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Formability Analysis of Steel and Copper Based Alloy Sheet by Using Erichsen Cupping Test Machine

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Abstract

Metallic material formability study is critical in a variety of industrial areas, including automotive, aerospace, and manufacturing. The present study aims to investigate the formability properties of steel and copper-based alloy sheets using the Erichsen cupping test machine, an established technique for evaluating sheet metal formability. The process involves manufacturing identical steel and copper-based alloy specimens and subjecting them to the Erichsen cupping test. The test determines the maximum deformation depth of a metal sheet before fracture, providing significant information on its formability. The test results were examined and compared to identify the differences in formability between steel and copper-based alloy sheets. The formability properties of each material factor, such as strain distribution, ductility, and fracture behavior, were studied. The study reveals that steel has greater formability than copper-based alloys. This conclusion is based on the fact that when steel sheets are tested using the Erichsen cupping test, they may endure a greater degree of deformation before fracturing. The strain distribution study demonstrates the distinct ways the two materials respond to the deformation process, exhibiting their differential formability characteristics. The study offers precise information on the maximum deformation depth of copper-based alloy and steel sheets before fracture. This quantity acts as an evident predictor of formability. Steel sheets have greater deformation depths than copper-based alloy, which indicates superior formability when measured in terms of maximum deformation before failure, according to the results.

Keywords: Formability, Steel, Copper, Erichsen Cupping test

INTRODUCTION

Formability analysis of metallic materials is critical to sheet metal processing, influencing product design, manufacturing processes, and material selection. The Erichsen cupping test machine is a widely adopted method for evaluating the formability of metal sheets. An alloy sheet's capacity to withstand plastic deformation processes, such as bending, stretching, or deep drawing, is crucially assessed by formability analysis [1]. It aids in comprehending the material's behavior and forecasting how it will react to various forming processes. The formability of alloy sheets is evaluated using different techniques and tests. A few frequently used methods are the Tensile, Erichsen Cupping, Bendability, and Nakazima Test. Steel sheets are primarily made of iron, with small amounts of carbon and other alloying elements added for increased strength [2]. They are extreme, durable, and have excellent mechanical properties. Steel sheets are frequently used in manufacturing,

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automotive, aerospace, and construction [3, 4]. Copper alloys contain copper as the base metal and nickel as the primary alloying element. They offer good resistance to corrosion biofouling and have high strength. These sheets are commonly used in marine environments, offshore structures, and heat exchangers.

A test technique called Erichsen Cupping is used to assess the adaptability and formability of thin sheet materials. The Erichsen Cupping test is frequently used in sectors including automotive, aerospace, and those requiring sheet metal components. Finding the most significant deformation that a sheet metal specimen can tolerate before breaking is the central goal of the Erichsen Cupping test. The Erichsen cupping test measures an alloy sheet's capacity for deep drawing. A clamped sheet specimen is tested by being pushed upon by a hemispherical punch until failure or fracture is evident. The penetration depth shows the material's capacity for deformation without cracking or tearing before loss occurs [5]. To assess the cupping behavior of alloy sheets, the Erichsen cupping test can be performed in line with relevant standards or specifications, such as ASTM E643 or ISO 20482. The test results can help producers decide whether an alloy sheet is appropriate for deep-drawing applications and ensure it complies with the requisite performance and quality standards.

