [30].

The compound die for forming, which is a union between a transfer die and a semi-progressive die, was made in other research. Initially, a semi-progressive die was used to produce the blanks, and then the parts were moved inside the transfer die to produce the cushion panel of the seat. Simulated sheet forming and seat cushion and seat plate forming were adopted to deform the cushion panel of the seat without any defects while meeting all design specifications. The successful manufacturing of the compound die dedicated to the car seat cushion panel, consisting of the transfer and semi-progressive dies, was achieved [31].

Previous research focused on the design of the compound die for cutting blades for Nonactive Rotary Paddy Weeder. The clearance was calculated to reduce material consumption and production time. The production time was reduced by 73%, contributing to a 40% increase in productivity while improving product quality [32].

The process of modeling and predicting the life of the stripping tool in the compound die was discussed in this research. The knowledge-based system (KBS) was utilized for choosing the approximate stripper size. The production rules were coded in the AutoLISP language to create the knowledge base. A CAD system was developed to automate the modeling process for the die remover, and an artificial neural network (ANN) system was used for predicting the life of the stripper. Finite element methods were analyzed to determine critical values. The system was successfully tested after conducting experiments and analyses on several sheet metal [33].

An expert system that plans the process of sheet metal pieces produced by the compound die for use in stamping industries was studied. The proposed system, organized into 6 modules, was developed through knowledge gained from different sources and organized into a set of production rules. The system modules were coded in AutoLISP language, and the user interface was created using Visual Basic. The proposed system automates most of the activities necessary for process planning, including blank nesting, blank modeling, choosing the clearance between die and punch, determining the required punching force, and determining the sheet operations. The system can be easily implemented at a reasonable cost with a computer equipped with AutoCAD and Visual Basic software [34].

A combination die was designed using a computer-aided system for parametric design, as discussed in their article. Artificial intelligence and knowledge-based methods were employed to develop the system. The AutoCAD software was linked with Visual Basic for coding the system. The system significantly reduced the modeling and design time, allowing the creation of data files formatted as graphics for the dimensions of the die components. The system's output was accepted by the CAM package for manufacturing die components, resulting in cost savings and reduced effort and time for designers in medium and small metal industries [35].

A framework for the simulation-driven design of stamping dies, considering elastic deformation, was discussed in this research. Ways to counter the negative effects of elastic deformation were clarified, and the possibility of improving and supporting production by reducing time was explored. A simplified die was studied using a finite element model to find the elastic deformation. MATLAB and ABACUS software were used for simulation, and the method proved to be fast, accurate, and reduced the need for manual rework. However, further research is needed to apply this method to an industrial die [36].

In a previous thesis, the design of a progressive die for mass production of high-quality and low-cost sheet metal parts was discussed. The progressive die was designed using SOLIDWORKS software, and a cost comparison showed that the part could be produced at a lower cost and higher quality with the die [37].

A design for a compound die that performs the process of blanking and two piercing operations for an industrial sheet metal part was presented in their paper. Design calculations were made to determine the required clearances, shear force, and erosion force. The die was modeled using CATIA V5 software and manufactured accordingly. Combining blanking and piercing in one die and one process resulted in a decrease in die size compared to a progressive die, leading to lower manufacturing costs [38].

A new method for designing deep drawing tools based on 3D CAD modeling was discussed in their paper. The use of 3D CAD modeling made the deep drawing tools modeling more flexible and efficient. Parameters associated with the 3D CAD model could be easily and quickly changed, improving the transparency and flexibility of the parametric CAD modeling process [39].

The development of a specific method enabling the simulation of sheet metal formation, including press deformations and an elastic tool, was discussed in this paper. The combination of two finite element models was used, with one model being a structural model of the press and die, and the other model being a sheet metal forming model with two-dimensional rigid tools. The structural model allowed for visualization of large deformations of the die structure and prediction of pressure distributions and surface shapes of the stamping die. The method of sub-modeling was introduced, which transfers deformations from the structural model to two-dimensional surfaces using finite element technology. Subsequent simulations of sheet metal forming demonstrated the effectiveness of the method, particularly when using the TriboForm friction model to calculate deformed surfaces. The ability to deform a die and the resulting geometry in forming simulations was verified, making the method useful for improving and analyzing new or existing dies [40].

In previous research, the use of a transfer die in the production technology of equivalent auto parts was discussed. The transfer die, along with an automatic feeding system, was applied to analyze the production of automobile parts with high-precision die design. The workpieces were fed using a pneumatic suction feeding mechanism. Finite element analysis was conducted on a galvanized panel sill, and it was found that the workpiece could be stamped without damage. The design of the die was based on the analysis results and met customer requirements. The application of the transfer die reduced costs, time, and risks in the production process [41].

A concept of the complete networking speed of the piston in the fine blanking process was introduced in their paper. Real-time analysis of the workpiece geometry was performed using the Feintool XFT 2500 machine. The aim was to improve the quality of the sheared edge by transferring process forces and aligning parts precisely. Embedded AI devices for GPU computing in the machine room were found to be feasible, although the work was still in its early stages [42].

In this research, the life of a compound die punch was predicted using a machine learning model. It was explained that the life of the punch depends on the material of the plates, as well as the punch area and plate thickness. The main maximum and minimum stresses affecting the punch were determined using the finite element technique. The prediction accuracy of the machine learning model was found to be higher than 99.5% compared to the previously mentioned neural network and other systems. The systems (ML Model), (ANN), and (ANFIS) were compared, and the results demonstrated the robustness and higher accuracy of the (ML Model). Consequently, it was concluded that designing in this way provides reliable predictions for the life of other die components [43].

The process of designing and developing a progressive die for the tailgate striker used in headlight assembly was discussed by Harshal A Chavan and Vijay P Wani. The die incorporated low-cost standardization tools to improve production efficiency. The die performed multiple operations in workstations, increasing overall production rate with low labor costs. CAE technology, using ANSYS software, was utilized for design and analysis of the progressive die [44].

In previous research, the design and development of a compound die for producing a hexagonal washer for a Standard M15 bolt were discussed. The importance of using measuring tools to align the various elements of the tool was emphasized due to the potential for significant losses caused by even small measurement errors. As explained in previous studies, one of the features of the compound die is that the ready-made piece is produced in a single strike, combining the piercing and blanking operations to create the required washer. The necessary calculations for die design, such as press capacity, minimum piercing diameter, die block thickness, relief angle, punching length, spring design, and calculation of punching force and blanking force, were initially performed. Subsequently, the design was created and drawn using SOLIDWORKS software [45].

The use of finite element analysis in the work of Topology Optimization of the combination die was discussed in their practical paper. This was accomplished by obtaining the critical parameter from finite element analysis during the blanking and deep drawing processes. The software utilized for the finite element analysis was Ansys software. Maximum stresses (Von Mises) during the blanking and deep drawing process were determined using this software. Subsequently, a topology optimization analysis of the blanking punch was performed using the same software, resulting in a new blanking punch with 40% less mass than the original. This analysis aids in preventing process failure and reducing the cost of sheet metal parts [46].

In previous study, the design of a compound die for the manufacture of the transmission part of the car cable was discussed. The compound die was chosen for its ability to perform blanking and piercing in a single strike. This die was preferred over other options, as alternative dies would require multiple processes and strokes to complete the same product. It was further explained that using this die, which produces the final product in one stroke, increases production rate and reduces costs. The design of this die depends on factors such as the thickness of the metal sheets, the material used, and the complexity of operations and design [47].

The creation of a trimming block was discussed in an intelligent manner in previous research to address three problems: surface construction, uncertainty of flange, and offset of the curve. The new method relies on parameters and sketches to achieve an intelligent and fast design for the trimming block. The proposed method offsets the three-dimensional curve of the trimming block based on the curve displacement criterion. It utilizes an inflection point feature, which is a characteristic of the curve in terms of curvature, offset, and perturbation. The entire design process of the trimming block was sequenced to achieve an intelligent and automated design method, which was integrated using the NX software. The intelligent system designed for the trimming block is implemented as a sub-unit in the modular design of the trimming die. An example of the design created for the trimming block demonstrates that the system effectively controls errors and ensures successful one-time design [48].

In a previous study, a study was conducted on the design of a virtual system for the compound die, with specific emphasis on the press tool within it. The system discussed can be used by the user to perform all calculations related to the design of the die for various dimensions. Additionally, other features such as the design characteristics of the die and punch can be displayed through the system [49].

The use of finite element analysis in the design and optimization of the compound die during the piercing process and two cutting operations was discussed in their research. The ANSYS software was employed for the analysis of the compound die to obtain various parameters and achieve the desired optimal design. The determination of the best hole was based on the minimum limit for the height of the product burr. Cutting parameters and edge heights were analyzed using the Minitab program. Their research addressed the shortcomings in previous studies related to cutting edges for the pressing process, such as flat edges, coated and flat edges with a concave hemisphere. It was concluded that as the thickness of the sheet metal plate increases, the burr on the final product becomes smaller, while a decrease in thickness results in a larger burr. Convex and chamfered punches were found to provide minimal burr, up to 0.034 mm, thereby improving product quality [50].

The design of a compound die for the mass production of the drum plate of the machine's parts for post-harvest processing was discussed in their research. The compound die combines piercing and blanking operations. Necessary calculations for the design, such as the economy factor, clearance, punch and die diameter, stripping force, blocking force, and press capacity, were performed. The analysis and study of such components were deemed crucial as they are integral to most machines, thus reducing losses and positively impacting the economy [51].

The design of a U-shaped bending stamping die was explored in their research. The U-shape of the chain plate was analyzed, and the necessary bending force was calculated. The bending stamping die consisted of a convex-concave die, a discharge device, a positioning column, a concave plate mounted on a convex die, and a floating block. Unilateral clearance of the convex-concave die was designed to reduce sheet metal rebound, and the circular angle radius of the concave die and rebound punch angle were also determined. Pre-formation testing of the die confirmed its suitability for the U-stamping process of the chain plate [52].

A new methodology for evaluating die features to characterize wear behavior in a forming die was presented in their study. The Diana program was employed for finite element analysis, enabling the analysis of die drawing wear and normal pressure. Critical areas on the die shoulder and drawbead, regarding the severity of erosion, were determined through simulation. The presence of chlorinated lubricants was identified as facilitating production using uncoated tool steel. The combination of empirical and numerical analyses for assessing the risk of galling in different regions of the forming die was highlighted. This methodology can reduce time and costs associated with die selection while improving die geometry [53].

Finite element analysis was applied to the analysis of a hexagonal washer for the M15 standard bolt in their research. Previous studies had already analyzed and designed the same component. Finite element analysis aided in determining the stresses and elastic strain of the die. The compound die was analyzed, with piercing and blanking being the two involved processes. The accuracy of the design and development of the die was verified through finite element analysis. The ANSYS software was utilized for simulation and analysis purpose [54].

The development of a tool and process to produce a bracket supporting the Peugeot battery in the Peugeot products manufacturing plant was discussed in the research conducted in previous study. The compound die, capable of performing both blanking and piercing operations with one stroke, was suggested for mass production. The tool's usage was deemed beneficial as it increased die lifespan through appropriate material selection and reduced production time and manpower costs [55].

The design of a compound die for the manufacture of an M20 ring was studied in their research. The compound die was chosen because it allows for the completion of two processes, blanking and piercing, in a single stroke. Displacement analysis, calculation of maximum stresses, and determination of the safety factor were performed using SOLIDWORKS software. The objective was to estimate the wear life of the punch and die in order to predict product failure in advance. The ring was manufactured using the material SAPH440 with a thickness of 2 mm. The analysis indicated that the use of a compound die in these processes can reduce product defects by achieving high dimensional accuracy and significantly speeding up the production process [56].

A new methodology aimed at designing and manufacturing sheet metal dies based on the characteristics of sheet parts was discussed and presented in this research. Integration between computer-aided design and computer-aided manufacturing was sought in this methodology. The MusumiTM catalog was utilized to obtain the relevant features and advantages from other sheet metal industries, particularly medium and small size industries. The work was divided into two phases. In the first phase, geometry and topological data were extracted from the STEP AP 203 file. The second phase involved the development of a matrix and a rule-based system to identify the characteristics of sheet metal for die manufacturing. The Visual Basic language was used to develop the system, and modeling was performed using SOLIDWORKS software. The proposed system demonstrated excellent performance for all features in the MusumiTM catalog and across various sheet metal industries. A test was conducted to evaluate the automated design of combination dies for deep-drawn industrial parts using the proposed system. It was observed that the design time for various die components was significantly reduced [57].

In their study, they designed and analyzed the different parts of the progressive die, such as the piercing die and the punch, as well as the Blanking die and punch, and they carried out

The different parts of the progressive die, including the piercing die, punch, blanking die, and punch, were designed and analyzed in their study. A piece of aluminum with a thickness of 1 mm was cut and pierced during the design process. Important mathematical calculations, such as the shear force, stripping force, press force, and press capacity for the blanking and piercing processes, were performed. The progressive die was then drawn using SOLIDWORKS, and crucial analyses were conducted to determine the values of maximum stresses (Von-Mises) and displacements [58].

In previous research, the design of a new industrial die was discussed after conducting several analyses and implementing changes, such as improving the structural rigidity of the die to overcome the chances of failure. The designed die is a filleted die that aims to reduce the pressure on the area by distributing the load, thus decreasing the possibility of failure. After conducting studies, the die was produced with enhanced structural stability, improved production rate, and reduced chances of failure. The new die (filleted die) was created using the CATIAV5 software and subsequently subjected to the necessary analyses using ANSYS. Calculations were performed for structural analysis, revealing a decrease in directional deformation and an increase in structural rigidity [59].

The parameters of cutting in the dies for sheet metal were studied in this research, where three shapes of benches were examined. These shapes included a punch inclined at an angle of 15 degrees, a convex punch, and a concave punch. The same material, namely 4340 steels, was utilized for all three shapes. The ANSYS software was employed to conduct the study, during which the von-Mises stresses, deformation, and skewness quality were calculated. Upon completion of the analysis, it was determined that the force required for cutting decreased by 12% when employing a concave punch and by 10.3% when utilizing a convex or inclined punch [60].

The research discussed the application of the finite element analysis technique in the design and study of the gradual die on dented steel bushers. The utilization of the FORGE software was made to apply finite element analysis in the study of the causes of tool wear and damage. Two indicators, namely FEAwear and FEAdamage, were suggested for predicting die damage and wear. Several comparisons were made between the results of the program and the real marks to verify the accuracy of the simulations. The accuracy of the simulations in predicting the strength of the stamping force and the quality of the final product was demonstrated. The critical tools and stations were accurately predicted by the suggested wear and tear indicators, revealing areas of significant damage to the tools. Subsequently, the steel washer was successfully produced, and the coining die was identified as the most vulnerable tool according to the wear indicator (FEAwear), which was confirmed by maintenance data. The vulnerability of the coining die was also confirmed by the damage indicator (FEAdamage) based on maintenance data [61].

In previous research, the Python programming language, which also functions within the AutoCAD software environment, was utilized for modeling the parameters of the compound die. The approach to constructing a set of compound dies is partially founded on modern parametric techniques and predominantly relies on the basic design parameters. Among the significant parts that were programmed are the calculation of the cutting force, clearance, punch design, die block, spring design, as well as the software for selecting the sheet metal material, etc. The time was greatly reduced by their design of this system, as manual modeling was eliminated and replaced with automatic modeling [62].

3. METHODOLOGY

The initial focus of this discussion will revolve around the essential dies employed in the fabrication of sheet metal products, along with the key operations performed by these dies. Subsequently, a detailed explanation of the components of the compound die, the subject of this research, will be provided. The theoretical knowledge underpinning the design of the dies will be explored, followed by the selection of a specific product as a reference. A step-by-step fabrication process will be executed on the chosen die, accompanied by comprehensive drawings of the die components using SOLIDWORKS software. The subsequent phase involves the assembly of these components. Once the drawing and design stages are completed, the ANSYS software will be employed for conducting stress analysis, assessing deformations, determining safety factors, and considering other factors.

3.1 SHEET METAL DIES AND THEIR OPERATIONS

3.1.1 Sheet Metal Dies

Dies are essential machine tools employed in various manufacturing industries to shape metal into desired configurations or cut threads on the outer surface of pipes, round rods, and similar components. These dies are meticulously designed to create threads of precise sizes. They are chamfered from one side to a specific length, allowing for easier thread initiation and smoother threading processes [63]. There are several types of sheet metal dies:

a. Simple Die

This type of die does a single blanking operation with each stroke of the press such as a die in the figure below [64].

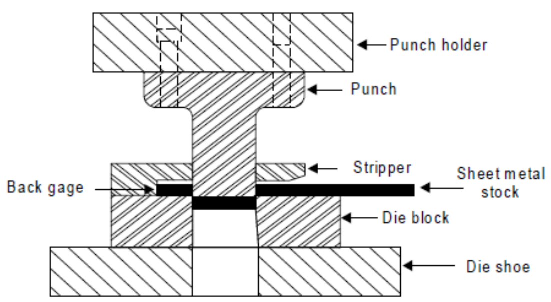


Figure 3.1: Simple Sheet Metal Die [65].

b. Progressive Die

Progressive die stamping is a specialized process in metal forming that plays a pivotal role in generating parts for a broad spectrum of industries and applications. This style of metal stamping utilizes multiple workstations, with each designated to perform varied operations on the given part [66].

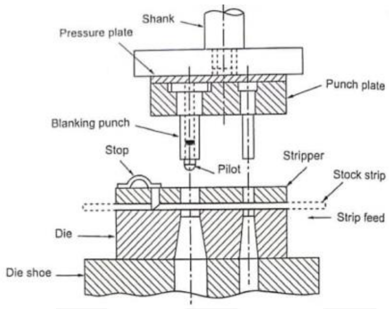


Figure 3.2: Progressive Die and its parts [67].

c. Combination Die

Combination dies serve a critical function when multiple operations are needed at a single workstation. Their distinguishing feature from compound dies is their ability to pair a cutting operation with either a bending or drawing operation. It's this unique feature that earns them the name combination dies [68].

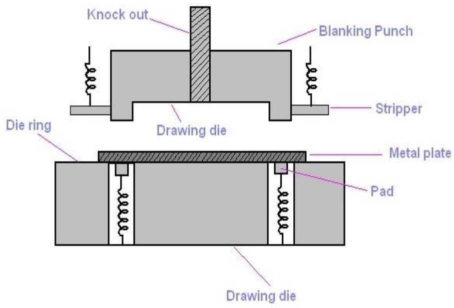


Figure 3.3: Combination Die parts [68].

d. Transfer Die

Transfer dies share similarities with progressive dies; however, their main distinction lies in the sequencing of operations. In transfer dies, the initial operation typically involves blanking. Subsequently, the blank produced in the first stage is conveyed or transferred from one stage to another to undergo further processing. This transfer of the blank between stages can be accomplished manually or through mechanical means. Ultimately, the blank traverses through the different stages to complete the overall manufacturing process [69].

e. Compound Die

A compound die is a press tool that combines multiple operations performed on sheet metal into a single stroke. It enables various operations to be executed simultaneously, streamlining the manufacturing process, and increasing efficiency [70].

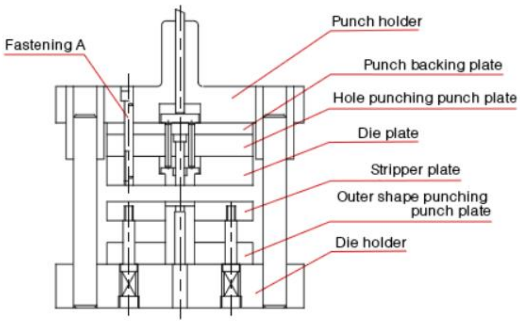


Figure 3.4: Compound Die and its Components [71].

