Review on Defect Minimization in Deep Drawing Process

Rajesh R[1], Manivasakam S[2], Sanjay S[3], Sweeton Vedhamuthu P[4], Praveen Kumar S[5]

{rrh.prod@psgtech.ac.in[1], 20p111@psgtech.ac.in[2], 20p120@psgtech.ac.in[3]}

Assistant Professor, Department of Production Engineering, PSG College of Technology, Coimbatore, India.[1],
Undergraduate Student, Department of Production Engineering, PSG College of Technology, Coimbatore, India.[2],
Undergraduate Student, Department of Production Engineering, PSG College of Technology, Coimbatore, India.[3]

Abstract. One of the essential metals forming methods used widely in the manufacturing sector to produce intricate, three-dimensional parts is deep drawing. But this process is prone to a number of flaws that can seriously affect the functionality and quality of the finished product. A variety of factors, such as material properties, process parameters, die design, and lubrication, can lead to common defects in deep drawing operations, such as tearing, earing, and wrinkles. By using a thorough and multifaceted approach, this research aims to address the crucial challenge of defects minimization in deep drawing. This study aims to systematically mitigate the occurrence of defects throughout the deep drawing process by integrating advanced finite element analysis (FEA) simulations, material selection optimization, die design modifications, and strategic lubrication techniques and methods. This research aims to both identify and comprehend the underlying causes of defects and suggest practical strategies for their prevention by combining theoretical modeling with real-world experimentation. By doing this, we hope to improve deep drawing processes' dependability and efficiency, which will eventually boost their competitiveness in industrial applications and improve the quality of their output.

Keywords: sheet metal forming; deep drawing; defects;

1 Introduction

Deep drawing is a manufacturing process used to transform flat sheet metal into three-dimensional shapes, typically involving a cylindrical or box-like structure. Nonetheless, akin to any manufacturing procedure, it remains vulnerable to an array of imperfections that have the potential to impact the caliber and soundness of the end product.[3] Reducing these imperfections holds paramount importance in guaranteeing the fabrication of top-notch components.

One common defect in deep drawing is wrinkling, which occurs when the material undergoes excessive deformation or is unable to flow properly into the die cavity. [6] This can be mitigated by selecting appropriate material properties, such as ductility and thickness, and

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employing lubrication techniques to reduce friction during the process. Another significant concern is cracking, which can occur due to excessive tensile stresses in the material. This issue can be addressed by controlling the blank holder force and optimizing the die geometry to distribute stresses more uniformly. [16] Additionally, material selection plays a vital role in preventing cracking, as certain alloys are more prone to this defect than others.

Surface imperfections, such as scratches or tool marks, are also common in deep drawing. [2] Proper die maintenance and surface treatments can help minimize these defects. Additionally, maintaining consistent process parameters and using high-quality tooling materials can contribute to a smoother surface finish.

Defects in deep drawing can have detrimental effects on the final product's quality and functionality. For Minimizing these defects requires a comprehensive approach, including careful material selection, die design, lubrication techniques, and process parameter optimization with the proper considerations. By implementing these strategies, manufacturers can achieve a higher level of precision and reliability in their deep drawing operations.

2 Defects

2.1 Wrinkling

When the material being produced experiences excessive deformation, it can cause wrinkles, which are common defects in deep drawing and result in undesired folds or ridges on the surface. [7] Usually, inadequate material flow or poor force control during the process are the causes of this problem. It's critical to use lubrication to lower friction and choose materials with the right ductility and thickness to minimize wrinkling. Furthermore, modifying variables such as die geometry and blank holder force can aid in more uniformly distributing stress, avoiding wrinkle formation and guaranteeing a successful deep drawing process.

2.2 Thinning

When a metal sheet is shaped into a three-dimensional shape, it is thinned by reducing the material thickness in certain places. [3] This happens as a result of the material being stretched and compressed during the sketching process. Thinning can compromise the integrity of the finished product and result in structural flaws. Engineers frequently modify process parameters, select materials with the right ductility, and make use of specific tooling designs to reduce thinning. Furthermore, utilizing pre-drawn blanks or multi-stage drawing can assist distribute distortion more evenly, reducing thinning and guaranteeing a higher quality final result.