The literature review aims to summarize the essential findings and advancements in the formability analysis of steel and copper-based alloy sheets using the Erichsen cupping test machine. Several researchers have employed the Erichsen cupping test machine to evaluate the formability of various metallic materials. Various experiments are performed to determine the formability behavior of different materials using the Erichsen cupping testing machine. Logesh et al. [6] fabricated four fiber metal laminates using the hand Lay-up method, with the core being an E-glass fiber and the skin being an aluminum alloy 5052-H32. The specimen's Erichsen cupping index ranged from 5.95 to 7.28, respectively. The test specimens were examined under a microscope and using a macroscopic method. Gupta et al. [7] studied dry, lubricated, and heated CRCA sheets to compare the draw depth and drawing force under various conditions. Teflon sheet and boric acid are used for lubrication, and the CRCA sheet is heated in a heating oven. The punch is driven into the sheet until a fracture forms in the Erichsen test. Szalai et al. [8] the PLA (polylactic acid) filament materials and printing techniques were utilized to develop deep drawing tools. The Erichsen test is employed in this study since the printed punches must be plate-produced. The active tool element's straightforward structure makes it simple to press, and the method's simplicity and speed make it the best option. Chen et al. [9] studied the evolution of the microstructure and deformation mechanism of the GZ31 sheet. The sheet was subjected to an Erichsen cupping test at room temperature with various reductions and four samples with IEs (Erichsen index) of 2.0, 4.1, 7.1, and 7.3 mm. Optical microscopy and Scanning Electron Microscope were used to study the deformation and fracture processes of the cupping deformation process. Singh et al. [10] explored heat treatment methods like annealing to improve the formability of aluminum sheets. Aluminum was found to have enhanced forming capabilities and flexibility. Satish et al. [11] analyzed the formability behavior of rolled Nb-Ti stabilized IF-grade ferritic and austenitic steel. An Nb-Ti stabilized IF grade steel was hot rolled in the ferritic regime at two different temperatures, followed by cold rolling and annealing to compare the structure and characteristics. The annealed sheets were tested for various formability characteristics since formability is a requirement that varies by application. Numerous experiments showed that high-temperature ferritic rolled sheets are better suited for deep drawing and stretching applications. In contrast, low-temperature ferritic rolled sheets should be preferred for stretch-forming applications.

Aydin M et al. [12] investigated sheet metal formability using the Digital Image Correlation (DIC) approach in the Erichsen Cupping Test, a commonly used method. The study aimed to use DIC to capture deformation behavior during testing. The purpose of the present work was to evaluate the formability properties of various sheet metals using the Erichsen Cupping Test in conjunction with Non-Destructive Testing (NDT) methodologies. NDT methods assessed the quality of manufactured parts while causing no damage. The study aimed to give insight into the formability of various sheet metals and the use of NDT in determining their quality. He et al. [13] reported the results of an experimental study on the formability of Al-Mg alloy 5052 sheet metal. The study evaluates the material's formability using tensile and cupping tests. The authors investigate the alloy's deformation behavior under various testing situations, offering valuable insights into its formability for prospective industrial uses. Vijaya A et al. [14] explored an innovative sheet metal formability testing approach employing a portable Erichsen cupping tester coupled with vision-based technologies. The study investigates the development of a system that uses cameras and image processing techniques to monitor and analyze the cupping test in real time. This novel approach attempts to improve the accuracy and efficiency of formability tests. Dwivedi et al. [15] performed an experimental and numerical investigation of an aluminum alloy cylindrical cup utilizing a unique deep drawing technique. The study investigates the deformation behavior and material response during the deep drawing. The authors integrate experimental data with numerical simulations to develop a thorough understanding of the forming process for this specific alloy and technology. This study aims to analyze and compare the formability qualities of a steel alloy and a copper alloy using the Erichsen cupping test method and forming limit diagrams (FLDs). The following were the objectives of the present study:

1. To analyze and contrast the Forming Limit Diagrams (FLDs) of copper-based alloy and steel sheets to visualize their differences in formability.
2. To quantitatively measure and investigate the maximum deformation depth that steel and copper-based alloy sheets may undergo before fracturing during the Erichsen cupping test.
3. To thoroughly examine and compare the strain distribution, flexibility, and fracture behavior displayed by steel and copper-based alloy sheets during the Erichsen cupping test.