3.1.2 Operations of Sheet Metal Dies

a. Cutting Operation

Sheet metal cutting involves the application of a shearing action, where two sharp cutting edges come together to separate the material [64].The cutting operation divided into two operations which are: piercing operation and blanking operation.

Blanking Operation is a manufacturing process in which a metal workpiece is extracted from a primary metal strip or sheet with punching. The removed portion becomes the newly formed metal workpiece, also known as the blank. This process is applicable to various types of sheet metal, where the separation of metals is necessary using punches and dies. The functioning of punches and dies during the metal blanking operation varies depending on the material being worked on and the tool steel's capacity to withstand the stresses encountered on the cutting edges [72].

Piercing Operation: Piercing involves the process of creating holes in sheet metal through punching. Both piercing and blanking are categorized as shearing operations. In piercing or punching, the portion of material that is cut out from the sheet metal is considered scrap, while the remaining material forms the actual desired part [73].

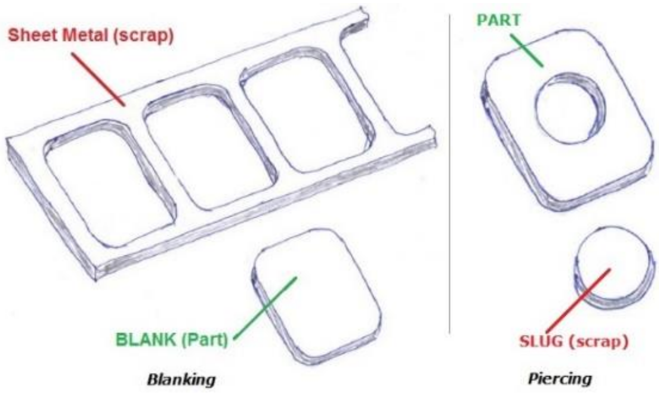


Figure 3.5: Piercing and Blanking Operations [73].

b. Bending operation

Bending in sheet-metal work refers to the deformation of the metal along a straight axis. When bending takes place, the metal on the inner side of the neutral plane experiences compression, while the metal on the outer side of the neutral plane undergoes stretching [64].

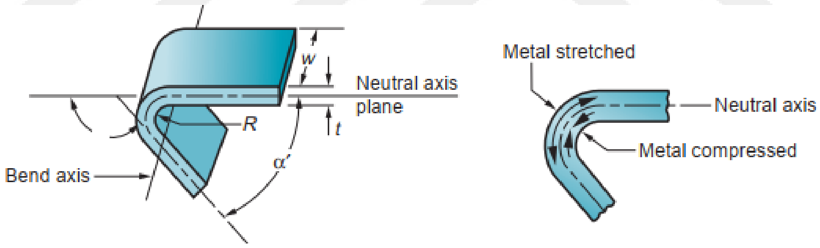


Figure 3.6: Sheet Metal bending and both tensile and compression elongation of the metal occur in bending [64].

c. Drawing Operation

It is a sheet-metal-forming process employed to create cup-shaped, box-shaped, or intricately curved and concave parts. This operation involves positioning a sheet metal piece over a die cavity and exerting pressure with a punch to push the metal into the cavity. To ensure proper forming, a blank holder is typically utilized to hold the blank securely against the die. Drawing finds application in the production of various everyday items, such as beverage cans, ammunition shells, sinks, cooking pots, and automobile body panels [64].

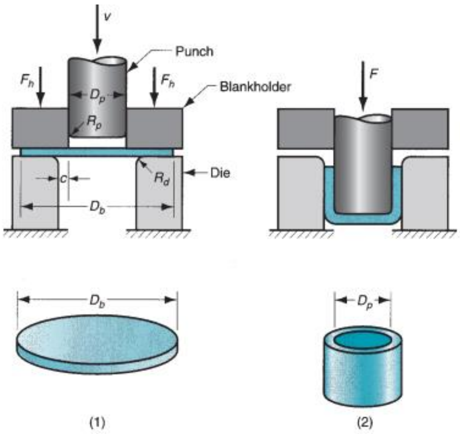


Figure 3.7: Clarify the Drawing Operation [64].

3.2 THEORETICAL BACKGROUND OF COMPOUND DIE

3.2.1 Forces, Energy and Other Sheet Parameters

Below, the most important equations and theories used in die design in general and the compound die in particular will be clarified. The cutting force of either the blanking punch or the piercing punch as well as the die opening properties are calculated from the equations below [64]. The first force affecting the die is the cutting force, and it may be the blinking force or the piercing force, and the two forces may be together, as in some dies, including the compound die.

i. Blanking Force:

$$F_{Bl} = S \times t \times L_{Bl} \tag{3.1}$$

Where,

S	:	Shear strength of sheet metal, Mpa.
t	:	Thickness of sheet metal, mm.
L_{Bl}	:	Perimeter of blanking cut, mm.

ii. Piercing Force:

$$F_{pr} = S \times t \times L_{pr} \tag{3.2}$$

Where,

S, t : The same in blanking operation

L_{pr} : Perimeter of piercing cut, mm

The shear strength of any material, especially if it is of the steel type, is equal to 60% of the value of the ultimate strength value [74]. so,

$$S = 0.6 \times S_{ut} \tag{3.3}$$

Where,

S_{ut} : Ultimate strength of material, Mpa.

The **total** cutting force can calculate using below formula [75]:

$$F_{Total\ cutting} = F_{Bl} + F_{pr} \tag{3.4}$$

iii. Dies and Punches Diameters

It is also important to calculate the diameter of the blanking punch and die diameter as well as the piercing punch and die, and this can be done using the equations below [64].

$$D_{bp} = D_b - 2c \tag{3.5}$$

Where,

D_{bp} : Blanking punch diameter, mm.

D_{bp} : Blank diameter, mm.

c : Clearance, mm.

For piercing cut operation:

$D_h = Hole\ punch\ diameter$

Where,

D_h : Hole to be punched diameter, mm.

$$Hole\ die\ diameter = D_h + 2 \times c \tag{3.6}$$

$$c = 0.0032 \times t \times \sqrt{S} \tag{3.7}$$

The Clearance c can calculate using equation below [76].

Where,

t : Sheet metal thickness, mm.

S : Shear strength of sheet metal, Mpa.

However, the characteristics of the cutting punch may differ if it is not circular, as if it is a rectangle, square, or any other non-circular shape, it can be calculated using the equations below [64].

Blanking punch dimensions:

$$L_{bl}\ (length\ of\ blanking\ punch\ face) = Length\ of\ product - 2 \times c \quad (3.8)$$

$$w_{bl}\ (width\ of\ blanking\ punch\ face) = width\ of\ product - 2 \times c \quad (3.9)$$

iv. Stripping Force

The other forces acting within the die are the stripping force. The stripping force in a die refers to the force required to remove the finished part or workpiece from the die after the forming or cutting operation is complete. It is an important consideration in the design and operation of compound dies used in metal stamping processes and its value between 5%-20% of cutting force [75].

$$F_{st} = (5\% - 20\%) \times F_{Total\ cutting} \quad (3.10)$$

v. Cutting Energy

The required energy for cutting the sheet metal parts is considered small compared with other cutting operations such as laser cutting and sawing. The reason for low cutting energy is related to the realistic shearing of the sheet metal which occurs when the cutting tools of the compound die penetrates the metal to about 1/3 of the sheet thickness. The below

$$E = 10 \times F_{Total\ cutting} \times D_{sd} \quad (3.11)$$

equation is used for calculating required cutting energy [77].

Where,

E : Total cutting energy, kJ.

D_{sd} : Blank diameter, mm.

vi. Deformation work

Deformation work refers to the mechanical work exerted on the material during the cutting or shearing operation. The deformation work of the blanking and the punching of the punch that with flat faces can be calculated using the equation below [78].

$$W = K \times F \times T \tag{3.12}$$

Where,

K : Coefficient depends on sheet metal thickness and shear strength of the material.

F : Deformation force (or total cutting force), N.

T : Sheet metal thickness, mm.

The value of K can be obtained from the table below.

Table 3.1: Coefficient k values for several materials [78].

Material	**Shear Strength lb/in2 (Mpa)**	**Material Thickness, inch (mm)**			
		< 0.040 in. < (1.0 mm)			< 0.040 in. < (1.0 mm)
Low carbon steel	35,000–50,000 (240–345)	0.70–0.65	0.64-0.60	0.58–0.50	0.45–0.35
Medium carbon steel 0.20 to 0.25% carbon	50,000–70,000 (345–483)	0.60–0.55	0.54–0.50	0.49–0.42	0.40–0.30
Hard steel0.40 to 0.60% carbon	70,000–95,000 (483–655)	0.45–0.42	0.41-0.38	0.36–0.32	0.30–0.20
Copper, annealed	21,000 (145)	0.75–0.69	0.70–0.65	0.64–0.55	0.50–0.40

vii. Maximum Press Capacity

The maximum press capacity in die design refers to the maximum force or tonnage that a press machine can exert during the forming or stamping process. It represents the upper limit of the force that can be applied to the die, and it is an important consideration in designing and selecting the appropriate die for a given manufacturing operation. The value if total press capacity can be calculated by equation below [79].

$$Total\ Press\ Capacity\ =\ F_{total\ cutting} +\ F_{st} \tag{3.13}$$

3.2.2 Compound Die Components Design Process in Details

In the beginning, the main components and main parts of the compound die will be explained. It was previously mentioned that the compound die performs two or more processes during one run, meaning that it makes the desired piece in one stroke, as will be clarified on a case study later [79]. The main components of a compound die are punch although piercing punch or blanking punch or both, punch (holder) plate (lower and upper), stripper plate, blanking holder, bottom and top plates, backup or thrust plate, die block, springs, shank, knockout bar, guide pillars and guide bushes.

a. Punches

In compound dies there are two types of punches which do all operations in one stroke, the first type is Blanking punch used to performed by punches in a compound die. The blanking punches are designed to cut out specific shapes or contours from the material, separating the desired part from the surrounding material. The punches create the cut edges and provide the cutting force required for blanking. The other type is piercing punches which are responsible for creating holes, slots, or other shaped features in the material being stamped. The punches exert downward force to penetrate the material and remove the desired portion. Multiple punches can be arranged to perform simultaneous punching operations. The selection and sizing of punches in a compound die primarily relies on the specific area that needs to be blanked or pierced. Punches in a compound die are categorized as plain punch, pedestal punch, and perforated punch. When designing a compound die, careful consideration is given to the appropriate type and size of punches based on the desired operations and outcomes [80]. The punch must be made of a very hard and strength material because it cuts different metals, and the greater the thickness and strength of the metal, the different type of material from which the punch is made [81]. Among the most famous materials usually used in the manufacture of punches: AISI O1, AISI D2, AISI A2, AISI M2, S7 and S5 steels [77]. The reason why these materials are widely used in the manufacture of punches is that the mechanical properties, specifically the maximum compressive strength and the ultimate limit strength, exceed 1000 in all of them. Of course, the type of piercing punch used varies according to the type of metal, as well as the thickness, and the data is shown in the Appendix (B.1). In the figures below are two of the most used types of punches, which are (Quill punch) and (Jektole punch) .

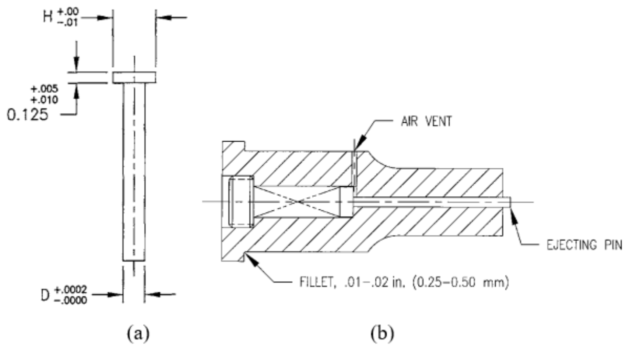


Figure 3.8 : a) Quill Punch b) Jektole Punch [81].

For the design of the bench, there are several things that must be considered. The first is to know the forces affecting it, which is the same force that will affect the piece or the place to be cut. Also, the maximum length of the punch must be calculated, and the critical force, maximum stress affecting it, as well as the amount of deformation on it, and to find this, the equations below. For maximum punch length [82]:

$$L_{pmax} = \frac{\pi \times d}{8} \times \sqrt{\frac{E \times d}{S \times t}} \tag{3.14}$$

Where,

L_{pmax} : The maximum length allowed to punch, mm.

E : Modulus of elasticity, Mpa.

d : Punch diameter, mm.

S : Shear strength of sheet metal

For maximum stress [82]:

$$\sigma_{comp} = \frac{F_{punch}}{A_{punch}} \leq \sigma \tag{3.15}$$

Where,

σ_{comp} : The maximum compressive stress on punch, Mpa.

σ : Maximum stress can punch withstand it before deformation, Mpa.

d : Punching force, N.

A_{punch} : Cross section area of punch, mm^2.

Calculating the Critical Force is very important, to ensure that the part or the bench specifically does not occur to Buckling, and it can be calculated from the equation below [83].

$$F_{cr} = \frac{2 \times \pi \times E \times I_{min}}{l^2} \tag{3.16}$$

Where,

σ_{comp} : Length of punch, mm.

E : Modulus of elasticity, Mpa.

I_{min} : Minimal moment of inertia, m^2.

The minimal moment of inertia of piercing punch can calculate using equation below [83].

$$I_{min} = \frac{\pi \times d^4}{64} \tag{3.17}$$

Where,

d : diameter of piercing punch, mm.

An important note is that in compound dies, the piercing die is inside blanking punch, and they are in the lower part of the die, and they are made of hardened steel such as D2, A2 and O1, as explained above.

b. Die block or Blanking Die

The die is the female component that provides the desired shape or profile, and it is made of hardened steel. When the punch and die come together, the material is sheared or formed into the desired shape. In the compound usually die the location of it is in the upper part [81]. The selection of die opening profiles plays a crucial role in achieving the desired precision and tolerance of the workpiece. A visual representation of four distinct opening profiles can be observed in Figure (3.9). Notably, among these profiles, the one depicted in Figure (3.9) the highest quality workpieces is given; however, it demands a more expensive machining process. To ensure optimal performance, die blocks often require frequent resharpening to maintain their sharpness and effectiveness. Interestingly, increasing the height of the opening die block, denoted as h, and outlined in Table (3.2), enables more frequent sharpening sessions, thereby enhancing the lifespan of the die block. This type of die opening configuration is primarily utilized for blanking parts that possess intricate contours, necessitating exceptional precision and accuracy [83].

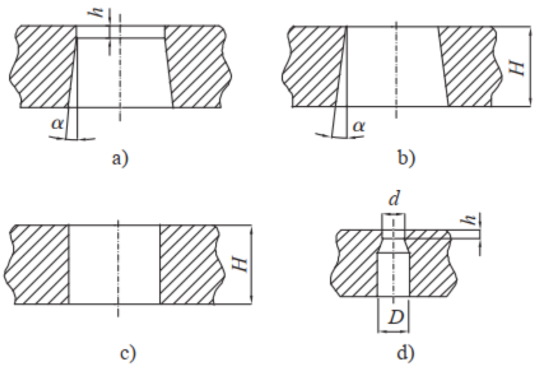


Figure 3.9: Die opening profile types [83].

Table 3.2: Dimension h values depend on material thickness [83].

Material thickness *T* (mm)	< 0.5	0.5 to 5.0	5.1 to 10.0
Height *h* (mm)	3.0 to 5.0	5.1 to 10.0	10.1 to 15.0
Angle α	3° to 5°		

One of the most important things that must be calculated when designing a die block is its total thickness of it, because the rest of the components of the die depend on it to a great extent. The equation below is used to calculate the total thickness of die block or blanking die [83].

$$H = (10 + 5 \times t + 0.7 \times \sqrt{a + c}) \times c \qquad (3.18)$$

Where,

t : Sheet metal thickness, mm.

a, b : Dimension of die opening, mm.

c : constant value depends on the mechanical properties of the product material.

The figure below explains the above dimensions.

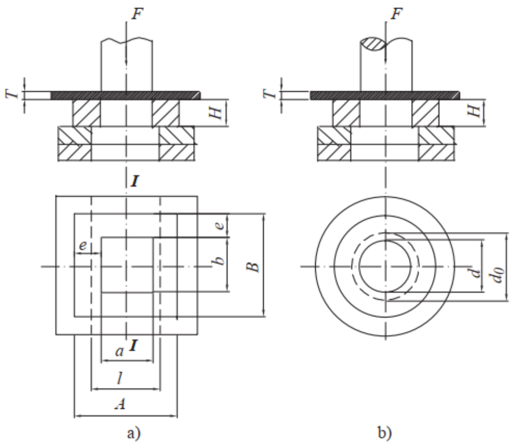


Figure 3.10: Die Block dimensions [83].

To calculate constant c the table below can be used.

Table 3.3: Different value of constant c [84].

Ultimate tensile strength (MPa)	117	245	392	784
c	0.6	0.8	1.0	1.3

But sometimes, to ensure the accuracy of manufacturing and to reduce problems, a small clearance is added to the hole of the die block as in the figure below, and this will lead to an increase in the number of factors in calculating the total thickness of the die block.

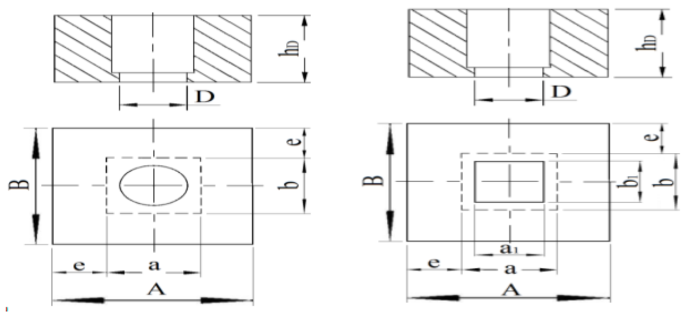


Figure 3.11: Die Block dimensions after a small clearance was add [77].

So, the new equation to calculate thickness of die block will be [77]:

$$H = (10 + 5 \times t + 0.7 \times \sqrt{a + b + a_1 + b_1}) \times c \tag{3.19}$$

For more clarify:

a_1 : Related to the length of Sheet metal or workpiece, mm.

b_1	:	Related to the width of Sheet metal or workpiece, mm.
a	:	Related to the little clearance of the length of Sheet metal or workpiece, mm.
b	:	Related to the little clearance of the width of Sheet metal or workpiece, mm.

The below equation uses to calculate the e value which is the wall thickness as shown in the above figure [83].

$$e = (10\ to\ 12) + 0.8 \times H \tag{3.20}$$

To find the total length (A) and width (B) of die block the equations below are used [83].

$$A = a_1 + 2 \times e \tag{3.21}$$

$$B = b_1 + 2 \times e \tag{3.22}$$

Also, it is important to calculate the stress on the die block, to ensure that it will not collapse due to the cutting process [83], [85].

$$\sigma_{db} = \frac{F_{bl}}{A_{db}} \leq \sigma_{dbmax} \tag{3.23}$$

Where,

σ_{db}	:	Stress on the die block, Mpa
σ_{dbmax}	:	Maximum stress can the die block withstand it before deformation, Mpa
A_{db}	:	Cross section area of the die block, mm^2.

c. Stripper Plate

The purpose of strippers is to separate the strip from the blanking and piercing punches. These strippers are necessary because the material being worked on tends to adhere to the punch, so a mechanism is needed to remove it effectively [86].