2.3 Necking

In deep drawing, necking describes the localized material thinning, usually at the vicinity of the drawn part's bottom. It happens when the material is overstretched, which causes the thickness to decrease. [1] This phenomenon has the potential to compromise the formed component's structural integrity and lead to its failure under stress. Manufacturers frequently modify process variables, such as blank holder force and lubrication, and choose materials with the right qualities to reduce necking. In deep drawing procedures, altering the die geometry can also aid in stress distribution by reducing the chance of necking and assuring a higher-quality end result.

2.4 Earing

A common flaw in deep drawing is called earing, which results from the material's tendency to stretch unevenly and leave elevated, ear-like formations all the way around the drawn section. [19] This happens because the grain structure of the material is anisotropic. Manufacturers frequently use methods like using materials with more uniform grain structures, lubricating properly, and modifying process variables like blank holder force to reduce earing. [18] Additionally, using controlled drawing speeds and using specific tooling designs can assist distribute stresses more uniformly, lowering the risk of earing flaws in deep drawing procedures.

2.5 Spring back

In deep drawing, spring back describes a metal sheet's propensity to partially revert to its initial shape after being shaped into the desired three-dimensional shape. [2] The material's elastic qualities are the cause of this. The metal deforms when pressure is applied during the drawing process, but it tries to return to its former state when the pressure is released. Spring back may cause errors in the finished product's measurements. Manufacturers frequently overdraw the original design in order to counteract this effect and allow the material to spring back into the required form, which produces a finished product that is more accurate.

2.6 Surface defects

In deep drawing, surface defects are blemishes or irregularities on the exterior of a formed sheet of metal. Tool marks, creases, and scratches are typical problems. Wrinkles are the consequence of incorrect material flow into the die cavity, whereas scratches are caused by abrasive contact between the metal and tools. [20] Imprints made by the forming tools are known as tool marks. The final product's functional and aesthetic quality may be jeopardized by these flaws. Careful material selection, accurate die design, and appropriate lubrication techniques are necessary to prevent surface defects and guarantee smooth and consistent metal deformation during the deep drawing process.

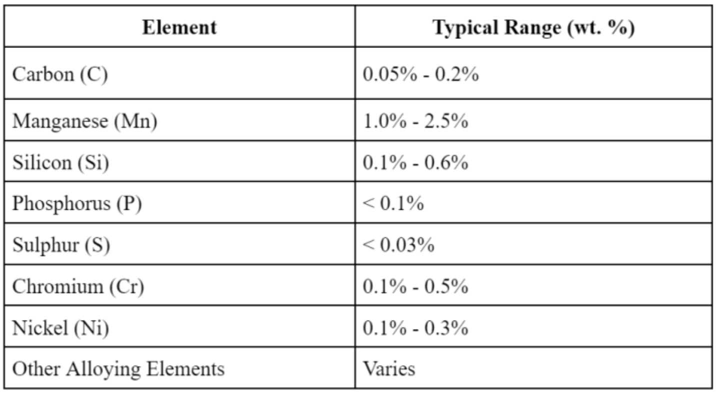
3 Materials

Usually, the deep drawing process entails shaping flat sheet metal into three-dimensional forms. Deep drawing success depends on the material selection because different metals have differing degrees of ductility, formability, and other qualities. Typical supplies for deep drawing consist of: Deep drawing is a common use for aluminum alloys because of their superior formability, low weight, and resistance to corrosion. Deep drawing is appropriate for some stainless steel grades, especially austenitic grades like 304 and 316. [23] Their strong corrosion resistance and excellent strength make them useful in applications where long-term dependability is essential. Deep drawing often makes use of low-carbon steels with good ductility and formability properties. They can be applied to many different situations and are reasonably priced. It is well known that copper and its alloys, including brass and bronze, have exceptional thermal and electrical conductivity as well as high ductility. Deep drawing is possible for nickel alloys like nickel-copper (Monel) and nickel-chromium-iron (Inconel). [8] They are ideal for specific applications because of their superior corrosion resistance and high-temperature capabilities. Certain grades of titanium can be used in applications where its special qualities, such as high strength-to-weight ratio and corrosion resistance, are required, despite the fact that they are difficult to deep draw due to their high strength and low formability. Certain applications allow for the use of other nonferrous alloys, such as lead, tin, and zinc, for deep drawing.