EXPERIMENTAL SETUP

A machine with a die, punch, and blank holder was used to conduct the cupping test. Figure 1 shows a device with a gauge known as a plunger-type comparator to assess the punch movement. This gauge had a minimum count of 0.01 mm (Table 1). The less than 0.1 mm movement did not affect the distance between the die's axis and the punch's spherical part's center. This investigation used commercially available Stainless Steel and copper Alloy sheets with a thickness of 1.5 mm. For chemical composition analysis, the ASTM E-1086-2014 Test Method was employed (Table 2). The shearing process cut the stainless steel and copper alloy sheets into 150 ×150 mm square blanks. The chemical etching procedure was used to mark the grid on one side of the blanks. The grids were rectangular arrays of circles. They measured 2 mm in diameter. After forming, these grid circles were employed for strain measurement. The Erichsen Cupping Test is standardized for determining sheet metal formability and ductility. Several critical procedures are included in this test to provide reliable and precise results. First, a circular sheet specimen of the material with a thickness ranging from 0.5 to 2 millimeters is created. For deformation, a cupping tool made of a polished punch is utilized. A lubricant, such as oil or grease, has been applied to the specimen's surface to reduce friction during the

Figure 1. Erichsen cupping test machine.

Table 1. Specifications of Erichsen cupping test machine.

S.N.	Machine Specifications	Value
1	Sample Width	70 to 90 mm
2	Sample Thickness	0.1 to 2 mm
3	Least Count of Micrometric Device	0.05 mm
4	One Turn of Hand Wheel	1.25 mm advance of penetrator
5	Overall Dimensions	Approx 450 × 500 × 500 mm
6	Weight	50 kg

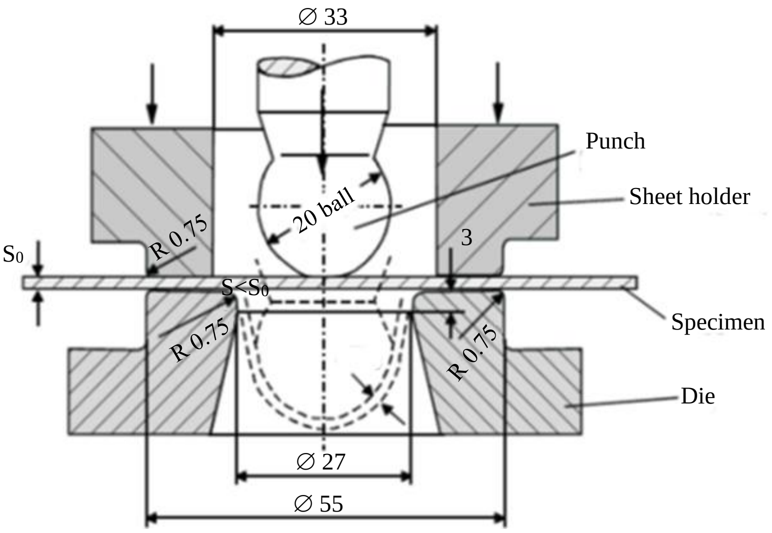

Figure 2. Schematic of Erichsen cupping test rig [16].

Table 2. Chemical Composition of Alloys.

Material	Component	Weight (%)
Steel Alloy	Cr	18.78
	Ni	8.68
	Mn	1.08
	Cu	0.44
	Co	0.2
	Fe	Balance
Copper Alloy	Zn	7.6
	Fe	0.18
	Sn	0.13
	Pb	0.06
	Ni	0.04
	Cu	Balance

test [5]. The sample is tightly fastened to prevent movement during testing, and the cupping instrument is first positioned slightly above its center. A hydraulic or mechanical press gradually exerts stress on the punch, causing it to deform. The point forms a cup-shaped depression in the specimen's center as it presses down, bending and thinning the material. During the test, characteristics such as maximum cup depth and applied force are carefully observed and recorded. The test terminates when a predefined cup depth is reached, cracks or fractures emerge, a defined force limit is reached, or the material fails to deform further without cracking (Figure 2). The critical evaluation is the maximum cup depth attained before failure, which serves as a crucial indicator of material formability. Multiple tests are often performed on different specimens of the same material to ascertain the reliability and consistency of the results. While the Erichsen Cupping Test provides valuable information about a material's ability to withstand deformation without failure, variations in test conditions, such as punch diameter and lubrication, may exist depending on industry standards and material requirements, emphasizing the importance of following specific protocols for accurate formability assessment.