There are different types of stripper plates used in compound die operations, each designed to suit specific requirements. Some common types include:

Fixed stripper plate: In this type of the stripper plate is affixed at a fixed height above the die block, ensuring proper operation in metal stamping. This height allows the sheet metal to move freely between the upper die surface and the underside of the stripper plate.

Typically, the dimensions of the stripper plate match those of the die block in terms of width and length. In simpler dies, the stripper plate is fastened using the same screws and dowels as those used for the die block. However, in more complex dies, the stripper plate's fastening is independent of the die fastening mechanism. This independent fastening approach provides flexibility for diverse stamping processes. The thickness of the stripper plate is crucial as it must withstand the force required to strip the scrap strip from the punch effectively. The usual range for the stripper plate thickness is between 9.5 mm and 16 mm, ensuring its durability and reliability during the stripping process [82].

Spring-Loaded Stripper Plate: Spring-loaded stripper plates incorporate springs that apply downward pressure on the material. The springs allow the stripper plate to retract when the punch descends. This mechanism is employed in situations involving large blanking tasks or when working with extremely thin and highly malleable materials, where it is advantageous to apply pad pressure to secure the surrounding stock during the blanking process. In this arrangement, the stripper plate is positioned above compression springs and suspended by bolts from the punch holder. The lower surface of the stripper is situated below the cutting end of the punch. As the punch moves downward to perform the blanking operation, the stripper plate initially contacts the stock strip, holding it in place until the punch clears the strip during its return stroke. When the punch ascends, the strip is retained by spring pressure, effectively stripping it away from the punch surface. The force required for stripping can range from 2.5% to 20% of the cutting force, with the most common values between 5 and 10% [82].

When designing the stripper plate, the stripping force must first be known, and of course it is calculated through the equation that was previously explained. Also, the thickness of the striper plate must be known through the equation below [82].

$$t_{str} = 0.5 \times H \tag{3.24}$$

The stress on stripper plate can calculate by using equation [87].

$$\sigma_{st} = \frac{F_{Total\ force}}{A_{st}} \leq \sigma_{str\ max} \tag{3.25}$$

Where,

A_{st}	:	Cross section area of stripper plate, mm^2.
$\sigma_{st\ max}$	:	Maximum stress can the stripper plate withstand it before deformation, Mpa

d. Blank Holder

Also referred to as the knockout pad, the blank holder stands as one of the paramount components of the compound die. It's primarily fabricated from heat-treated tool steel and machine steel, with the choice of material hinging on specific production demands. The core role of the blank holder is to provide a sturdy hold for the sheet metal, effectively keeping it stationary and preventing any form of movement. Furthermore, it maintains firm adhesion with the piercing punch and blanking die throughout the double cutting operation. When it comes to the particulars of the knockout, decisions concerning the geometric shape, quantity, depth, and diameter of the knockout spring holes, along with shoulder height, diameter, and overall height, are dictated by design specifications [88].

e. Upper and Lower Holder Plate

The punch holder plate refers to a component used in various manufacturing processes. It serves as a platform or support structure for holding and positioning the punches, which are tools used to cut or shape materials. The punch holder plate ensures stability and precise alignment of the punches during operations such as blanking or piercing. By securely holding the punches in place, the punch holder plate facilitates accurate and controlled material manipulation. Also, it is made of a hardened-tool steel, and it may consist of a single piece of steel or be sectioned. The sizes and shapes of the punch holder plates are designed to match the tooling they are intended to hold, except for the tolerance allowance for press fit [81].The upper plate holds the piercing punch, and the lower plate holds the blanking punch. To calculate the total thickness of this plate whether upper or lower plate the equation blow can used [38].

$$T_{hold} = 0.75 \times H \tag{3.26}$$

The maximum stress can be calculated using below equation [89].

$$\sigma_{hold} = \frac{F_{Total\ cutting}}{A_{hold}} \leq \sigma_{hold\ max} \tag{3.27}$$

Where,

A_{hold} : Cross sectional area of lower or upper punch plate, mm^2.

$\sigma_{str\ max}$: Maximum stress can the punches plate withstand it before deformation, Mpa

f. Backup or Backing Plate

The backup plate, also known as the support plate, is an integral component found in dies. In certain situations, it may be required to include a hardened backing plate between the punch head (Top plate) and the punch holder. The decision to use a backing plate depends on the specific pressure applied between the punch head and the punch holder. The size and shape (length and width) of the backup plate are typically customized to align with the dimensions of the die and meet the specific needs of the material being processed [83].

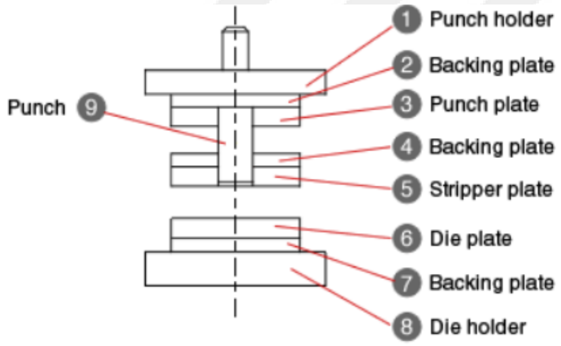


Figure 3.12: Location of Backup Plate [90].

g. Top Base and Bottom Base Plates

They are also called bolster plates; the bolster plate is an essential component in a die assembly. It is a large, flat plate that provides a sturdy and rigid base for supporting and holding various elements of the die system. The top and bottom plates serve several additional functions, including Providing pre-existing attachment holes for the dies, eliminating the need to drill these holes in the press bed. Supporting the die shoe when it is positioned over a sizable hole in the press bed. Occupying space within the press when the press shut height exceeds the die shut height. Offering chutes for the ejection of parts or scrap from the sides of the press. Typically, the bolster plate is referred to as the bottom bolster plate in the die assembly [82].

The thickness of the top and bottom plates is calculated from the equations below.

$$T_{top} \quad = 1.25 \times H \tag{3.28}$$

$$T_{Bottom} = 1.75 \times H \quad (3.29)$$

The stress value on the top and bottom plate can be calculated using the equations below, knowing that the top and bottom plate are affected by 80% of the total cutting force [85].

$$\sigma_{top\ or\ bottom} = \frac{0.8 \times F_{Total\ cutting}}{A_{top\ or\ bottom}} \quad (3.30)$$

h. Springs

As has been clarified, this type is used in movable striper plates to allow it to move. The primary purpose of the spring on the movable stripper is to exert pressure or force against the workpiece or material being processed. This pressure helps hold the workpiece in place during the operation, preventing it from moving or shifting unintentionally [82]. The type of spring present here is a compressive spring because the process here is compression, meaning it will move from its full length (l_o)to its compressed length l_s. It is very important to design the spring and choose the appropriate material for it to ensure that it performs its function properly and does not collapse. The figures below show the compressive spring properties [81].

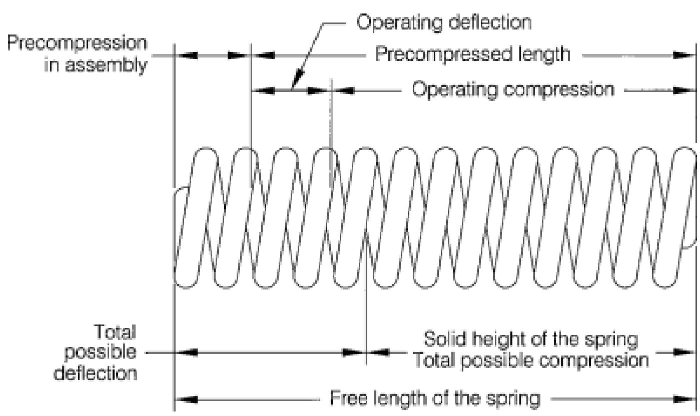


Figure 3.13: Compressive Spring properties in details [81].

It is designed in the steps below. The first step is to find out the maximum force that the spring can bear, from the equation below [82].

$$F_{spring,max} \geq 1.5 \times \frac{F_{st}}{i} \quad (3.31)$$

Where,

i : Number of springs

The maximum deflection of the spring could be calculated by equation below [82].

$$y_{spring,max} = (3\ to\ 4) \times y_{st} \tag{3.32}$$

Where,

$y_{spring,max}$	:	Maximum deflection of spring, mm
y_{st}	:	Deflection of movement stripper plate, mm.

Deflection of movement stripper plate could calculate using equation below [82].

$$y_{stripper} = t + 2\ mm \tag{3.33}$$

Where,

t : Sheet metal (product) thickness, mm

The other steps in the design are to determine the rest of the properties of the spring, such as the inner diameter, the outer diameter, and the mean diameter. The figure below shows these properties [81].

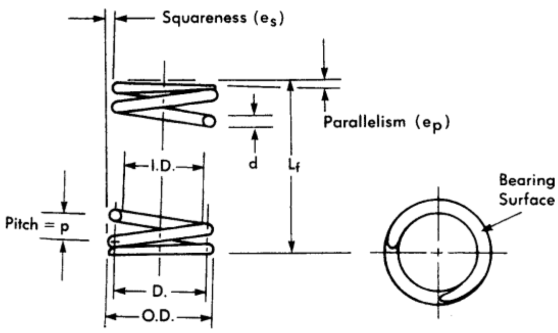


Figure 3.14: Dimensions and properties for Helical Compression Springs [81].

The minimum clearance C_{min} between the spring and its cavity (screw) must be calculated by equation below [81].

$$C_{min} = 0.05 \times D_{screw} \tag{3.34}$$

The inner diameter of spring can calculate by equation below [81].

$$ID = D_{screw} + C_{min} \quad (3.35)$$

For outer and mean diameter, the equations below can use [74].

$$OD = ID + 2 \times d \quad (3.36)$$

Where,

d : The wire diameter, mm

$$D_m = OD - d \quad (3.37)$$

Where,

D_m : Mean diameter of spring, mm.

The length characteristics of the spring, whether full or compressed, number of coils, and pitch depend largely on the type of spring end shown in the table below.

Table 3.4: Formulas for the Compression Springs dimensional characteristics [74].

Type of Spring Ends				
Term	**Plain**	**Plain and Ground**	**Squared and closed**	**Squared and Ground**
End coils, N_e	0	1	2	2
Total coils, N_t	N_a	$N_a + 1$	$N_a + 2$	$N_a + 2$
Free length, l_0	$pN_a + d$	$p(N_a + 1)$	$pN_a + 3d$	$pN_a + 2d$
Solid length, l_s	$d(N_t + 1)$	dN_t	$d(N_t + 1)$	dN_t

Other formula to calculate free length (l_o) [74].

$$l_o = y_{spring,max} + l_s \quad (3.38)$$

One of the most important things is also to make sure that the full length of the spring will not cause buckling to happen to it, and the equation below is used to make sure of this [74].

$$l_o < 2.63 \times \frac{D_m}{\alpha} \quad (3.39)$$

Where,

α : End-Condition Constants.

The value of α can selected from table below [74].

Table 3.5: Different values for α of Compression Spring [74].

End Condition	**Constant α**
Spring supported between flat parallel surfaces (fixed ends)	0.5
One end supported by flat surface perpendicular to spring axis (fixed); other end pivoted (hinged)	0.707
Both ends pivoted (hinged)	1
One end clamped	2

i. Other Compound Die Components

There are other components of the compound die such as the guide pillars, the guide bush as well as the shank and some screws, and these are permanently present in any compound die, with specific functions such as alignment of the die elements and fixing.

3.3 COMPOUND DIE DESIGN FOR L-SHAPE BRACKET PLATE

This piece will be referred to (product) during the research. Where, at the beginning, a specific product will be selected, which is in the form of it is L shape with 3 holes, and its dimensions will be determined based on the applications used and based on research and companies. After that, the compound die will be designed to manufacture this product, and then the necessary analyses will be made for some parts of the compound die.

3.3.1 Product Specifications and Model

In this section, a specific and famous used product will be selected to design the compound die and do a study on it. This product is a joint plate containing 3 holes as in the figure below.

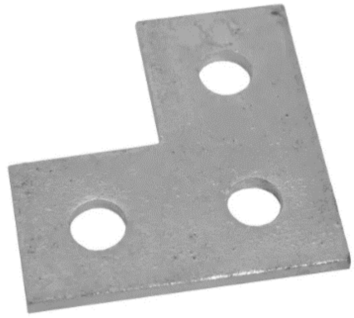


Figure 3.15: Stainless Steel L-shape Bracket Plate with 3 Holes [91].

The L shape bracket with 3 holes has a wide range of applications across various industries Flat plate fittings play a crucial role as essential accessories in the construction of customized frameworks, shelving units, and support systems using Unistrut metal channels. These fittings are available in various sizes and materials to cater to different requirements. L-shaped brackets are used in combination with channel nuts and bolts to create a robust connection, eliminating the need for welding. Once installed, they form a durable union that provides strength and stability to the overall structure. These fittings are designed to seamlessly integrate with Unistrut channels, ensuring a secure and reliable assembly [91].

Through research, the dimensions of such products are 80 X 80 or 86 X 86 or 90 X 90. As for the thickness, it ranges between 5 or 6 mm and usually these products are manufactured from 316 stainless steel or hot dipped galvanized [91]. SOLIDWORKS software will be used to design this product first and show its dimensions in detail as in the figures below.

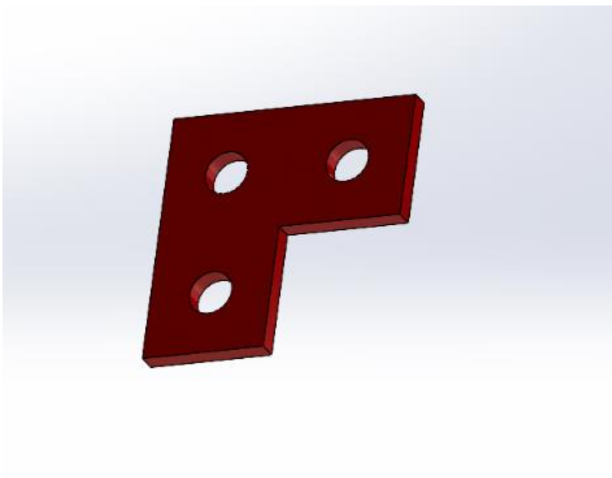


Figure 3.16: Model of Stainless-Steel L-Shape Bracket Plate with 3 holes.

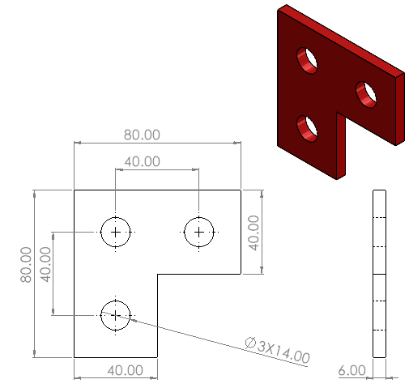


Figure 3.17: Product Drawing That Clarifies all Dimensions.

Data:

Total length of product (L): 80 mm.

Total width of product (W): 80 mm.

Total thickness of product (T): 6 mm.

Material: 316 Stainless Steel.

Diameters of holes: 14 mm.

Distance between holes: 40 mm.

3.3.2 Compound Die Design for The Product

3.3.2.1 Forces, energy, and other sheet parameters calculations

The first thing in any die design process is knowing the cutting forces and other forces, and the equations that are used for this purpose and the equations used in the design of the compound die have been clarified in the previously theoretical part in detail. But before that, the perimeter of the blanking operation and the piercing operation will be calculated, as well as finding the shear strength for stainless steel.

a. Product Perimeter and Stainless-Steel 316 Shear Strength Calculations.

$$L_{Bl} = 80 + 40 + 40 + 40 + 40 + 80 = 320\ mm.$$

$$L_{pr} = 2 \times \pi \times 7 = 43.98\ mm.$$

$$L_{total\ cutting} = 43.98 + 320 = 364\ mm$$

For Shear strength by using eq (3.3) and from Appendix (A.1) The ultimate strength of 316 stainless steel is 550 Mpa so the shear strength will be:

$$S = 0.6 \times 550 = 330\ Mpa$$

b. Cutting Forces Calculations

By using This result and from eq (3.1) and eq (3.2) the values of blanking and piercing forces will be:

$$F_{Bl} = 330 \times 6 \times 320 = 633.600\ kN$$

$$F_{pr} = 330 \times 6 \times 43.98 = 87.08\ kN$$

But because of there is 3 holes and the 3 piercing punches are needed so the total piercing force will equal $=3 \times 87.08 = 261.21\ kN$.

For total cutting force the eq (3.4) will use

$$F_{Total\ cutting} = 633.600 + 261.21 = 894.81\ kN$$

c. Dies and Punches Diameters Calculations

At first the clearance between the die and the bench is calculated using eq (3.7)

$$c = 0.0032 \times 6 \times \sqrt{330} = 0.07\ mm$$

Because the shape of the blanking punch is not circular, eq (3.8) and eq (3.9) will be used to calculate the dimensions.

$$L_b\ (length\ of\ blanking\ punch) = 80 - 2 \times 0.07 = 79.86\ mm$$
$$w_b\ (width\ of\ blanking\ punch) = 80 - 2 \times 0.07 = 79.86\ mm$$

For piercing cut operation, the hole to be punched (hole die) diameter will calculate be eq (3.6) and as it was clarified previously the piercing punch diameter equal the hole round diameter D_hWhich is 14 mm.

$$Hole\ die\ diameter = 14 + 2 \times 0.07 = 14.14\ mm$$

d. Striping Force, Cutting Energy and Deformation Work Calculations

The stripping force was calculated using the eq (3.10) and was taken as 10% of the value of the total cutting force.

$$F_{st} = 10\% \times 894.81 = 89.481\ kN$$

From eq (3.13) the maximum press capacity could calculate:

$$Total\ Press\ Capacity = 894.81 + 89.481 = 984.291\ kN$$

In Tons: $\frac{984.291}{9.81} = 100.33\ Tons$

For cutting energy the eq (3.11) used to calculate it.

$$E = 10\ \times 894.81 \times 6 = 53.69\ kJ$$

For Deformation work the value of K is taken as 0.35 from table (3.1) depend on material shear strength and material thickness then, by eq (3.12) the deformation work was calculated.

$$W = 0.35 \times 894.81 \times 6 = 1879.101\ kN.mm$$

3.3.2.2 Punches design

After calculating the cutting forces and finding the cutting energy, it is the turn to design the parts of the compound die to design the required product, as explained in the theoretical explanation. At the beginning, the maximum length of the piercing punch is calculated using eq (3.14) below.

From Appendix (A.1) the modulus of elasticity (E) of 316 stainless steel is 193 Gpa, so the maximum length of piercing punch will be:

$$L_{pmax} = \frac{\pi \times 14}{8} \times \sqrt{\frac{193 \times 1000 \times 14}{330 \times 6}} = 203.09\ mm$$

This is the maximum length that can be for this type of punch so that it does not have buckling, and this means that the required length must be less than this, and a length of **84 mm** was selected because it is geometrically appropriate. Also, according to some research, the lengths of the benches for this type of application are between (50 mm) and (125 mm) These data are certified in Appendix (B.1). It must be ensured that the force acting on each piercing punch will not lead to buckling, and equation (3.16) is used to find the value of the critical force. But before that the eq (3.17) will be used to calculate the minimal moment of inertia.

$$I_{min} = \frac{\pi \times 14^4}{64} = 1885.75\ mm^4$$ so, the critical force will be:

$$F_{cr} = \frac{\pi^2 \times 193 \times 1000 \times 1885.75}{4 \times 84^2} = 127.27\ kN$$

As calculated above, the cutting force on each piercing punch = $87.08\ kN$ and it is $< 127.27\ kN$. So, the piercing punch is safe among buckling analysis.