3.1 Need for Dual Phase Steel

One kind of advanced high-strength steel (AHSS) that is frequently utilized in the manufacturing and automotive sectors is dual-phase steel. It is made up of two different microstructures: the hard, robust martensite phase and the soft, ductile ferrite phase. [12] For uses like deep drawing, this combination offers a special balance between high tensile strength and good formability. The composition in the dual phase steel is shown in Table. 1. Significant deformation of the material occurs during the deep drawing process. While the hard martensite phase offers strength and resistance against fracture, the soft ferrite phase permits easy deformation. Because of its dual-phase structure, the steel can endure deep drawing's stresses and strains without experiencing too much thinning or cracking. [10] Because of the excellent strength-to-weight ratio of dual-phase steel, lightweight components with excellent structural integrity can be produced. This makes it the material of choice for parts requiring both strength and formability, such as automotive body panels and chassis components. Additionally, because of the decreased material consumption and increased fuel efficiency brought about by the weight reduction, using it can save money.

Table 1. Composition of Dual Phase Steel.

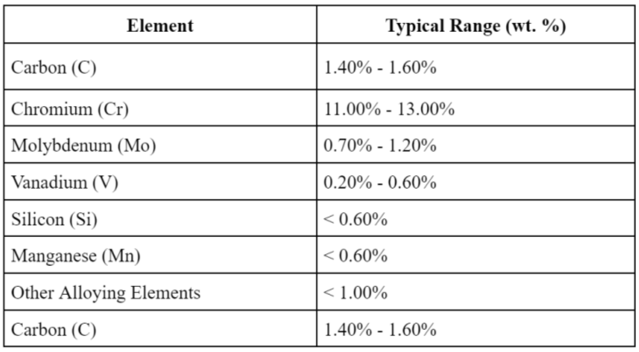


Element	Typical Range (wt. %)
Carbon (C)	0.05% - 0.2%
Manganese (Mn)	1.0% - 2.5%
Silicon (Si)	0.1% - 0.6%
Phosphorus (P)	< 0.1%
Sulphur (S)	< 0.03%
Chromium (Cr)	0.1% - 0.5%
Nickel (Ni)	0.1% - 0.3%
Other Alloying Elements	Varies

3.2 Need for Die Steel

Die steel, more especially D2 steel, is a material that is frequently used in the metalworking and stamping industries to fabricate die punches and blank holders. These parts are essential for cutting, shaping, and forming a variety of materials because they must have extraordinary hardness, wear resistance, and dimensional stability. Because of its high carbon and chromium content, D2 steel offers exceptional hardness, with a typical hardness of 58 to 62 HRC. [17] This hardness guarantees that blank holders and die punches keep their cutting edges after prolonged use. It is also very resistant to wear, which makes it perfect for rough uses like punching and cutting. Even after heat treatment, D2 steel maintains precise dimensions and tolerances and shows good dimensional stability. It is strong enough to endure the mechanical strains that come with working with metal. The composition of the die steel is shown in Table 2.

Table 2. Composition of Die Steel.



Element	Typical Range (wt. %)
Carbon (C)	1.40% - 1.60%
Chromium (Cr)	11.00% - 13.00%
Molybdenum (Mo)	0.70% - 1.20%
Vanadium (V)	0.20% - 0.60%
Silicon (Si)	< 0.60%
Manganese (Mn)	< 0.60%
Other Alloying Elements	< 1.00%
Carbon (C)	1.40% - 1.60%

4 Role of Non-axisymmetrical Process

Although axisymmetrical deep drawing techniques have many benefits, they also have some drawbacks. For example, axisymmetrical deep drawing works best when producing parts with symmetrical shapes centered on a central axis. If the desired component has complex or irregular geometry, this limitation may be a disadvantage. Deep drawing causes the material to deform significantly, which may cause some areas of the material to thin. This may compromise the finished product's structural integrity, particularly if it is not appropriately taken into consideration during the design and material selection process. [19] It can be difficult to achieve uniform material flow during deep drawing, and problems like material tearing or wrinkling can result from incorrect setup or excessive deformation. The final part's functionality and quality may be jeopardized by these flaws. Over time, the forming tools may experience wear and tear due to the forces involved in deep drawing. To maintain constant quality and precision, routine maintenance and possibly tool replacement may be required. It can be costly to design and manufacture specialized tooling for axisymmetrical deep drawing, especially for complex shapes or small-scale production runs. The entire production budget may need to take this expense into account. Process engineering and tooling design knowledge, along with a little bit of trial and error, may be needed to get the best process parameters and setup for axisymmetrical deep drawing. This may make the production process more complicated and time-consuming. While many materials can be used for deep drawing, due to their special material properties, some high-strength or exotic alloys might not be as good for axisymmetrical deep drawing.