RESULTS AND DISCUSSION

Forming limit curves have been frequently used to examine the formability of sheet materials for many years. They are widely used in tool design, particularly in combination with finite element analysis as a simulation tool. The Forming Limit diagram (FLD) graphically represents material failure tests like the punched dome test [17]. A mechanical test is carried out to assess whether a specific portion of the sheet has failed. The formability limit diagram, which represents the failure threshold, is constructed by repeating this mechanical test throughout a variety of stress states. The Forming Limit Diagram (FLD) is critical in comprehending and predicting material formability, optimizing the manufacturing process, and ensuring product quality. FLD is used to determine the formability of a specific material. In this context, formability refers to a material's ability to endure deformation without defects or failure during a forming process. A grid pattern of two-millimeter circles is cautiously imprinted into the sheet material in a rectangular configuration to generate the FLD [18]. This grid is used to calculate strain during the forming process. In general, strain is the amount that a material deforms when subjected to external forces. The deformation in this instance is indicated by the changing of the initially circular grid into an elliptical shape. The circular grid deforms when the material experiences plastic deformation (a permanent change in shape). A toolmaker's microscope is used to measure the strain. This specialized tool measures the major and minor axis dimensions of the elliptical shape developed on the grid precisely. These measurements are performed close to the area where the material eventually fractures or fails. With the major and minor axis dimensions measured, the next step is to use mathematical formulae, known as equations 1 and 2, to determine the major and minor strains, respectively. These strains give critical information to construct the Forming Limit Diagram.

$$\in_1 = \mathrm{In}\left(\frac{m_1}{m}\right) \tag{1}$$

$$\in_2 = \mathrm{In}\left(\frac{m_2}{m}\right) \tag{2}$$

Where, $\in_1$ and $\in_2$ are the principal strains and m_1 and m_2 are the major and minor axes of the deformed ellipses and m is the original diameter of the grid circle.

Following the creation of sheet metal, the initially designated circles distort and turn into ellipses of varied diameters. Figure 3 and Figure 4 represents the FLD of the steel and copper material. It was observed that the major strain is higher in the case of steel than that of copper. Therefore, the formability of steel is higher as compared to copper material.

Draw Force

The force the punch applies to press a circular blank into the die represents the forming party (P) necessary for a cylindrical drawing process [19]. The blank material's resistance to deformation is the primary determinant of the forming force. The friction between the blank material and the die and the energy needed to hold the blank in place adds strength. These elements work together to create the necessary pulling power.

The interaction of several elements produces the total force needed for this process. The energy required is increased by the initial friction between the blank material and the die, which prevents the fabric from moving [20]. Another factor is the force used to maintain the blank securely in place throughout the drawing process. These components work together to create the necessary pulling force to shape the blank into the required shape.

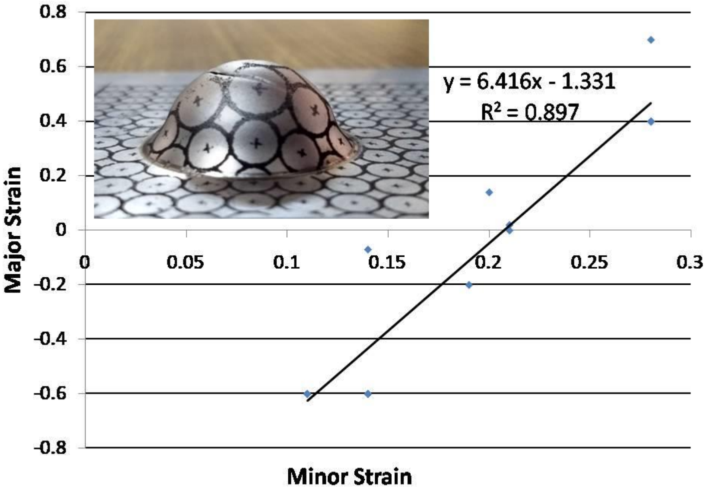

Figure 3. Forming limit diagram Steel.