After that, the maximum stress on the bench will be calculated to ensure that it does not collapse during work, noting that the maximum stress will also be calculated later using the scales. The maximum stress is calculated theoretically using equation (3.15).

$$\sigma_{comp} = \frac{87.08 \times 1000}{\frac{(\pi \times 14^2)}{4}} = 565.82\ Mpa$$

In all cases, it is safe, because the materials used have a compressive strength that exceeds 1000 in most of them, as will be clarified later mentioning the characteristics of the materials and conducting analysis by ANSYS software.

After completing the calculations, the bench was designed and drawn using the SOLIDWORKS software.

Figure 3.18: 3D model of Piercing Punch.

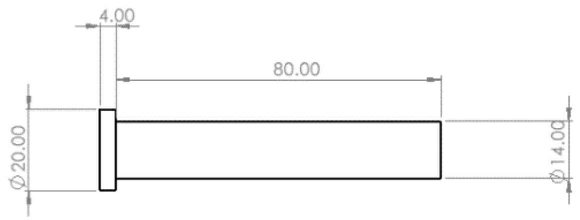


Figure 3.19: Piercing Punch 2D drawing that clarifies dimension.

Where, Total length 84 mm, Head diameter 20 mm, punch diameter 14 mm.

For Blanking punch and piercing die, the first thing will do is to calculate the stress using eq (3.15) below:

The $A_{blanking} = 7866.21\ mm$^2 so, the compressive strength:

$$\sigma_{comp} = \frac{633.6 \times 1000}{7866.21} = 80.547\ Mpa$$

From dies diameters and dimensions calculations from eq (3.7) to eq (3.9) above the dimension of blanking punch and piercing die as in the figure below. For Length of blanking die it is selected depending on the assembly and geometry length and take another out of profile clearance which is 5 mm to fixed blanking punch in lower holder plate.

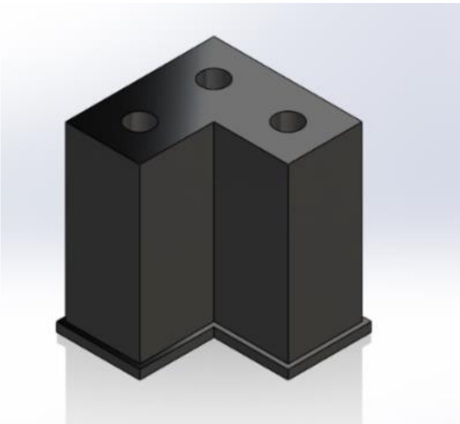


Figure 3.20: 3D model of Blanking Punch and Piercing Die.

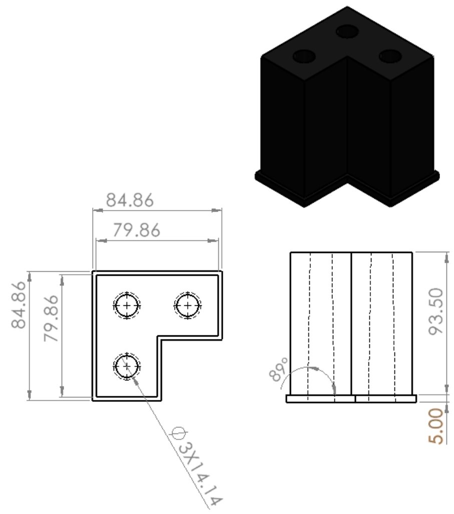


Figure 3.21: Detailed drawing of Blanking Punch and Piercing Die.

As can be seen in the figures, the value of angular clearance 1° was also taken. because in this type of applications the angular of clearance the angular clearance is between 0.25° to 1°[64].

3.3.2.3 Die block or blanking die design

For the sake of more accuracy and to avoid any problems during the cutting process, the profile in the figure (3.10 a) was chosen, and this means that there is several parameters that must be calculated, such as (e, A, and B) and these parameters depend on total thickness (H) of die block.

Data:

$a_1 = 80\ mm$, $b_1 = 80\ mm$, $a = 90\ mm$, $b = 80\ mm$,*T=6 mm, c from* table (3.3) depending on Ultimate tensile strength range will equal 0.9.

So, by using eq (3.19) the total thickness of the die block will be:

$$H = \left(10 + 5 \times 6 + 0.7 \times \sqrt{90 + 90 + 80 + 80}\right) \times 0.9 = 47.6\ mm \approx \boldsymbol{48mm}.$$

For value of e it will calculate using eq (3.20).

$$e = 10 + 0.8 \times 48 = 48.4\ mm$$

After that, the total length (A) and width (B) of the die block will calculate using eq (3.21) and eq (3.22) as shown below:

$$A = 80 + 2 \times 48.4 = 177 \approx 180$$

$$B = 80 + 2 \times 48.4 = 177 \approx 180$$

Since the thickness of the product is greater than 5 mm, and based on table (3.2), the h value that was taken is 14 mm.

The calculation of the maximum stress on the die block is done using the equation (3.23)

But firstly, the Cross-section area of die block = $(A\ or\ B\ \times H) = 180 \times 48 = 8640\ mm^2$.

so, the maximum stress will be:

$$\sigma_{db} = \frac{633600}{8640} = 73.34\ Mpa$$

Thus, the die block can be drawn using the SOLIDWORKS software in all its details as shown in the figures below.

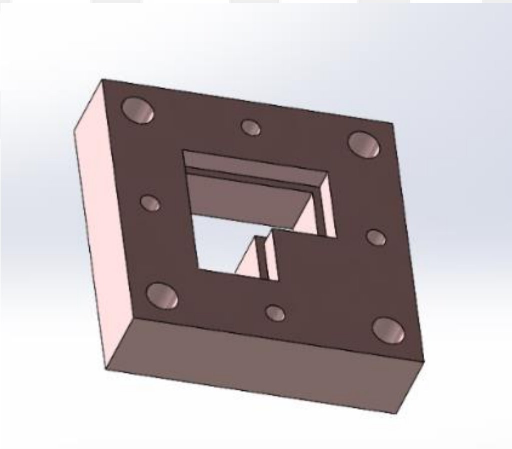


Figure 3.22: 3D model of the Blanking Die Block.

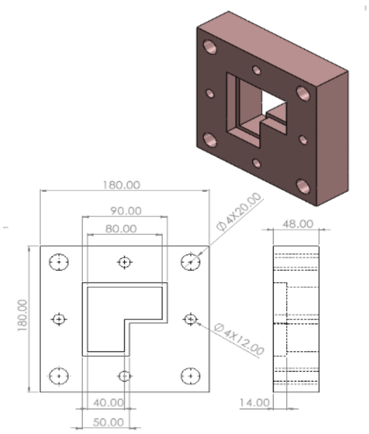


Figure 3.23: The drawing of the Blanking Die in details.

3.3.2.4 Stripper plate design

Since the total thickness of the die block or plinking die block has been calculated, it is possible to calculate the thickness of the stripper plate from eq (3.24).

$$t_{str} = 0.5 \times 48 = 24\ mm.$$

The total length and width of stripper plate is the same as the die block as is clarified in theriacal part.

The stress on stripper plate can be calculated by using eq (3.25).

$$\sigma_{st} = \frac{984.291 \times 1000}{24 \times 180} = 227.84\ Mpa$$

Deflection of movement stripper plate could calculate using eq (3.33) below:

$$y_{st} = 6 + 2\ mm = 8\ mm$$

The figures below show the striper plate after it has been drawn on SOLIDWORKS in detail.

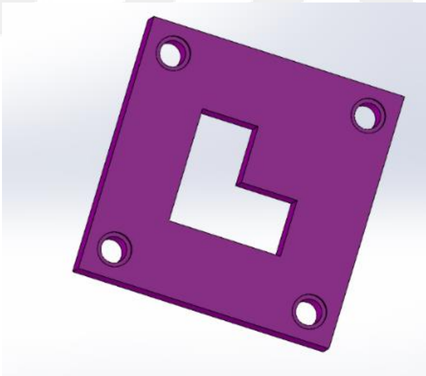


Figure 3.24: Stripper Plate 3d model.

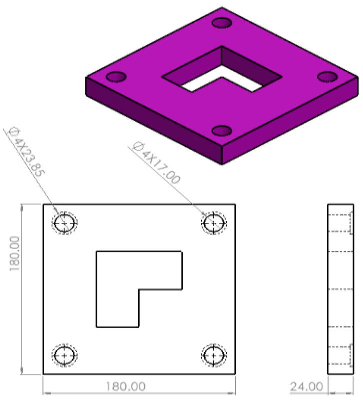


Figure 3.25: Stripper Plate drawings in details.

Some dimensions such as 17 mm and 23.85 mm as in the stripper plate above are related to the screws and springs and it will be clarified in the coming analysis.

3.3.2.5 Blank holder

As it was clarified, the design of this part depends on the rest of the parts and the requirements of shape and design, and it was designed with the shape and dimensions below.

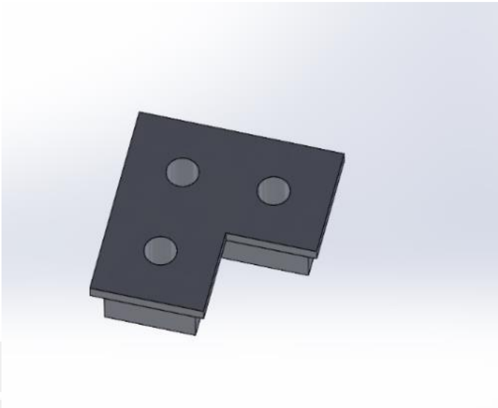


Figure 3.26 : 3D model of Blank Holder.

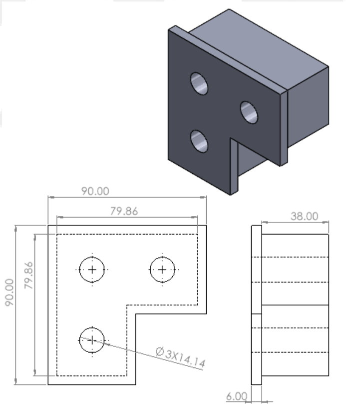


Figure 3.27: Blank Holder drawings.

3.3.2.6 Upper and lower holder plate

The thickness of these two parts is equal and can be calculated by the eq (3.26).

$$T_{hold} = 0.75 \times 48 = 36\, mm\,.$$

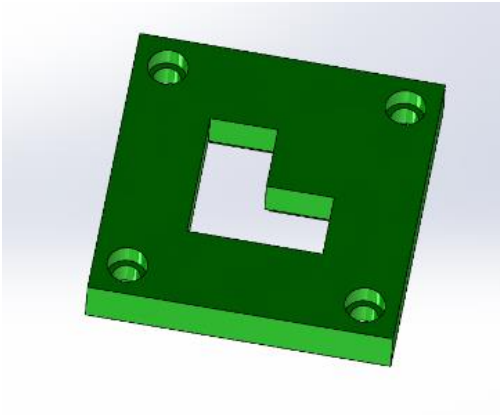


Figure 3.28: 3D model of Lower Holder Plate.

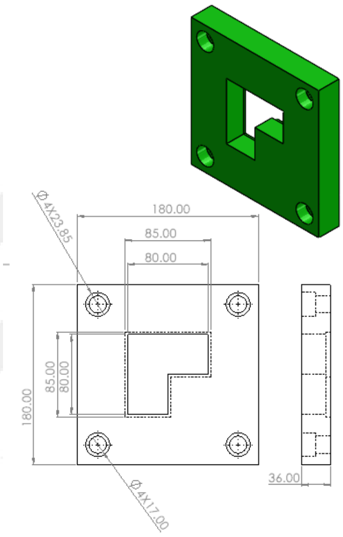


Figure 3.29: 2D model of Lower Holder Plate.

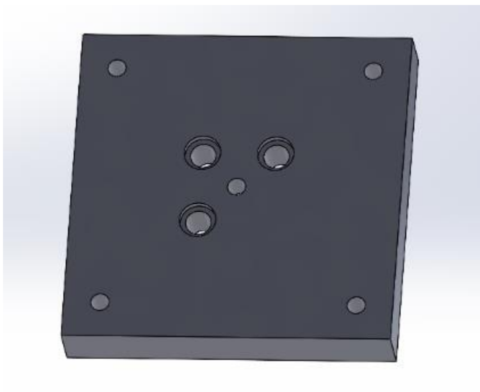


Figure 3.30: 3D model of Upper Holder Plate.

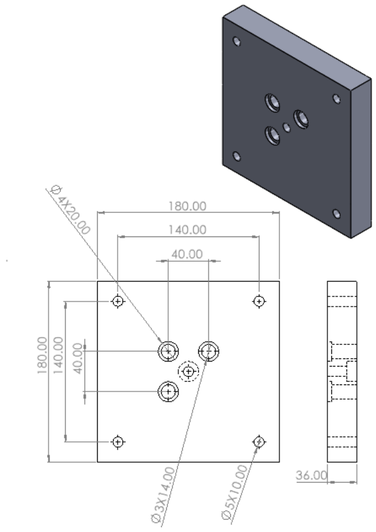


Figure 3.31: 2D model of upper Holder Plate.

3.3.2.7 Backup or backing plate design

Thicknesses are usually chosen between 6 and 12 mm. And sometimes it reaches 15 mm, especially for applications where the thickness of the product is more than 5 mm [92].

And in the figures below, the model and drawings of the backup plate.

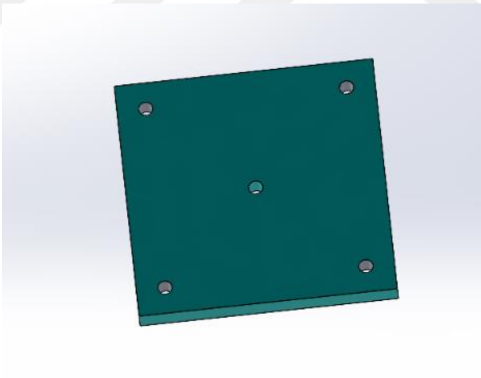


Figure 3.32: 3D model of Backup Plate

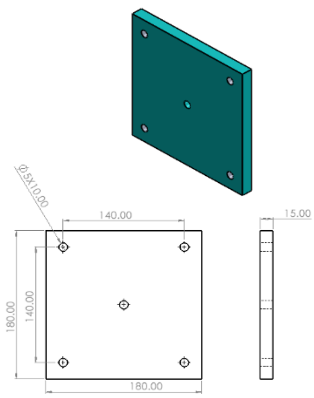


Figure 3.33: Drawings of Backup Plate.

3.3.2.8 Top base and bottom base plates design

These two plates are the thickest two parts in the die and the thickness of each piece is calculated using eq (3.28) and eq (3.29).

$$T_{top} = 1.25 \times 48 = 60 \, mm$$

$$T_{Bottom} = 1.75 \times 48 = 84 \, mm$$

The total length and width of the bottom and top plate was chosen as $280 \; X \; 280$.

The Maximum stress can be calculated using eq (3.30).

$$\sigma_{top} = \frac{0.8 \times 894.84 \times 1000}{60 \times 280} = 42.61 \; Mpa$$

$$\sigma_{bottom} = \frac{0.8 \times 894.84 \times 1000}{84 \times 280} = 30.44 \; Mpa$$

Model the upper base with its drawings in the figures below.

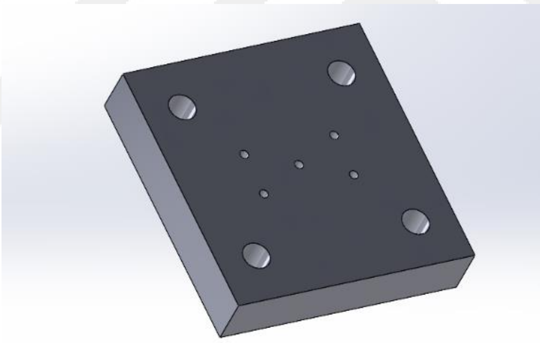


Figure 3.34: 3D model of the Upper Base Plate.

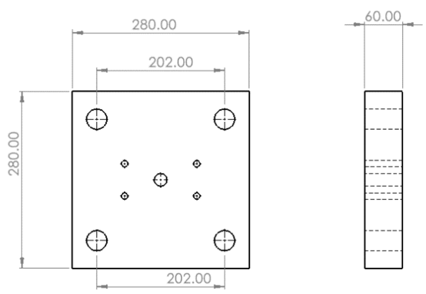


Figure 3.35: Drawings of the Upper Base Plate.

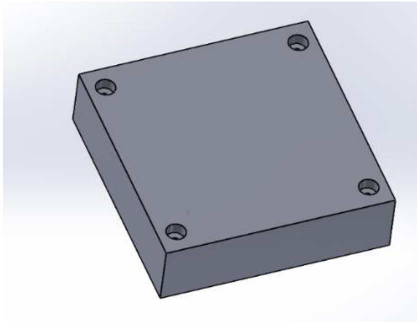


Figure 3.36: 3D model of the Bottom Base Plate.

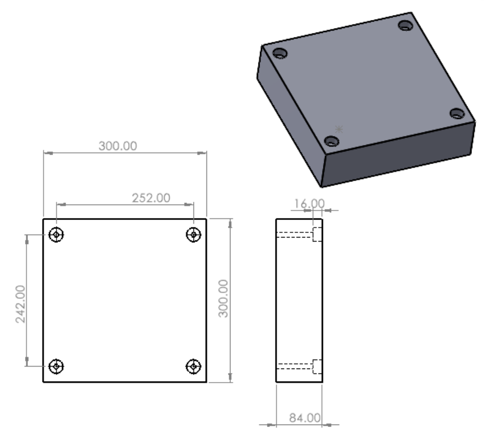


Figure 3.37: Drawings of the Bottom Base Plate.

3.3.2.9 Spring design

4 springs will be used in this research, which is the most common number. In the beginning, the maximum force acting on the spring must be calculated, and this is done using equation (3.31).

$$F_{spring,max} \geq 1.5 \times \frac{89.481}{4}$$

$$F_{spring,max} \geq 33.55\ kN$$

Using equation (3.32) the maximum deflection on the spring can be calculated.

$$y_{spring,max} = 4 \times 8 = 32\ mm$$

Knowing that the diameter of the screw in which the spring will be is 17 mm so, the minimum clearance C_{min} between the spring and its cavity (screw) could calculate using eq (3.34).

$$C_{min} = 0.05 \times 17 = 0.85\, mm$$

The wire diameter (d) that selected for this compressive spring is 3 mm.

Total number of coil (N_t) is 11.5 turn.

The inner and outer diameter of compressive spring can calculate by eq (3.35) and eq (3.36).

$$ID = 17 + 0.85 = 17.85\, mm$$

$$OD = 17.85 + 2 \times 3 = 23.85\, mm$$

For mean diameter (D_m) the eq (3.37) was used to calculate it as below:

$$D_m = 23.85 - 3 = 20.85\, mm$$

The type of spring used in the project is Plain and Ground, and from the relationship in table (3.4), the Solid Length (l_s) can be calculated.

$$l_s = 3 \times 11.5 = 34.5\, mm.$$

The total length of the compressive spring calculated by eq (3.38).

$$l_o = 34.5 + 32 = 66.5\, mm$$

Using eq (3.39), it is ensured that the total length of the calculated spring will not lead to a buckling, the value of α that will be use in eq (3.39) is from table (3.5) and it is equal 0.5. now, by eq (3.39):

$$66.5 < 2.63 \times \frac{20.85}{0.5}$$

$$66.5 < 109.671$$

So, the calculating length of the compressive spring is **safe.**

The famous material of the compressive spring in these types of applications is Music wire. because of the following reasons: exceptional tensile strength, this spring material surpasses all others in its ability to withstand elevated stresses during repeated loading. It is readily available in diameters ranging from 0.12 to 3 mm (0.005 to 0.125 in). However, it is important to note that it should not be utilized in temperatures exceeding 120°C (250°F) or in subzero conditions [74].