Compared to axisymmetrical processes, non-axisymmetrical deep drawing processes have the following advantages: More intricate and distinctive shapes can be created using non-axisymmetrical processes than with axisymmetrical techniques. This adaptability makes it possible to produce a wide range of creative components. Manufacturers can reduce waste and maximize material usage by utilizing non-axisymmetrical shapes. [1] This is especially helpful for industries with high material costs. When compared to their axisymmetrical counterparts, non-axisymmetrical designs can produce components with higher strength and stiffness and better structural integrity. This is important for applications where strong, long-lasting parts are needed. Applications such as fluid flow control, aerodynamics, or structural support can benefit from the more effective and efficient performance that non-axisymmetrical shapes can provide when they are customized to meet specific functional requirements. Since non-axisymmetrical designs can have more aesthetic appeal, they are a good fit for products where visual appeal is important. Because non-axisymmetrical processes have a more controlled distribution of stresses during deformation, they can occasionally lead to shorter tool life and less wear. When compared to conventional, axisymmetrical designs, non-axisymmetrical components can offer distinctive features or functionalities that give them a competitive advantage in the market. More customization options are provided by non-axisymmetrical processes, which enable producers to mold components to meet particular client demands or industry norms.

5 Residual Stress

Because of the manufacturing process, residual stresses may be present in hot rolled dual-phase steels. Internal stresses that persist in a material even after external loads have been removed are known as residual stresses. These stresses in hot-rolled dual-phase steels can result from a number of things: Hard martensite and soft ferrite phases make up dual-phase steels. Because the phases cool at varying rates, the phase transformation that happens after hot rolling can cause internal stresses. [3] It's possible that the material did not undergo uniform cooling during manufacturing. Differential contraction and the emergence of residual stresses are two possible outcomes of cooling rate variations. High pressure and deformation are involved in the first step of the hot rolling process. Internal stresses may be introduced as a result, especially in regions with significant deformation or curvature. [13] Remaining stresses in the material can also be introduced or changed by additional procedures like surface coatings or heat treatments. The amount and distribution of residual stresses can be influenced by the particular composition of the dual-phase steel, including the ratios of ferrite and martensite.

5.1 Reduction of Residual Stresses

For hot-rolled steels, reducing residual stress is essential to raising the material's dependability and performance. There are numerous methods and procedures that can be used to reduce levels of residual stress. Here are a few efficient techniques: [5] Hot rolled steels can have residual stresses effectively relieved by slow cooling and controlled heating procedures like annealing or normalizing. This makes it possible to modify the internal structure, which lowers stress levels. The material is heated to a precise temperature range and then allowed to cool gradually in a controlled environment as part of the stress-relieving process. This lessens the overall residual stress and helps to distribute internal stresses. Remaining stresses can also be reduced by machining away material, especially on the surface. [13] In order to create compressive stresses, surface treatments like shot blasting or grinding can also be used. Cold straightening techniques can be used when the residual stresses are mostly on the surface. This entails neutralizing the residual stresses by exerting force in the opposite direction.

6 Stress Zones in Deep Drawing

In deep drawing, stress zones refer to particular areas of a metal blank that go through different stages of mechanical stress development during the forming process. Comprehending and regulating the distribution of stress in these areas is crucial for accomplishing prosperous deep drawing procedures and generating superior components with minimal flaws.[8] The four major stress zones are shown in Fig. 1:

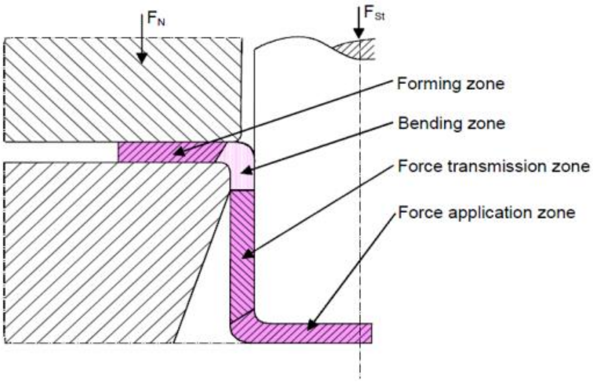


Fig. 1. Stress zones in deep drawing process.