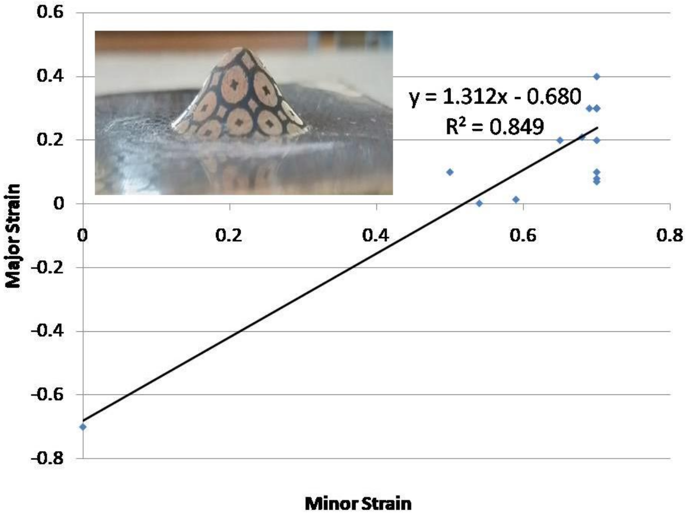

Figure 4. Forming limit diagram copper.

The tensile strength of the material, the drawing ratio, and the relative plate thickness are a few variables that significantly influence the drawing force. These variables greatly affect the size of the pulling force.

One crucial factor, the material's tensile strength, directly impacts the force needed to draw. Greater drawing forces are required for materials with higher tensile strengths because they resist deformation better [21]. The drawing ratio, which indicates how much the blank must be shrunk to fit inside the die, has a significant effect. Greater power is required to accomplish the necessary reduction at higher drawing ratios.

A comparison of the maximum draw forces attained by the Steel Alloy and Copper Alloy is shown in Figure 5. The steel alloy's pull force value was found to exceed that of the copper alloy. This conclusion implies that the steel Alloy can sustain a more significant force during the drawing process.

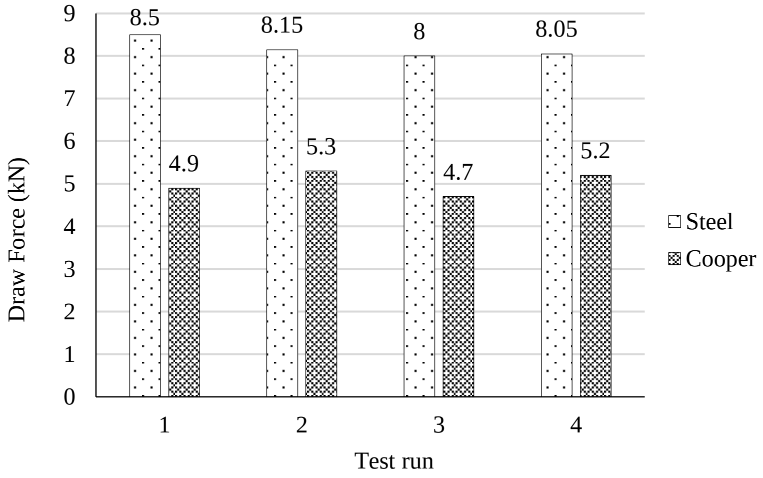

Figure 5. Comparison of Draw Force.