After all these calculations, the SOLIDWORKS software was used to design and draw the spring with the calculated dimensions as in the figures below.

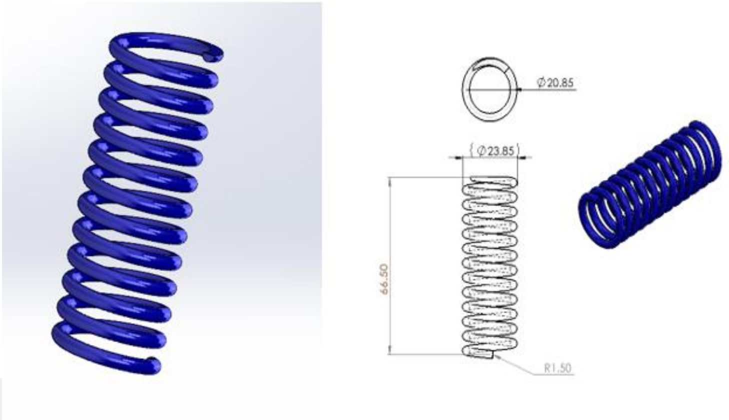


Figure 3.38: Compressive Spring 3d modal and its drawings.

3.3.2.10 Other compound die components

Such as Shank and knock out rod and some screws, and these are drawn and designed based on the final shape of the die, given that they are complementary. In the figure below, there are Shank and knock out rods. As for some screws, they are found in the library of any design software such as SOLIDWORKS.

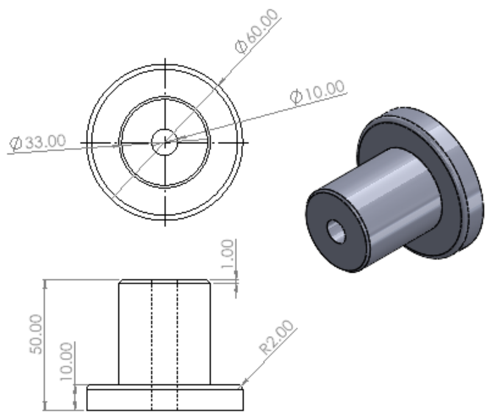


Figure 3.39: Shank model and its drawings.

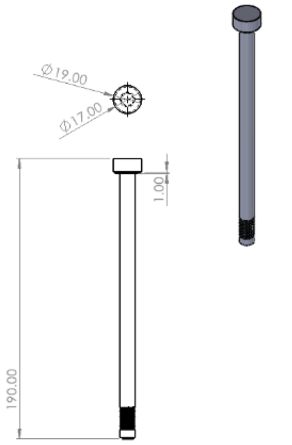


Figure 3.40: Knock Out Rod model and its drawings.

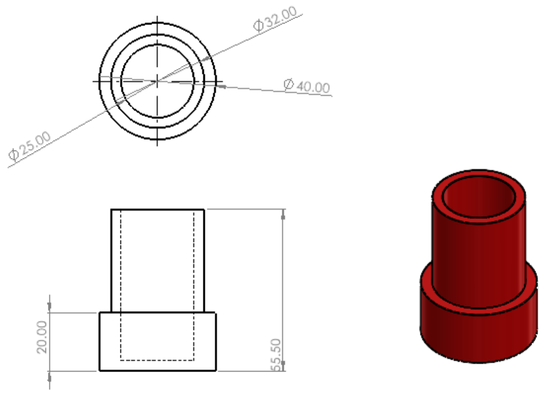


Figure 3.41: Guide Bush model and its drawings.

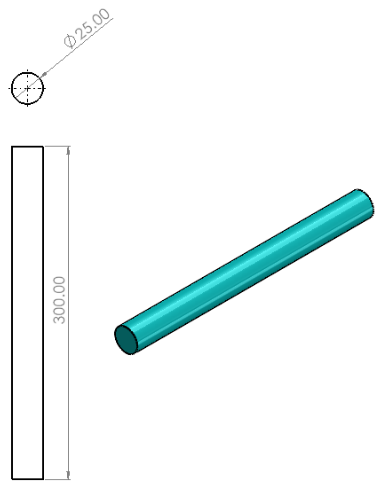


Figure 3.42: Guide Pillar model and its drawings.

3.3.2.11 Full die assembly and its bill material

Firstly, the assembly of piercing, blanking punches and product will clarify as below:

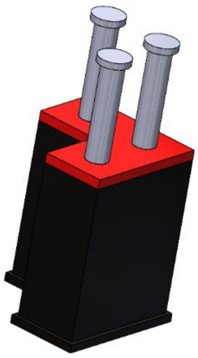


Figure 3.43: Assembly of Punches with Product.

The assembly below clarifies all die components and their location.

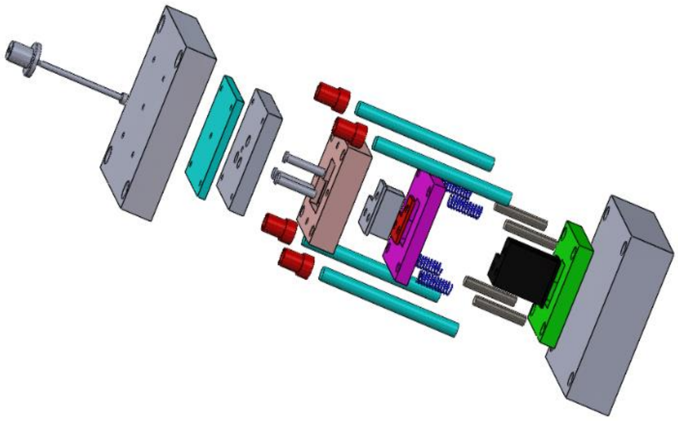


Figure 3.44: Exploded view of Compound Die assembly.

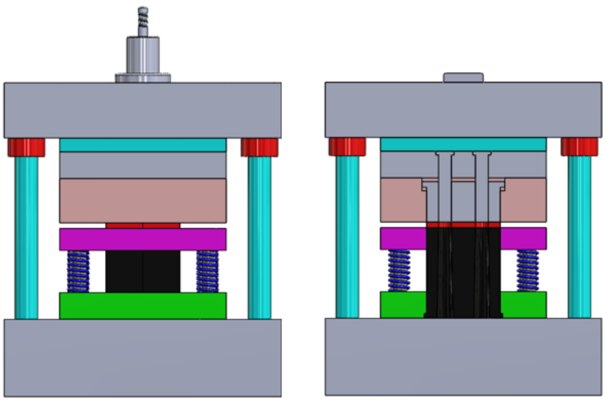
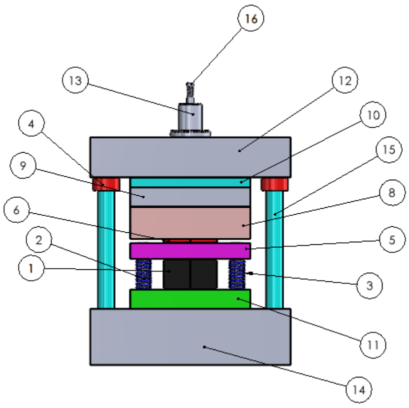


Figure 3.45: Front view of full Die assembly and section from it.



ITEM NO.	PART NUMBER	QTY.
1	Blanking Punch	1
2	Screw	4
3	SPRING	4
4	Guide Bush	4
5	STRIPPER plate	1
6	Product	1
7	Blank Holder	1
8	Blanking Die block	1
9	Upper Punch Plate	1
10	Backup plate	1
11	Blanking Punch Holder	1
12	Upper Plate (Punch Holder)	1
13	Shank	1
14	Bottom Plate (Die Holder)	1
15	Guide Pillars	4
16	Knock-Out Rod	1
17	Piercing Punch	3

Figure 3.46: Bill of material of Compound Die.

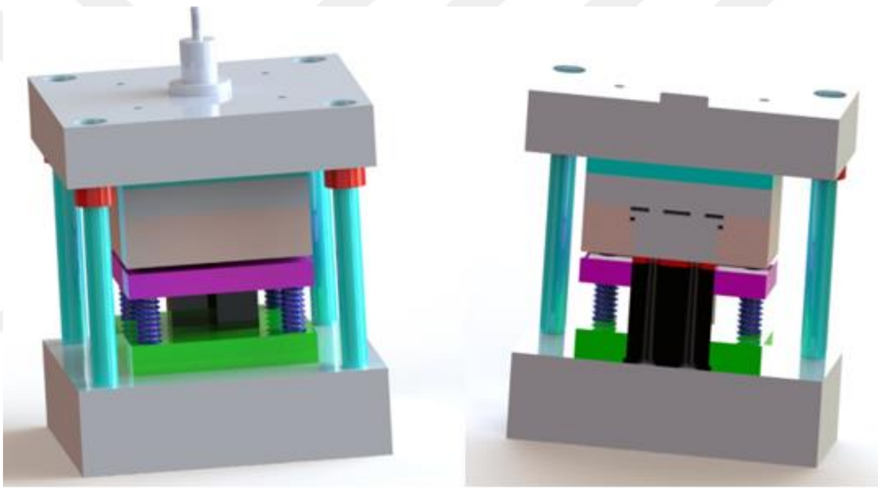


Figure 3.47: Full Compound Die and its section after rendering.

3.4 ANALYSIS AND SIMULATIONS USING ANSYS WORKBENCH

3.4.1 Finite Element Method And Its Software

The Finite Element Method (FEM), also known as Finite Element Analysis (FEA), is a computational technique that simplifies complex objects by dividing them into smaller, more manageable elements. This method revolutionizes engineering practices by leveraging computer technology. Traditionally, designing a product involved laborious manual drawings, but with the advent of computer-aided design (CAD), the process has become more efficient. CAD software utilizes computer graphics to create and visualize product designs accurately. Similarly, the analysis of designs used to rely on manual calculations and extensive testing. However, computer simulations powered by computer-aided engineering

(CAE) software have replaced many of these testing procedures. CAE enables engineers to simulate and evaluate designs using advanced algorithms, reducing the need for physical prototypes. By employing the FEM and utilizing CAD and CAE software, engineers can tackle complex problems and make informed design decisions. This integration of computational tools has significantly enhanced the efficiency, accuracy, and speed of engineering processes, transforming the field of engineering [93].

The Finite Element Method (FEM) finds numerous applications across various fields. Here are some examples of its applications:

Structural and Solid Mechanics: FEM is used for tasks such as analysing the reliability of offshore structures, simulating vehicle crashes, assessing the integrity of nuclear reactor components, and optimizing wind turbine blade designs. Heat Transfer: FEM is applied to model heat transfer phenomena, including electronics cooling analysis, casting simulations, and heat transfer analysis in combustion engines. Fluid Flow Analysis: FEM is utilized to study fluid flow fields, such as aerodynamic analysis of race car designs, modelling airflow patterns in buildings, and analysing seepage through porous media. Electrostatics/Electromagnetics: FEM is employed in the calculation of electric fields in sensors and actuators, predicting the performance of antenna designs, and analysing electromagnetic interference suppression [93].

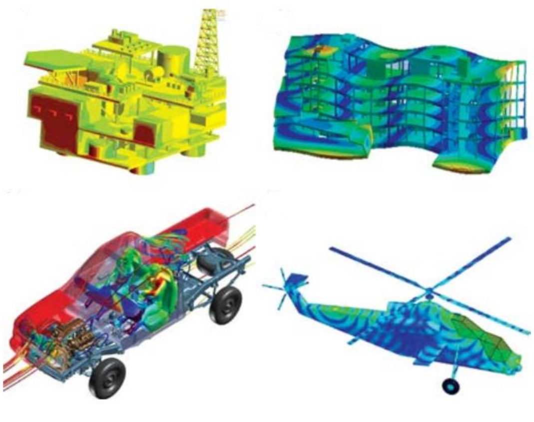


Figure 3.48: Some applications of FEM analysis [93].

There are several software packages available for implementing the Finite Element Method. Some popular FEM software options include:

ANSYS: is a widely used commercial software suite that offers comprehensive capabilities for structural analysis, fluid dynamics, electromagnetics, and other engineering simulations. Abaqus: Abaqus, developed by Dassault Systems, is a powerful FEM software that provides advanced simulation capabilities for structural, fluid, and Multiphysics analyses. COMSOL: COMSOL is a Multiphysics simulation software that allows users to solve a wide range of problems using the Finite Element Method. It provides a flexible and user-friendly interface for modelling and analysing complex systems. LS-DYNA: LS-DYNA is a general-purpose finite element software that specializes in simulating complex nonlinear phenomena, such as crash analysis, impact simulations, and Multiphysics problems [94].

3.4.2 Analysis And Simulations Of Compound Die Parts

In this section, the ANSYS software will be used to analyse the stresses and deformation and calculate the safety factor and other factors for some of the main components of the die, such as the piercing punch and the blanking punch, as well as the die block and the stripper plate. These components that have been mentioned and for which analyzes will be made are usually manufactured from the same material to be able to withstand the different cutting forces and in order not to collapse during cutting operations. 3 different materials will be used in the simulation process, and these materials are mainly used to make the punch and the rest of the components as usual. To prove that the manufacture of this product is compatible with it and to make a simple comparison between them. The materials are (AISI D2 Cold Work Tool Steel), (AISI O1 (Oil-hardening) Tool Steel), and (AISI D2 Cold Work Tool Steel) and the tables below show the properties of each material.

Table 3.6: AISI D2 Steel mechanical properties [95], [96].

Properties	**Value**
Density (kg/m^3)	7670
Modulus of elasticity (Gpa)	190
Poisson's ratio	0.28
Tensile Strength, Yield (Mpa)	1510
Tensile Strength, Ultimate (Mpa)	2000
Compressive Strength, Yield (Mpa)	1650

Table 3.7: AISI O1 Steel mechanical properties [97], [98].

Properties	Value
Density (kg/m^3)	7830
Modulus of elasticity (Gpa)	190
Poisson's ratio	0.29
Tensile Strength, Yield (Mpa)	1500
Tensile Strength, Ultimate (Mpa)	1690
Compressive Strength, Yield (Mpa)	1350

Table 3.8: AISI A2 Steel mechanical properties [99], [100].

Properties	Value
Density (kg/m^3)	7720
Modulus of elasticity (Gpa)	190
Poisson's ratio	0.29
Tensile Strength, Yield (Mpa)	1269
Tensile Strength, Ultimate (Mpa)	2040
Compressive Strength, Yield (Mpa)	1350

These materials will be added to the ANSYS Workbench library first, and then an analysis will be made for each of the parts that were mentioned on each material. In this chapter, the analysis steps will be clarified, and in the next chapter, the results will be presented in detail. The analysis steps are similar in all materials and parts. The type of analysis that will be conducted is the Fatigue Failure analysis by adding fatigue tool in ANSYS, because the components perform many operations per minute. Such products are manufactured hundreds or thousands of them daily. This means that the forces affecting the punches will change from zero to the maximum force (which is the cutting force).

3.4.2.1 Piercing punch analysis and simulation

The first step in the process of analyzing a piece or part on the ANSYS software is to bring it from the design software, and in this research, it is SOLIDWORKS in a specific format such as (x_t) or (igs).

After that it is added to the static structure analysis and then the material is determined. Then a mesh is made to improve the analysis of the part and obtain more accurate results. The meshing process was performed for the piercing punch and a body size of 2 mm was made, and the results were as shown in the picture below.

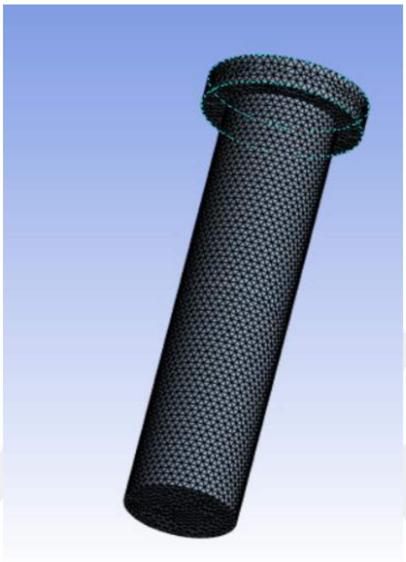


Figure 3.49: Mesh result of the Piercing Punch.

After the mesh done, the boundary conditions are determined, and this means determining the supports and forces affecting the part, where the piercing punch is fixed to the upper holder (fixed support) and the force affecting it is the piercing force that affects the product for piercing which is $87.08\ kN$.

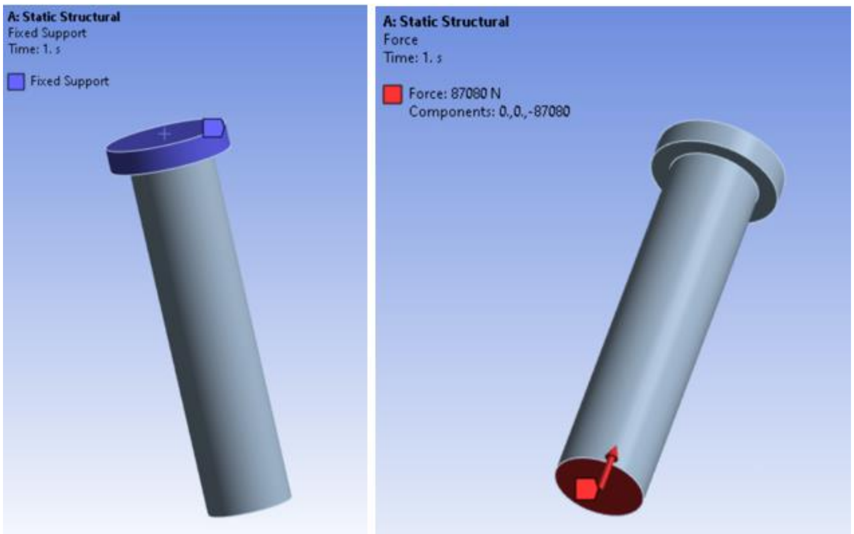


Figure 3.50: Support and Force on the Piercing Punch.

After that, the results will be obtained, but they will be presented in the fourth (next) chapter, and they will be commented on all the analyzed parts, as well as the materials.

3.4.2.2 Blanking punch analysis and simulation

The steps will be performed as in the piercing punch, but the body sizing was taken with a 3 mm mesh process. The picture below shows the results of the mesh process on the blanking punch.

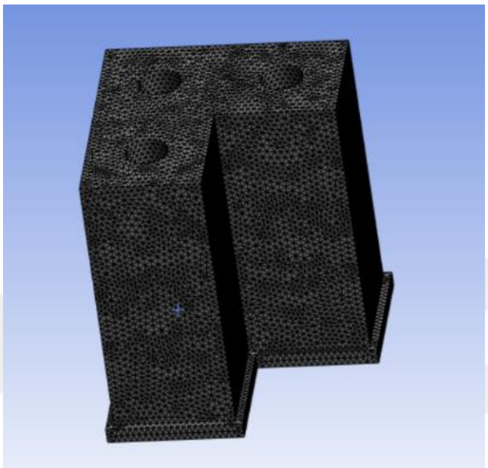


Figure 3.51: Mesh result of the Blanking Punch and Piercing Die.