6.1 Forming zone

In deep drawing, the area where the blank (flat sheet metal) and die come into contact is called the forming zone. [6] This is the process by which the material is significantly deformed to assume the required three-dimensional shape. The blank in this region experiences both compressive and tensile forces, shaping it to conform to the die cavity. As it determines the ultimate shape and size of the drawn component, the forming zone stands as a critical stage in the deep drawing process. Achieving a successful forming operation relies on meticulous material choice, precise control of process parameters, and effective lubrication.

6.2 Bending zone

When sheet metal is drawn into a die cavity to form a three-dimensional shape, it experiences significant deformation in that area, which is known as the bending zone in deep drawing. This is the area where the material is under the most stress and strain. The metal experiences plastic deformation in this area, which results in a permanent shape change. [1] Compressive stresses are applied to the material on the outer edges of the bending zone, and tensile stresses are applied to the material on the inner edges. In order to minimize flaws like wrinkling or cracking and produce precise and consistent deep-drawn shapes, it is essential to properly control and comprehend the bending zone.

6.3 Force Transmission Zone

In deep drawing, the area where the main forces involved in the process are concentrated is referred to as the Force Transmission Zone (FTZ). It is a crucial area because that is where the material is most stressed and deformed. The FTZ, which is situated around the punch nose, die radius, and blank holder periphery, is vital to forming the metal into the correct shape. In this instance, the blank material experiences a substantial amount of plastic deformation, which enables it to flow and take on the shape of the die. To ensure a successful deep drawing process, the FTZ must be designed and controlled properly. Careful consideration is given to elements like tool geometry, lubrication, and material qualities to guarantee uniform deformation and avoid flaws like tearing or wrinkling in high stress region.

6.4 Force Application Zone

In deep drawing, the area on the blank where the punch applies pressure to shape the material into the desired shape is referred to as the Force Application Zone (FAZ). It is an essential step in the process of deep drawing. Since this is where the material deforms the most, the FAZ is usually found near the edge of the blank. This is because during the drawing process, the blank's outer regions are subjected to greater stretching and bending forces. Ensuring a steady material flow and minimizing issues such as thinning or wrinkling in a deep-drawing process necessitates the establishment of a well-maintained Force Application Zone (FAZ). Properly managing the FAZ involves techniques like controlling the blank holder force and optimizing the die geometry, resulting in a more efficient and accurate deep-drawing procedure with even force distribution.

7 Process Parameters

Key parameters that must be taken into account, with some of them requiring optimization to reduce defects in the deep-drawing process, are as follows:

7.1 Blank Holder Force (BHF)

A key factor in the deep drawing process, which turns flat sheet metal into three-dimensional forms, is the blank holder force (BHF). [2] When the blank material is held against the die surface during the drawing process, pressure is used to hold it in place. BHF keeps the material from folding or wrinkling when it experiences severe deformation. Material type, thickness, and lubrication are some of the factors that determine the right amount of BHF. A material that is overly forceful may fracture, whereas a material that is under forced may wrinkle or form insufficiently. By precisely controlling the deformation process through BHF adjustment, a deep-drawn component with the correct shape and dimensional accuracy is guaranteed.

7.2 Blank shape

The first flat sheet of metal that is used as the starting material for the forming process is referred to as the blank shape in deep drawing. Usually circular, but depending on the final result that is wanted, other shapes like rectangles or squares can also be used. [7] The dimensions of the blank are selected in accordance with the final dimensions and requirements of the component that is being manufactured. The blank is positioned over a die during the procedure, and force is applied with a punch to force the material into the die cavity and take on the required shape. The geometry and material characteristics of the blank are critical to the deep drawing operation's success, impacting elements like material flow, thickness distribution, and the avoidance of defects.