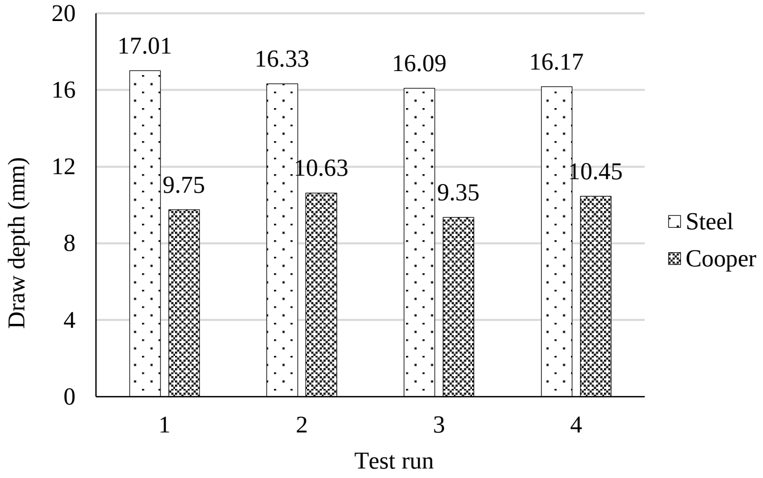

Figure 6. Comparison of Draw depth (mm).

Draw Depth

Figure 6 depicts the draw depth method, which includes radially pulling a sheet metal blank into a forming die using a mechanical punch. This procedure transforms the sheet metal into the appropriate shape while keeping its material qualities.

Due to the material retention feature, the flange region in the die's shoulder area suffers both radial drawing stress and tangential compressive stress throughout the draw depth process [22]. These compressive forces, also known as hoop stresses, cause wrinkles, especially wrinkles of the first order, to grow on the flange.

These hoop stresses appear as wrinkles, especially first-order wrinkles, often arising along the flange. The interaction between the radial drawing stress, which aims to lengthen the material, and the tangential compression stress, which aims to compress it, results in these wrinkles. The tug-of-war between these opposing pressures causes the distinctive wrinkling on the flange seen throughout the process.

Figure 6 essentially serves as a visual depiction of the draw depth method, emphasizing its critical function in shaping sheet metal while maintaining its inherent material properties. It also highlights the intricate mechanical relationships at work in the flange area, where radial drawing stress and tangential compressive stress produce the hoop stresses that lead to the emergence of wrinkles, notably those of the first order, on the flange's surface. Based on the results shown in Figure 6, it is clear that the draw depth attained by the Steel Alloy is larger than that of the Copper Alloy. This implies that the Steel Alloy has higher formability in terms of being able to go through the draw depth process. The difference in draw depth between the two alloys is due to differences in their material characteristics.

CONCLUSIONS

Formability, the ability of a material to deform without fracture, is an essential consideration in assessing its applicability for various applications. In this work, we examine the formability properties of two different metallic materials: a steel alloy and a copper-based alloy. A multifaceted approach that combines quantitative and qualitative measurements offers a comprehensive knowledge of these materials' behavior during the Erichsen cupping test, a commonly used method for testing sheet metal formability. The following findings can be inferred from the experiments mentioned above:

1. The draw force needed for the steel alloy is 62.68% higher than the copper alloy's. The outcome highlights the steel alloy's significantly increased strength and resistance to deformation.
2. According to the analysis of the deepest point reached during the cupping test, the depth of the steel alloy is 62.85% more than that of the copper alloy. This significant difference in draw depth suggests the steel alloy has higher formability since it can sustain significantly more deformation before breaking.
3. The Forming Limit Diagram (FLD) for the 1.5 mm thick steel alloy sheet reveals an apparent straight-line trend with a positive slope of 6.4129. This proved the steel alloy's exceptional formability characteristics. The FLD model's high R^2 value of 0.897 shows a significant correlation.
4. The Forming Limit Diagram (FLD) developed for the 1.5 mm thick copper alloy sheet shows a similar straight-line behavior with a positive slope of 1.3127. Even though the hill is smaller than the steel alloy, it shows that the copper alloy is suitable for shaping. The R^2 of 0.849 confirms the FLD model's reasonable fit for the copper alloy.

In conclusion, it is apparent from the results of the Erichsen cupping test that the steel alloy performs better than the copper alloy in terms of draw force and draw depth. Developing the forming limit diagrams for both metals offers insightful information about their formability behaviors, with the steel alloy demonstrating a greater slope and better overall formability than the copper alloy. These results enhance the knowledge of material choice and process improvement in sectors where sheet metal formability is crucial.

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