The boundary conditions for the blanking punch involve fixing it onto the lower holder plate, with the blanking force acting upon it to cut the outer shape of the product. The following figures illustrate the boundary condition of the blanking punch and piercing die. The value of the blanking force as it calculated previously is $633.6\ kN$.

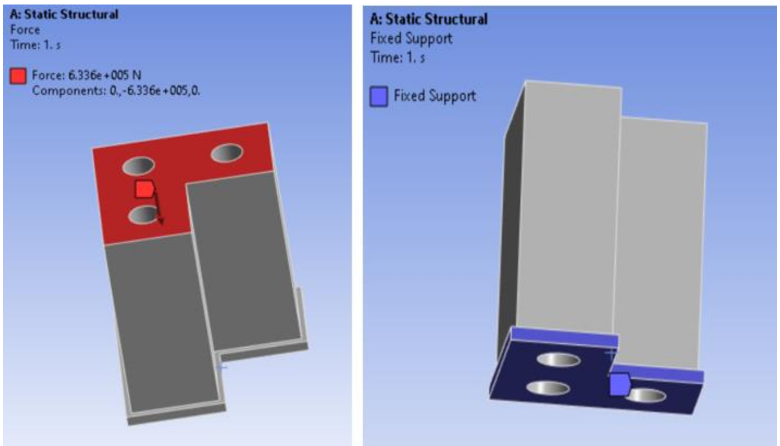


Figure 3.52: Support and Force on the Blanking Punch and Piercing Die.

3.4.2.3 Blanking die analysis and simulation

A 3mm body sizing was used, and the figure below shows the blinking die after the meshing process.

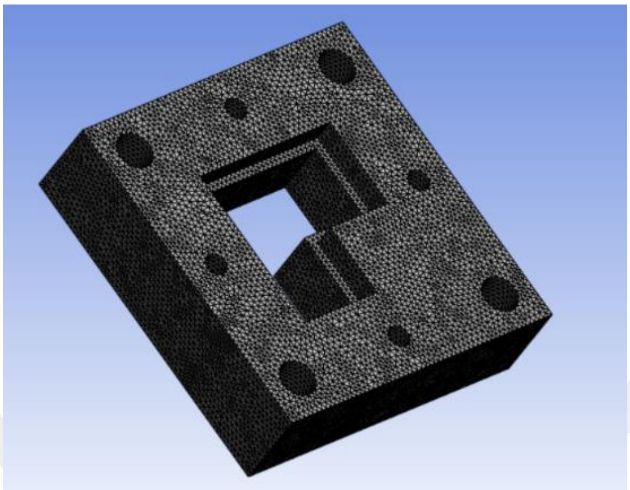


Figure 3.53: Mesh result of the Blanking Die.

Regarding the boundary conditions, in addition of the fixed support, there will be frictionless support due to screws. As for the forces involved, it will be the blanking force. The figure below show that.

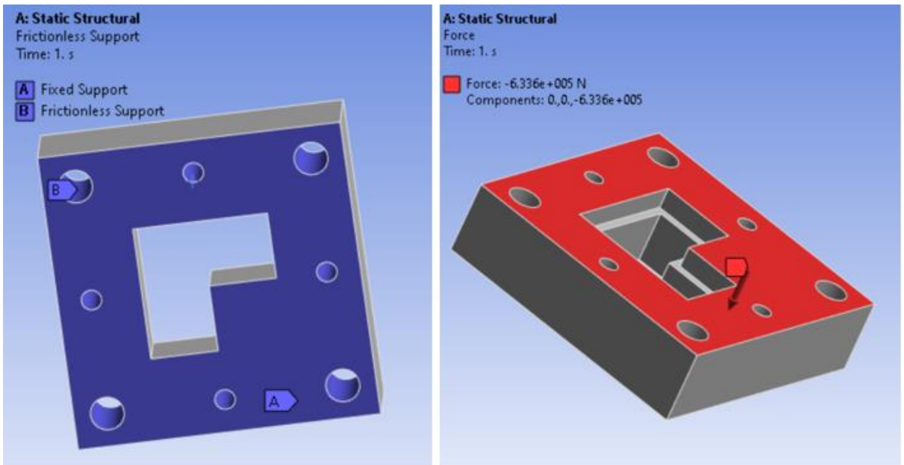


Figure 3.54: Support and Force on the Blanking Die.

3.4.2.4 Stripper plate analysis and simulation

The body sizing used to divide it is 2 mm, the figure below shows the mesh result on stripper plate.

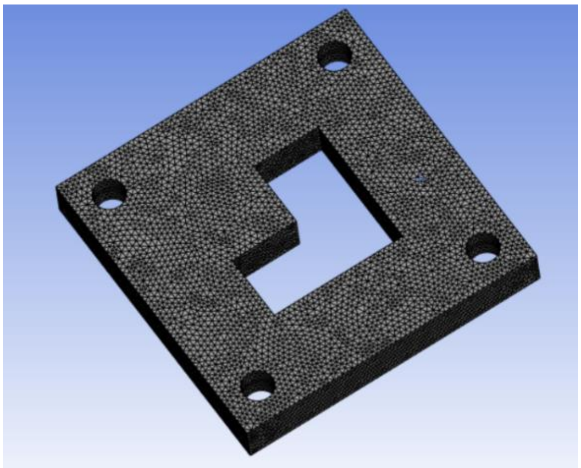


Figure 3.55: Mesh result of the Stripper Plate.

The stripper plate is affected by the combined impact of the total cutting force and the stripping force it generates. To withstand these forces, the stripper plate is constructed using hardened steel, similar to punches and dies.so, the force effect on stripper as it clarified before in calculation is $984.291\ kN$, and there are two type of support here fixed support which is between stripper plate and the spring and the other is frictionless support which is between screw and stripper plate, the figure below shows that.

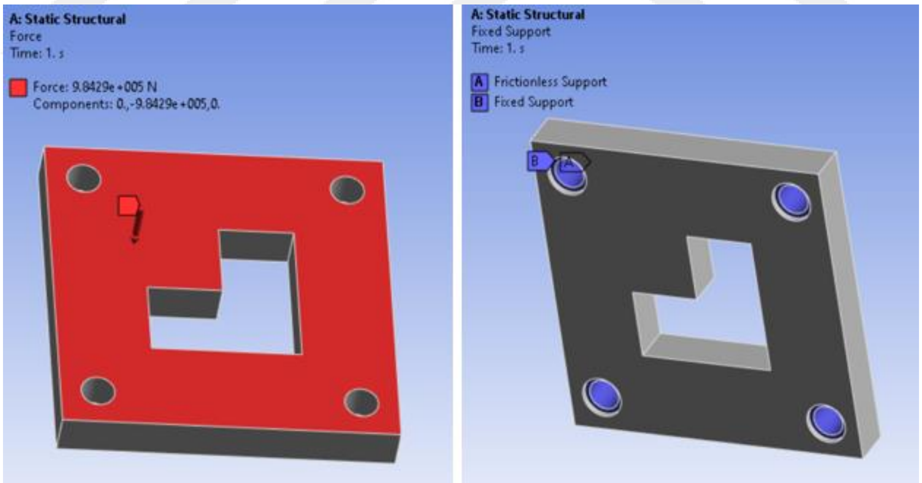


Figure 3.56: Support and Force on the Stripper Plate.

4. RESULTS AND DISCUSSION

In addition to the theoretical results that were reached in the previous chapter, in this chapter the results obtained from the ANSYS software will be reviewed on the parts that were simulated using the 3 different materials, where the results of maximum stress and maximum deformation will be reviewed, as well as the elastin stain, the life of the parts and the safety factor.

As for the maximum stress, it will be reviewed in each part only once, because it is not affected by the type of material, but rather by the force and the area of the cross section that affects it. Therefore, each part will have the same stress on the 3 materials. As for the deformation, it will differ in the event of a difference in the modulus of elasticity of the materials.

The type of analysis that will be done is fatigue failure, because this product will produce a lot of it daily, meaning that the cutting tools will move a lot, as has been clarified, which generates an alternating stress on the parts.

4.1 PIERCING PUNCH ANALYSIS AND SIMULATIONS RESULTS

4.1.1 Results When The Material AISI D2

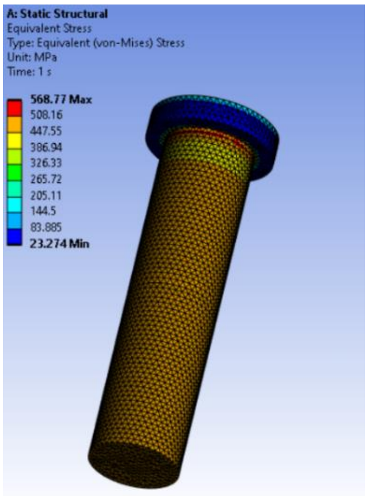


Figure 4.1: Maximum stress on Piercing Punch when material is D2.

The maximum stress for is 568.77 Mpa (it is close to Maximum stress that calculate in the theoretical part).

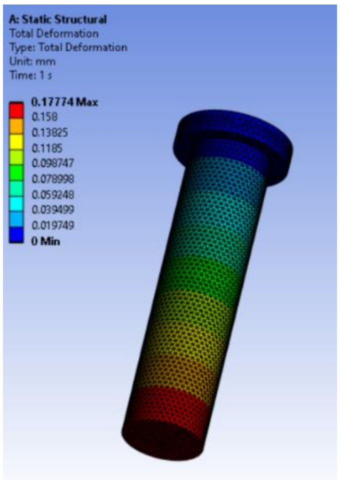


Figure 4.2: Total deformation on Piercing Punch when material is D2.

The total deformation is 0.177 mm.

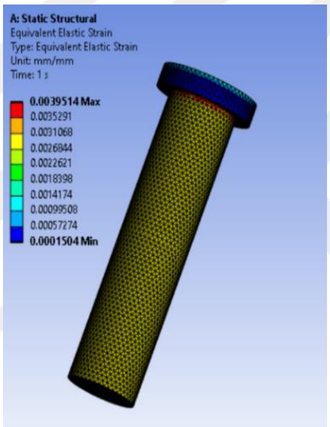


Figure 4.3: Equivalent elastic strain on Piercing Punch when material is D2.

Maximum Elastic Strain is 0.00395 mm/mm.

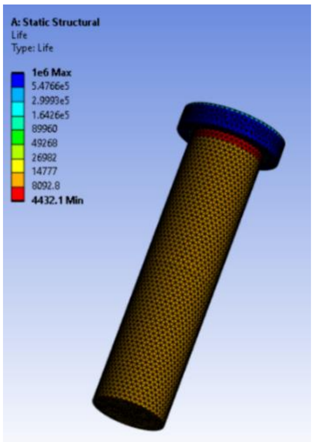


Figure 4.4: Life of Piercing Punch when material is D2.

The weakest region life is 4432.1 min.

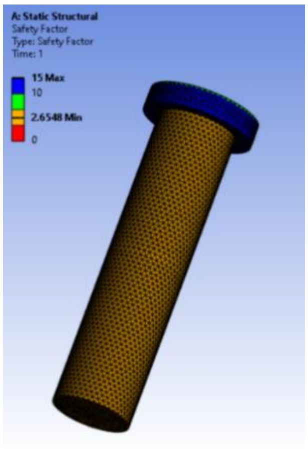


Figure 4.5: Safety factor of Piercing Punch when material is D2.

The factor of safety is 2.65 (safe because it is larger than 1).

4.1.2 Results When The Material AISI O1

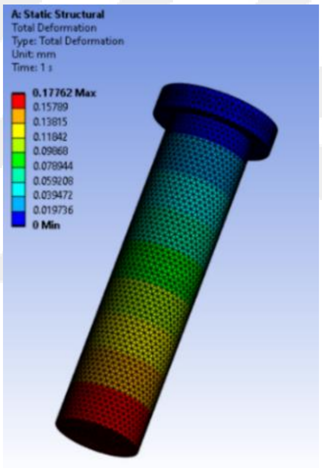


Figure 4.6: Total deformation on Piercing Punch when material is O1.

The total deformation is 0.177 mm.

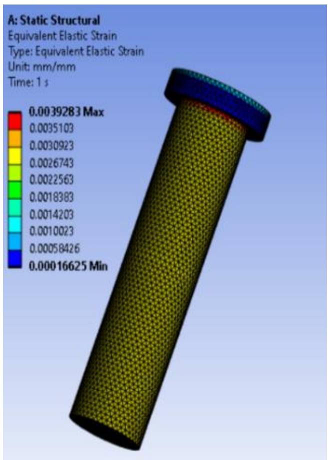


Figure 4.7: Equivalent elastic strain on Piercing Punch when material is O1.

The equivalent elastic strain is 0.0039 mm/mm.

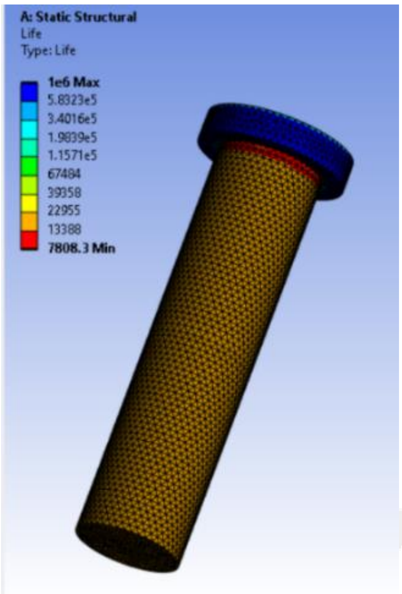


Figure 4.8: Life of Piercing Punch when material is O1.

The weakest region life is 7808.3 min.

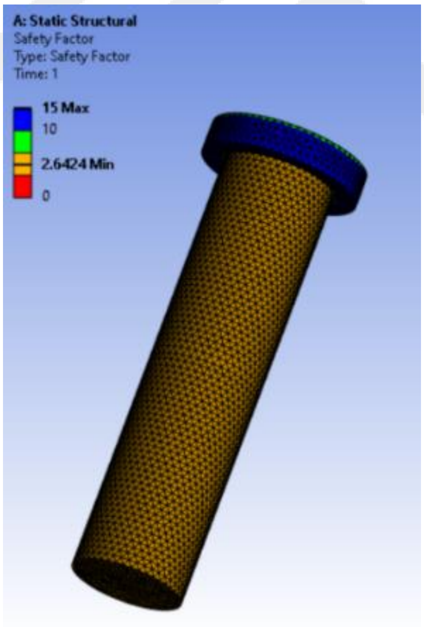


Figure 4.9: Safety factor of Piercing Punch when material is O1.

The factor of safety is 2.64 (safe because it is larger than 1).

4.1.3 Results When The Material AISI A2

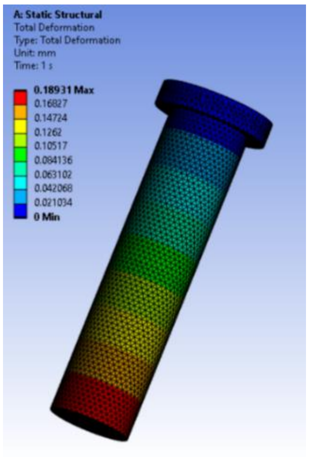


Figure 4.10: Total deformation on Piercing Punch when material is A2.

The total deformation is 0.189 mm.

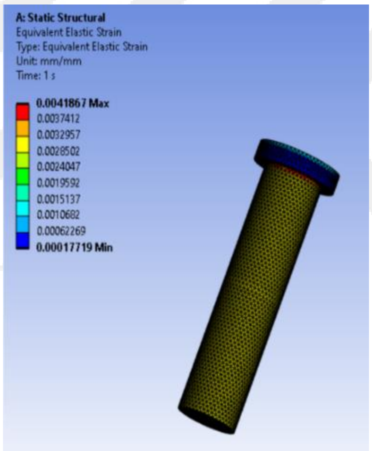


Figure 4.11: Equivalent elastic strain on Piercing Punch when material is A2.

The equivalent elastic strain is 0.0041 mm/mm.

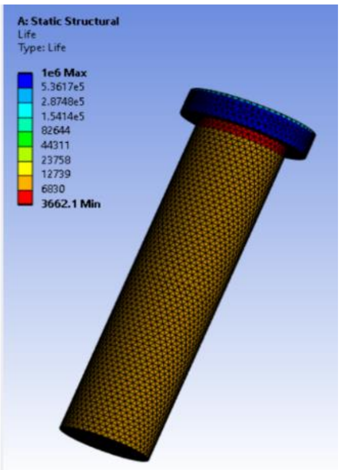


Figure 4.12: Life of Piercing Punch when material is A2.

The weakest region life is 3662.1 min.

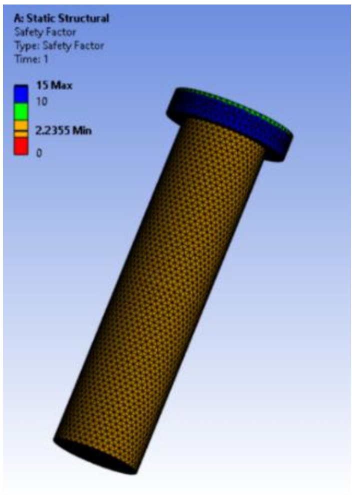


Figure 4.13: Safety factor of Piercing Punch when material is A2.

The factor of safety is 2.2355 (safe because it is larger than 1).

4.2 BLANKING PUNCH ANALYSIS AND SIMULATIONS RESULTS

4.2.1 Results When The Material AISI D2

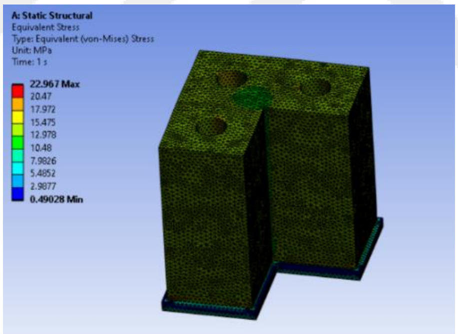


Figure 4.14: Maximum stress on Blanking Punch when material is D2.

The maximum stress is 22.96 Mpa

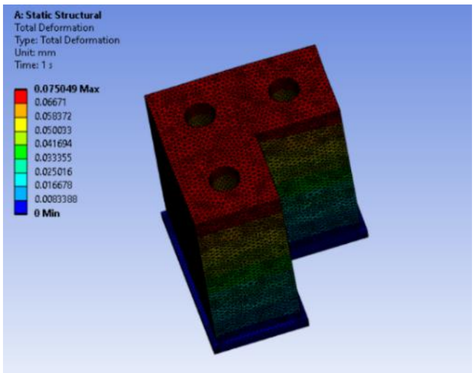


Figure 4.15: Total deformation on Blanking Punch when material is D2.

The total deformation is 0.075 mm.

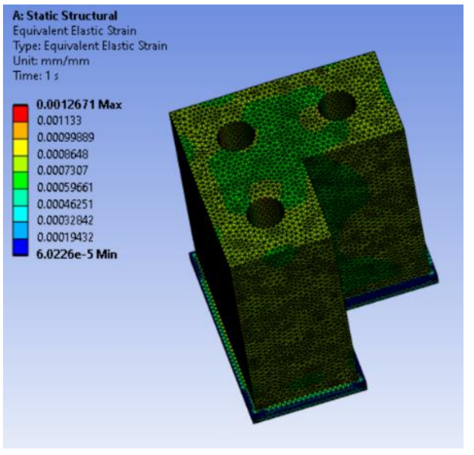


Figure 4.16: Equivalent elastic strain on Blanking Punch when material is D2.

The equivalent elastic strain is 0.00126 mm/mm.