7.3 Punch force and Punch speed

Punch force and punch speed are two essential factors in deep drawing that affect the effectiveness and caliber of the forming process. Punch force is the amount of force that the punch applies to the blank in order to shape it into the desired shape. Higher strength or thicker materials usually call for a larger punch force. [9] A balance must be struck because too much force can cause the material to rip or thin and too little force can cause the forming to be incomplete. The rate at which the punch moves during the deep drawing operation is referred to as punch speed. In order to achieve a consistent material flow and reduce flaws like wrinkling, punch speed control is essential. Punch speed adjustments guarantee that the material deforms smoothly and without excessive stress or strain.

7.4 Friction

The resistance that the blank material faces when it passes over the surface of the die and punch during the forming process is known as friction in deep drawing. It has a significant impact on the final product's quality and shapes the material. [2] Elevated levels of friction have the potential to cause defects such as wrinkling or surface imperfections, as well as increased wear and tear on the tools and increased energy consumption. Lubricants are frequently used to lower the resistance between the blank and the forming tools in order to minimize excessive friction. [1] In addition to facilitating smooth material flow and lowering heat generation, proper lubrication increases the deep drawing operation's overall efficiency. In deep drawing processes, maintaining and improving friction levels is crucial to producing reliable, high-caliber results.

7.5 Stress and Strain distribution

The distribution of strain and stress throughout the material is essential to deep drawing in order to form the desired shape. The blank first experiences compressive stresses in the vicinity of the punch, which progressively give way to tensile stresses in the periphery. [11] The neutral axis, which is this transition zone, deforms very little. Tensile strain is the result of the material's elongation along its axial direction as it is drawn into the die. On the other hand, the material undergoes radial compressive strain. Because of the bending effect, the blank's edges have the highest stresses. In order to ensure a successful and accurate deep-drawn component, it is imperative to properly manage stress and strain distribution in order to prevent defects like wrinkling or cracking. methods like lubricating, die geometry, and blank holder force control the distribution.

7.6 Thickness variation

In deep drawing, the term "thickness variation" describes the unequal dispersion of material thickness throughout a formed component. [9] The sheet metal experiences significant deformation during the process, which modifies the material's thickness. Stretching causes thinning in the outer regions, and compressive forces may cause thickening in the central area. This non-uniformity may compromise the final product's functionality and cause problems with structural integrity. Achieving the desired part quality requires controlling thickness variation. [7] To reduce thickness variations, try methods like changing the blank holder force, applying the right lubricant, and refining the die geometry. Additionally, minimizing thickness discrepancies during the deep drawing process is greatly aided by the selection of materials with appropriate ductility and thickness.

7.7 Forming limits

In deep drawing, forming limits refer to the maximum amount of deformation a material can undergo prior to the occurrence of defects like wrinkling or fracture. [2] The viability and outcome of the deep drawing process depend heavily on these boundaries. There are two different kinds of forming limits: the minor strain limit, which shows the point at which the material starts to wrinkle, and the major strain limit, which indicates the maximum amount of stretching a material can undergo before necking (localized thinning) occurs. [9] Forming limit diagrams, or FLDs, are a visual representation of these limits that engineers use to help them control and predict how materials will deform during deep drawing. In the manufacturing process, forming limits must be understood in order to produce components that are flawless and of the highest caliber.[3]

8 Research Gap

The conducted literature review reveals that there exists a research gap in combining heat treatment of dual phase steel and process parameter optimization to minimize the defects during deep drawing process.

9 Novelty

To reduce the residual stress present in hot-rolled dual-phase steels, a variety of heat treatment techniques have been used. Furthermore, appropriate punch, die, and blank holder designs, as well as process parameter optimization, effectively minimize defects in the non-axisymmetric deep drawing process. When taken as a whole, these actions help to increase manufacturing efficiency and produce final goods of superior quality.

10 Conclusion

The main defects that occur during the process, initial stress development in hot rolled sheet metals and its reduction techniques, causes for the occurrence of the defects, different stress zones in the process, and its significant process parameters for the deep drawing operation have all been reviewed in this paper. Future scope of optimizing techniques for the production of minimized defects products by deep drawing process will be implemented based on the research gap and novelty from the literature survey.

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