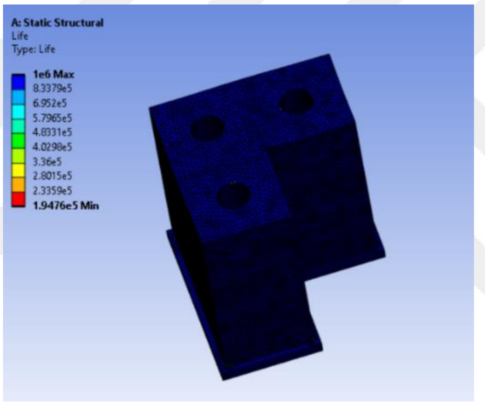


Figure 4.17: Number of life cycle of Blanking Punch when material is D2.

The weakest region life is 194760 min.

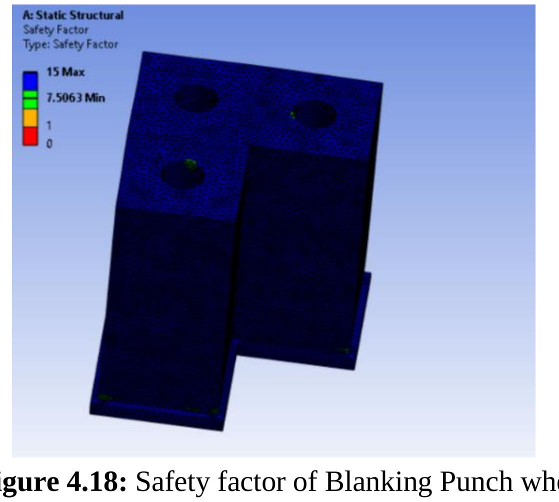


Figure 4.18: Safety factor of Blanking Punch when material is D2.

The safety factor is 7.5 so, it is safe because its more than 1.

4.2.2 Results When The Material AISI O1

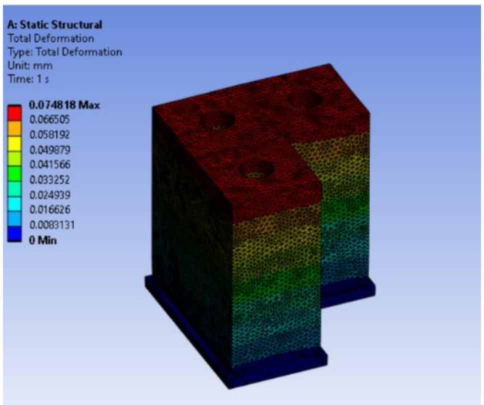


Figure 4.19: Total deformation on Blanking Punch when material is O1.

The total deformation is 0.075 mm.

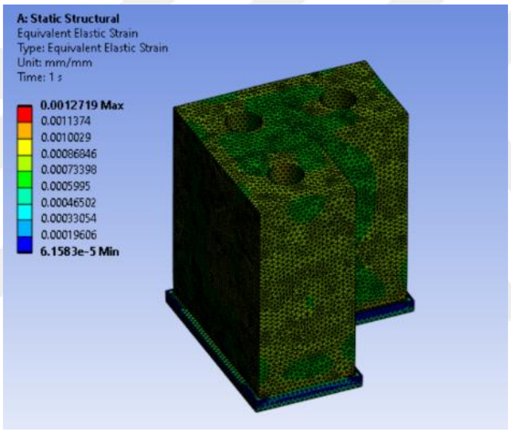


Figure 4.20: Equivalent elastic strain on Blanking Punch when material is O1.

The equivalent elastic strain is 0.00127 mm/mm.

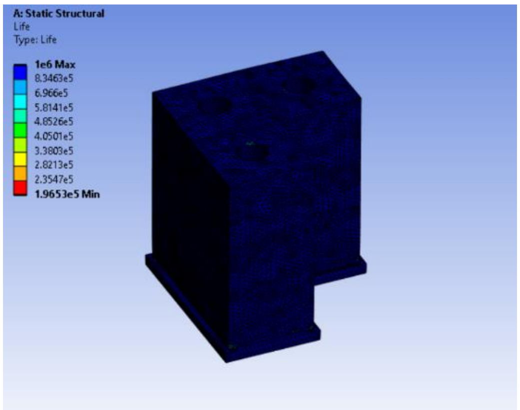


Figure 4.21: Life of Blanking Punch when material is O1.

The weakest region life is 196530 min.

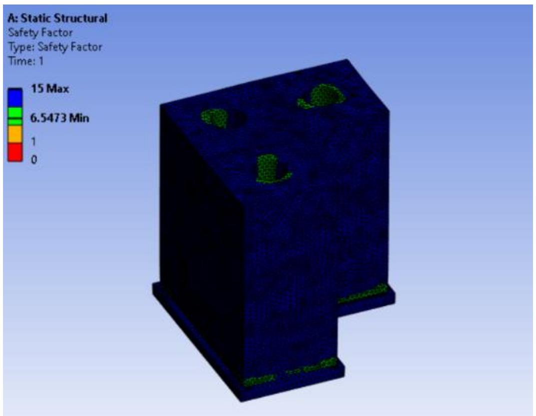


Figure 4.22: Safety factor of Blanking Punch when material is O1**.**

Safety factor is 6.54, it is safe because its safety factor greater than 1.

4.2.3 Results When The Material AISI A2

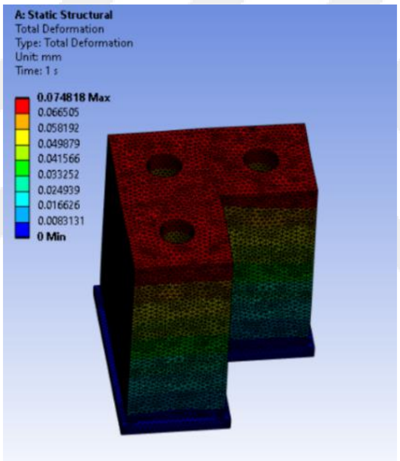


Figure 4.23: Total deformation on Blanking Punch when material is A2.

The total deformation is 0.0748 mm.

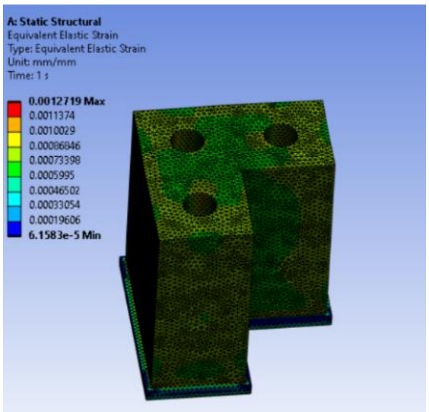


Figure 4.24: Equivalent elastic strain on Blanking Punch when material is A2.

The value of elastic strain is 0.00127 mm/mm.

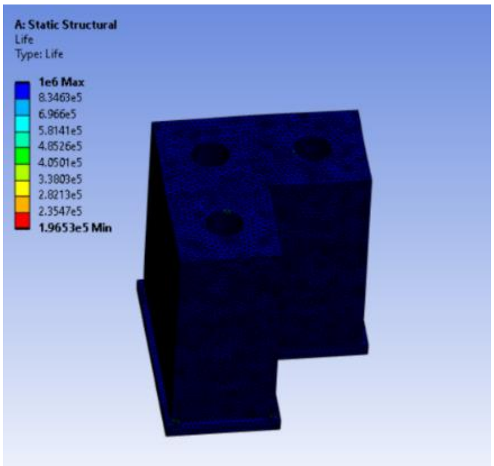


Figure 4.25: Life of Blanking Punch when material is A2.

The weakest region life is 196530 min.

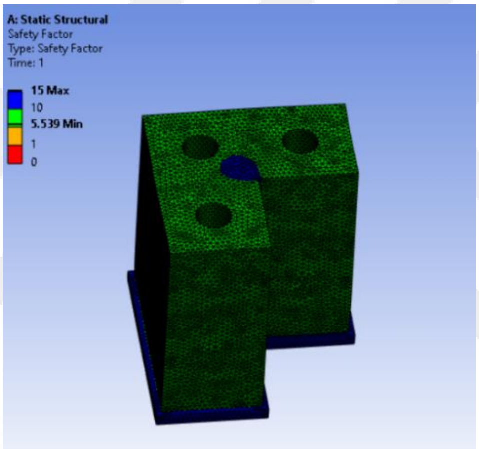


Figure 4.26: Safety factor of Blanking Punch when material is A2.

The value of safety factor is 5.539 it is safe because its greater than 1.

4.3 BLANKING DIE ANALYSIS AND SIMULATIONS RESULTS

4.3.1 Results When The Material AISI D2

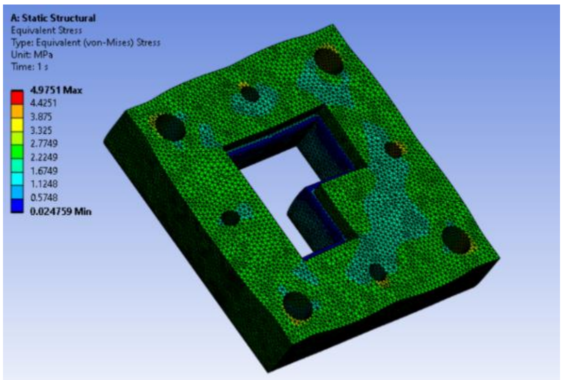


Figure 4.27: Maximum stress on Blanking Die when material is D2.

The maximum stress is 4.9751 Mpa.

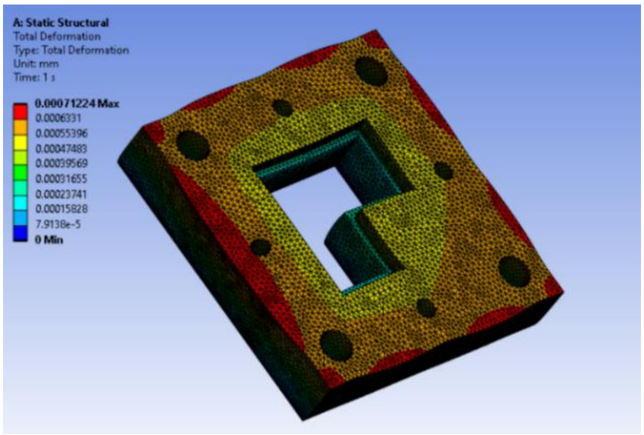


Figure 4.28: Total deformation on Blanking Die when material is D2.

The total deformation is 0.00071 mm.

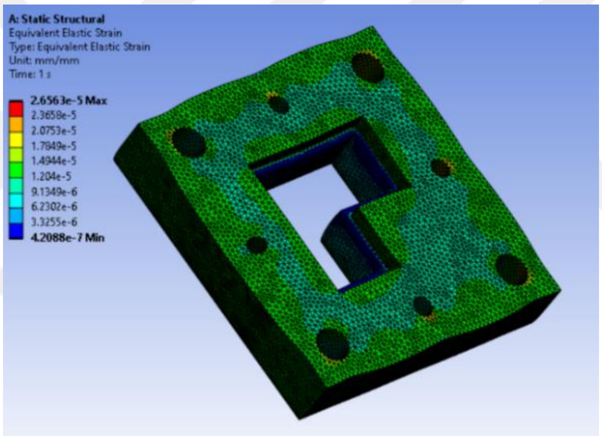


Figure 4.29: Equivalent elastic strain on Blanking Die when material is D2.

The equivalent elastic strain is 0.00265 mm/mm.

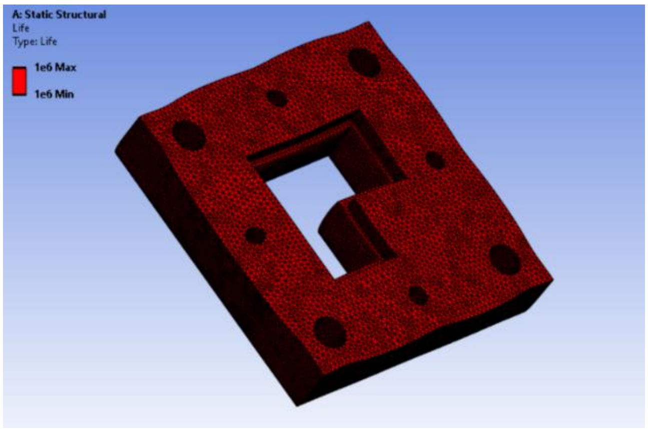


Figure 4.30: Life of Blanking Die when material is D2.

That means the die block has unlimited life when material is D2.

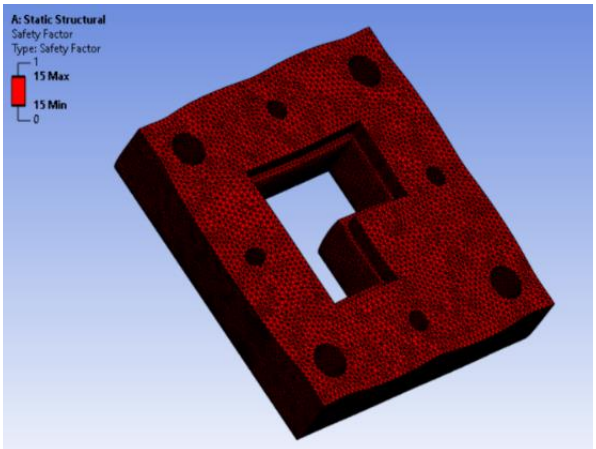


Figure 4.31: Safety factor of Blanking Die when material is D2.

The safety factor is 15 or above.

4.3.2 Results When The Material AISI O1

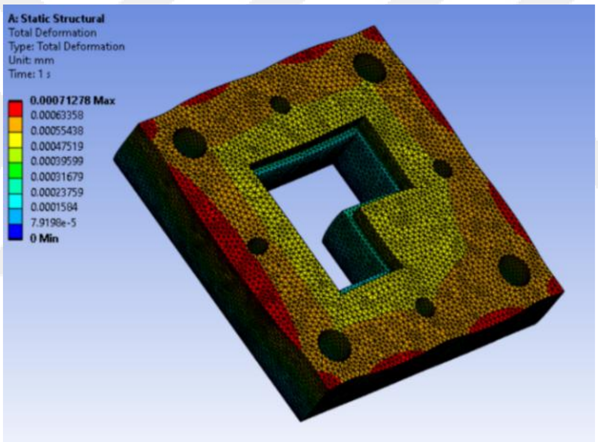


Figure 4.32: Total deformation on Blanking Die when material is O1.

The total deformation is 0.000712 mm.

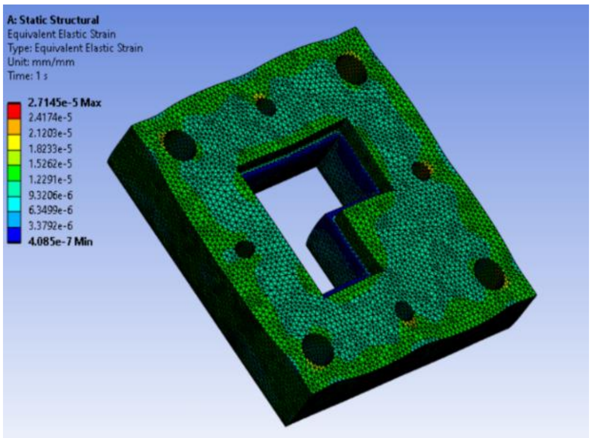


Figure 4.33: Equivalent elastic strain on Blanking Die when material is O1.

The equivalent elastic strain is 0.0000271 mm/mm.

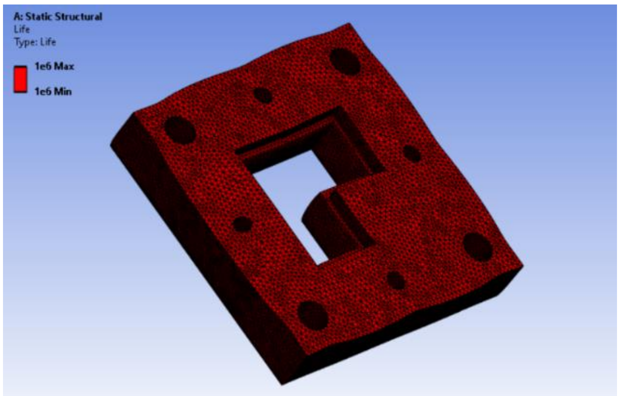


Figure 4.34: Number of life cycle of Blanking Die when material is O1.

That means the die block have unlimited life when material is O1.

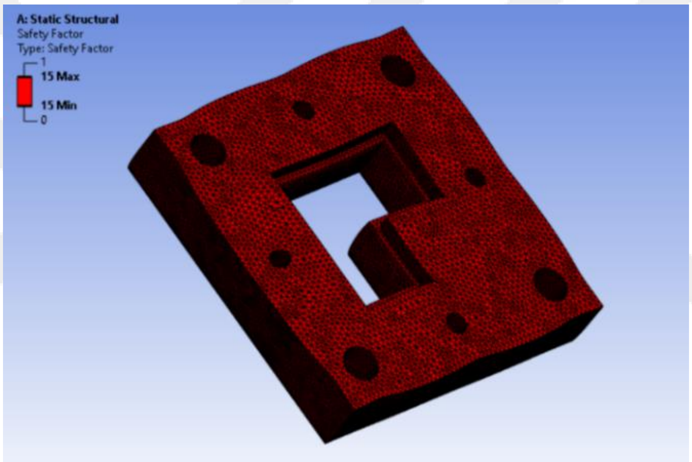


Figure 4.35: Safety Factor of Blanking Die when material is O1.

The safety factor is 15 or above.

4.3.3 Results When The Material AISI A2

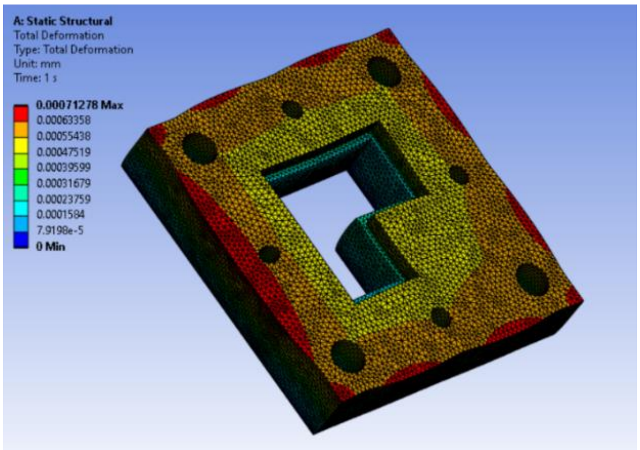


Figure 4.36: Total deformation on Blanking Die when material is A2.

The total deformation is 0.000712 mm.

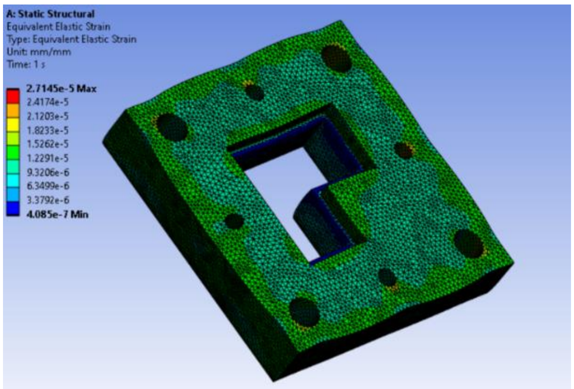


Figure 4.37: Equivalent elastic strain on Blanking Die when material is A2.

The value of equivalent elastic strain is 0.0000271 mm/mm.

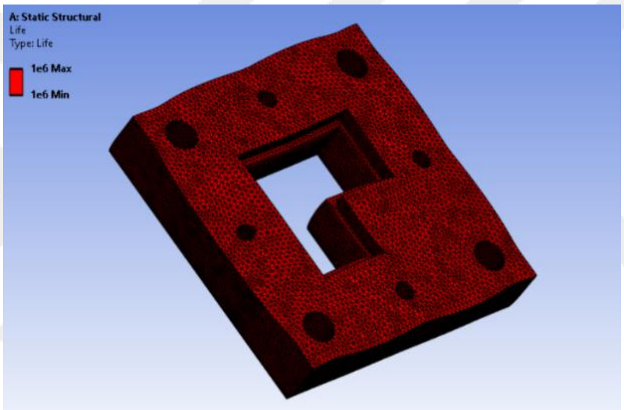


Figure 4.38: Number of life cycle of Blanking Die when material is A2.

That means the die block have unlimited life when material is A2.

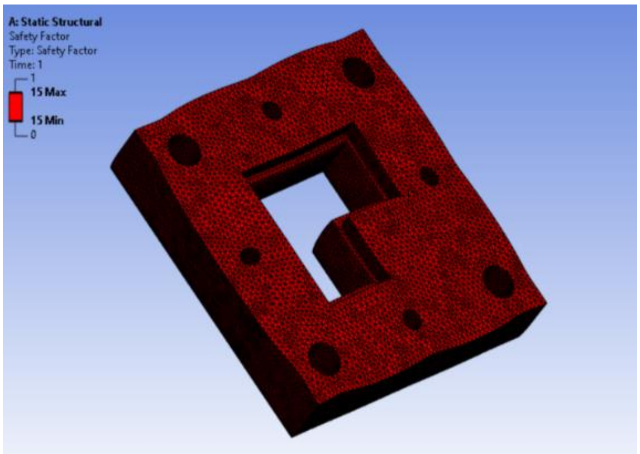


Figure 4.39: Safety factor of Blanking die when material is A2.

The safety factor is 15 or above.

4.4 STRIPPER PLATE ANALYSIS AND SIMULATIONS RESULTS

4.4.1 Results When The Material AISI D2

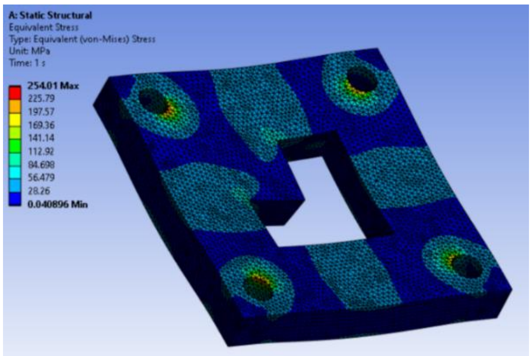


Figure 4.40: Maximum stress on Stripper Plate when material is D2.

Maximum von-mises stress is **254.01 Mpa,** it is close to theoretical stress that calculated in the previous chapter.

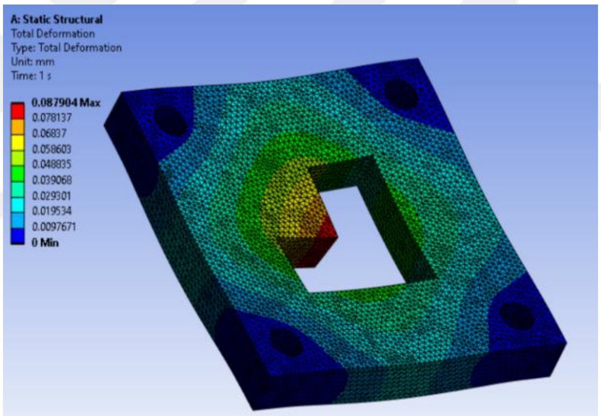


Figure 4.41: Total deformation on Stripper Plate when material is D2.

The total deformation is 0.087 mm.

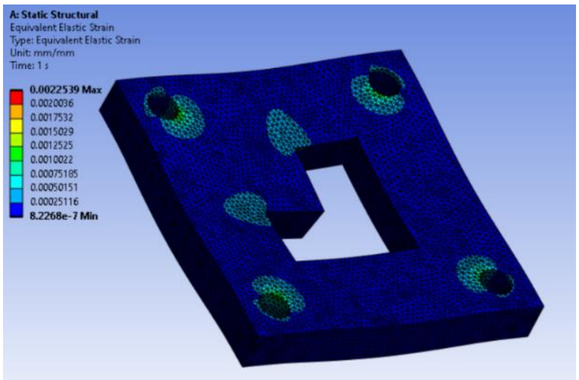


Figure 4.42: Equivalent elastic strain on Stripper Plate when material is D2.

The value of equivalent elastic strain is 0.00225 mm/mm.

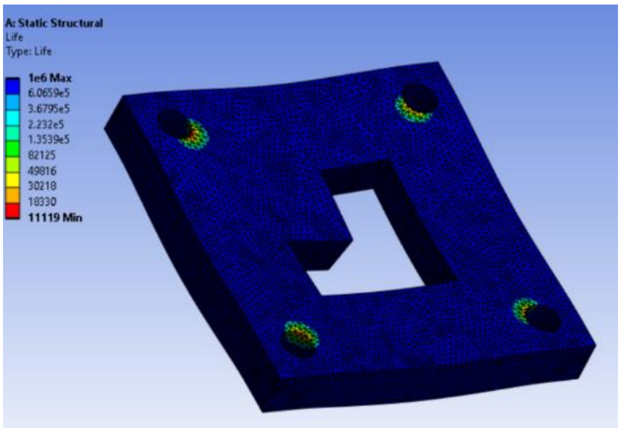


Figure 4.43: Number of life cycle of Stripper Plate when material is D2.

The weakest region life is 11119 min.

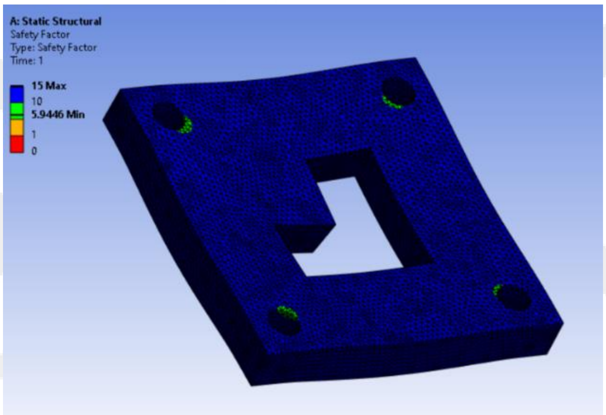


Figure 4.44: Safety factor of Stripper Plate when material is D2.

The Safety factor is 5.94 **(**(safe because it is larger than 1).

4.4.2 Results When The Material AISI O1

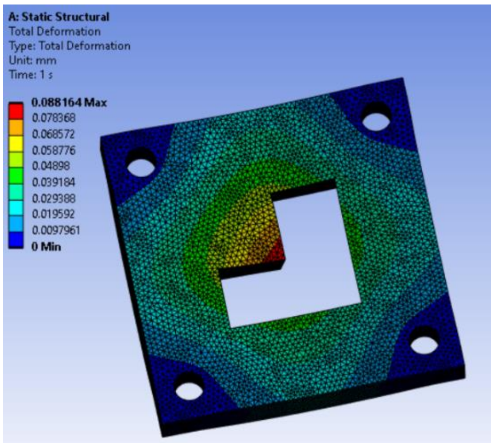


Figure 4.45: Total deformation on Stripper Plate when material is O1.

The value of total deformation is 0.088 mm.

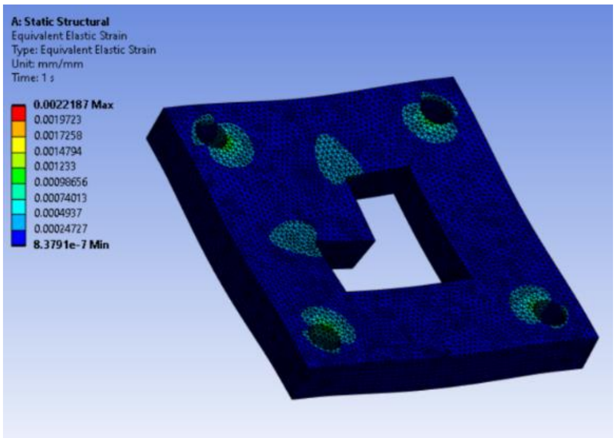


Figure 4.46: Equivalent elastic strain on Stripper Plate when material is O1.

The value of equivalent elastic strain is 0.0022 mm.

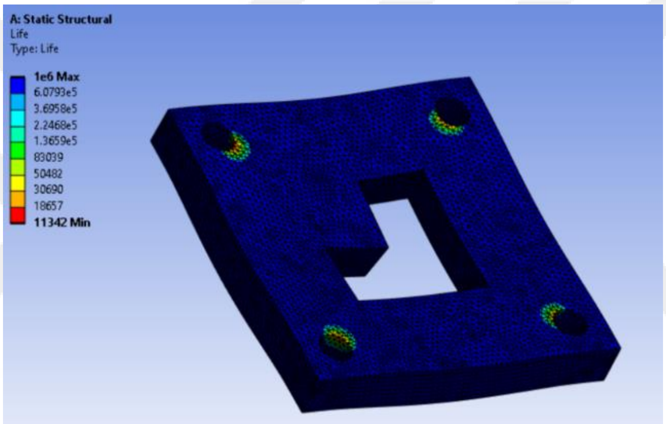


Figure 4.47: Number of life cycle of Stripper Plate when material is O1.

The weakest region life is 11342 min.

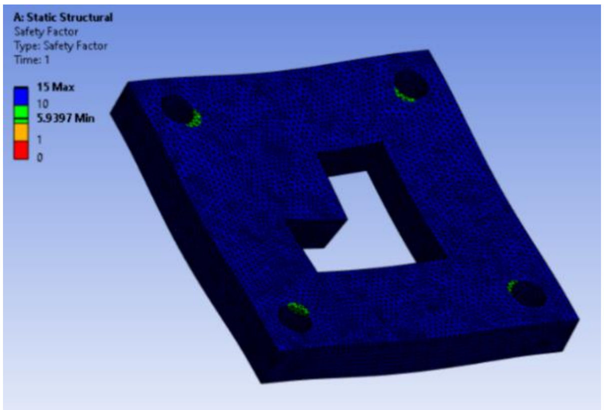


Figure 4.48: Safety factor of Stripper Plate when material is O1.

The safety factor values are 5.94 (it is safe because it is more then 1).

4.4.3 Results When The Material AISI A2

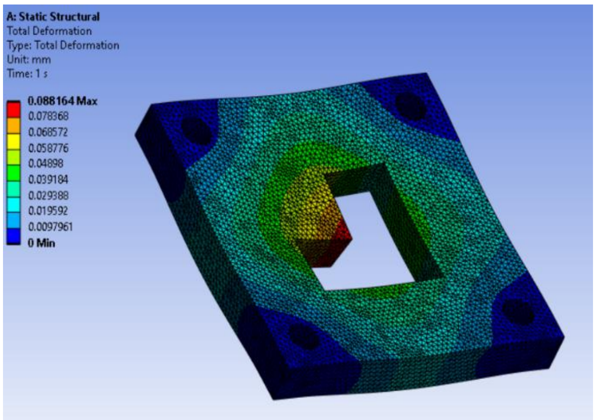


Figure 4.49: Total deformation on Stripper Plate when material is A2.

The total deformation value is 0.088 mm.

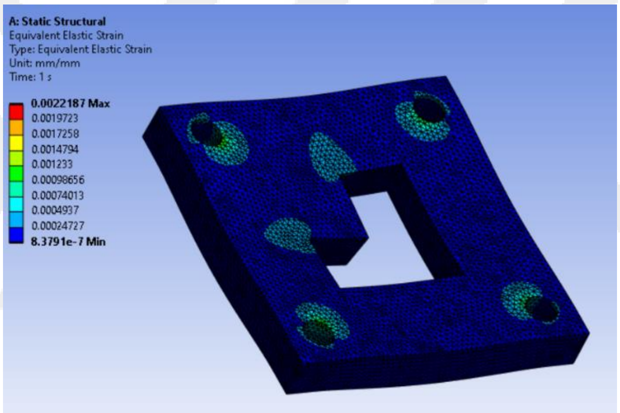


Figure 4.50: Equivalent elastic strain on Stripper Plate when material is A2.

The value of elastic equivalent elastic strain is 0.0022 mm/mm.

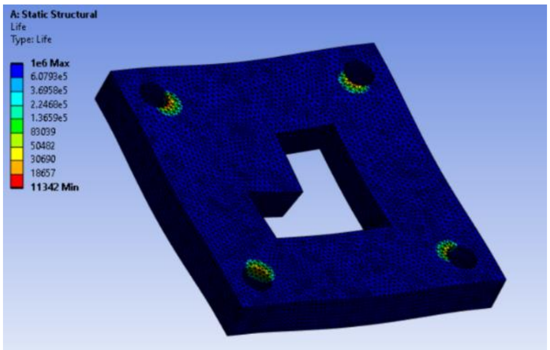


Figure 4.51: Number of life cycle of Stripper Plate when material is A2.

The weakest region life is 11342 min.

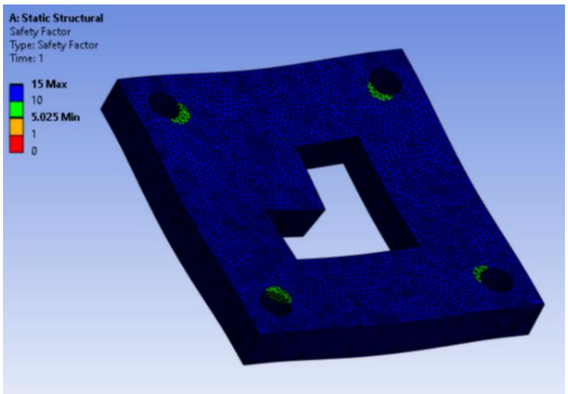


Figure 4.52: Safety factor of Stripper Plate when material is A2.

The safety factor values are 5.025 (it is safe because it is more then 1)

In view of all the results above, whether the theoretical results in chapter 3 or the simulation results in this chapter, it turns out that all materials are safe to use in the manufacture of simulated parts, and this is not surprising because these materials are mainly used in this type of applications frequently, there are some similarities between Theoretical and simulation results such as the maximum stress on the piercing punch as well as the maximum stress on the stripper plate. The results also showed the importance of accuracy in the design. For example, the thickness of the die block is very important because the rest of the parts depend heavily on it, and this is shown by the equations, and because of the accuracy in its calculation, the die was designed correctly, and this is what the assembly showed. However, although computerized software facilitates the solution, especially the CAD integrated science feature, care must be taken when dealing with it, because any mistake may give errors results, but in all cases its results will not correspond to the real results 100%, and that, as previously explained, these programs rely on FEM., which gives an approximate answer and is not 100% accurate.

5. CONCLUSION AND FUTURE WORK

After completing the design and simulation, several important issues were concluded, including the importance of using computerized software and the use of CAD Integrated science in manufacturing processes. In this research, its effectiveness was proven in the process of designing and analysing dies after selecting a product from the market with specific specifications. Its design succeeded in the theoretical test in terms of mathematical calculations, and the evidence for this is the completion of its design as required on SOLIDWORKS, and it also succeeded in the simulation test on ANSYS workbench software, because the results proved that there is no part threatened with collapse in the event of cutting such products, and another thing that was concluded is the importance Caution when cutting metals with a thickness of more than 5 mm, because the thickness greatly affects the cutting forces.

In the future, it is recommended to manufacture this die with the dimensions and characteristics that have been found. It is also recommended to do other types of simulations, such as explicit dynamic and Modal analyses. It is recommended to apply other dies such as the progressive die and make a comparison between the two dies to find out the best in terms of cost and speed. It is also recommended to simulate using other materials and make a comparison between them and determine the best in terms of cost and endurance. It is also recommended to make a design and simulation of such products, because the dies are characterized by the speed of production and accuracy also, especially the compound die.

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APPENDIX A

MATERIAL PROPERTIES

A.1 STAINLESS STEEL 316 PROPERTIES

Table A.1: Stainless Steel 316 properties [101].

Physical Properties	**Metric**	**English**	**Comments**
Density	8 g/cc	0.289 lb/in³	
Mechanical Properties			
Hardness, Brinell	149	149	
Hardness, Knoop	169	169	Converted from Brinell hardness.
Hardness, Rockwell B	80	80	
Hardness, Vickers	155	155	Converted from Brinell hardness.
Tensile Strength, Ultimate	550 MPa	79800 psi	
Tensile Strength, Yield	240 MPa	34800 psi	
Elongation at Break	60%	60%	in 50 mm
Modulus of Elasticity	193 GPa	28000 ksi	
Electrical Properties			
Electrical Resistivity	7.4e-005 ohm-cm	7.4e-005 ohm-cm	at 20ºC
Magnetic Permeability	1.008	1.008	at RT
Thermal Properties			
CTE, linear 20°C	16 µm/m-°C	8.89 µin/in-°F	0 – 100ºC
CTE, linear 250°C	16.2 µm/m-°C	9 µin/in-°F	at 0-315°C (32-600°F)
CTE, linear 500°C	17.5 µm/m-°C	9.72 µin/in-°F	0 – 540ºC
Heat Capacity	0.5 J/g-°C	0.12 BTU/lb-°F	from 0-100°C (32-212°F)
Thermal Conductivity	16.3 W/m-K	113 BTU-in/hr-ft²-°F	100ºC
Melting Point	1370 – 1400 °C	2500 – 2550 °F	
Maximum Service Temperature, Air	870 °C	1600 °F	Intermittent Service
Maximum Service Temperature, Air	925 °C	1700 °F	Continuous Service

APPENDIX B

PUNCHES PROPRTIES

B.1 SOME PUNCHES DETAILS

Table B.1: Quill and Perforator Punches details and dimensions [77].

Perforator punch							Quill punch			
d_P (mm)	r_{PF} (mm)	D_{PB} (mm)	D_{PH} (mm)	B (mm)	H_{PH} (mm)	L_P (mm)	d_P (mm)	D_{PH} (mm)	H_{PH} (mm)	L_P (mm)
1.5		51.5	54.5		4.2-5		3	6	4.2-5	
1.5		51.5	54.5		4.2-5		4	7	4.2-5	
1.5		51.5	54.5		4.2-5		5	8	4.2-5	
1.5		51.5	54.5		5		6	9	5	
1.5		51.5	54.5		5		7	10	5	
2.3		52.3	55.3		5		8	11	5	
3.2		53.2	56.2		5		10	13	5	
3.2		53.2	56.2		5		12	15	5	
3.2		53.2	56.2		5		13	16	5	
4		54	57		5		14	17	5	
4.8		54.8	57.8		5		16	19	5	
5	12.5	55	58	7, 13, 19, 25	5	50-125	18	21	5	50-125
5		55	58		5-6.4		19	22	5-6.4	
5		55	58		5-6.4		20	23	5-6.4	
5		55	58		5-6.4		22	25	5-6.4	
5		55	58		5-6.4		25	28	5-6.4	
5		55	58		5-6.4		28	31	5-6.4	
5		55	58		5-6.4		30	33	5-6.4	
5		55	58		5-6.4		32	35	5-6.4	
5		55	58		5-6.4		35	38	5-6.4	
5		55	58		5-6.4		40	43	5-6.4	
5		55	58		5-6.4		45	48	5-6.4	