

# **Analysis of Springback in Incremental Forming**

## **PROJECT REPORT**

submitted by

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to

*the APJ Abdul Kalam Technological University  
in partial fulfillment of the requirements for the award of Master of  
Technology in Mechanical Engineering with specialization as  
Computer Integrated Manufacturing.*



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T. K. M. College of Engineering, Kollam

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**DEPARTMENT OF MECHANICAL ENGINEERING  
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**CERTIFICATE**

Certified that this report entitled '**Analysis of Springback in Incremental Forming**' presented by **RAMVALSAL S, TKM22MECI03** during **2022-2024** in partial fulfillment of the requirements award of **Master of Technology in Mechanical Engineering** with specialization as **Computer Integrated Manufacturing** of the *APJ Abdul Kalam Technological University*

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I, **Ramvalsal S** hereby declare that, this project report entitled “ **Analysis of Springback in Incremental Forming** ” is the bonafide work of mine carried out under the supervision of **Dr. Sadiq A.**, Professor in Mechanical Engineering. I declare that, to the best of my knowledge, the work reported herein does not form part of any other project report or dissertation on the basis of which a degree or award was conferred on an earlier occasion to any other candidate. The content of this report is not being presented by any other student to this or any other University for the award of a degree.

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Finally, I thank my parents and friends near and dear ones who directly and indirectly contributed to the successful completion of my project.

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## **ABSTRACT**

Incremental forming process is having greater industrial relevance for developing minimum or batch number of pieces by forming metals to complex shapes even without using a die. The springback phenomenon is an inherent feature of this incremental forming process, which is to be identified and controlled for precision in the dimension of metal product developed, in the context of incremental forming. This project focuses on the comprehensive analysis of springback in incremental forming of aluminium, copper and stainless steel sheets using a CNC milling machine, with multipoint forming tool. The study involves the systematic variation of key parameters such as tool speed, feed and vertical step depth in nine distinct experiments for each material following Taguchi's orthogonal array. The springback of each formed shape is meticulously measured using a Coordinate Measuring Machine (CMM), and the results are compared with the given dimensions to identify relationships between the selected parameters and the observed springback behaviour. The springback results from different experiments have been compared to find pattern, trends and propose optimized adjustments to minimize springback.

**Keywords:** Springback, Incremental Forming, CNC, Multi point tool, Process Optimization.

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## **ABBREVIATIONS**

CNC: Computer Numerical Control

CMM: Coordinate Measuring Machine

SB: Springback

IF: Incremental Forming

SS: Stainless Steel

rpm: Revolutions Per Minute

mm/min: Millimeters Per Minute

mm: Millimeters

Cu: Copper

Al: Aluminum

SS: Stainless Steel

XRD: X-ray Diffraction

# CHAPTER 1

## INTRODUCTION

Metal forming processes play a pivotal role in the manufacturing industry, enabling the creation of intricate shapes and structures with precision. Among these processes, incremental forming has emerged as a versatile technique with widespread applications. However, a persistent challenge in incremental forming is the occurrence of springback, the tendency of a formed material to return to its original shape after the forming process. Understanding and mitigating springback are critical for achieving accurate and repeatable results in metal forming applications.

The primary objective of this project is to conduct a comprehensive analysis of springback in the incremental forming process, with a specific focus on Aluminum, Copper and Stainless-Steel sheets.

Aluminum is renowned for its lightweight yet robust nature, making it a preferred choice in industries where weight reduction is critical without compromising on strength. Its exceptional corrosion resistance, high thermal and electrical conductivity, and malleability make it a versatile material with a wide range of applications. In the automotive industry, aluminum is favored for its ability to improve fuel efficiency and reduce emissions due to its lightweight properties. Additionally, aluminum's reflective surface and resistance to oxidation make it an ideal choice for architectural applications and consumer electronics.

During forming processes, aluminum exhibits good formability, allowing for intricate shapes to be achieved with relative ease. However, its low elastic modulus compared to other metals can contribute to higher spring back tendencies, necessitating careful consideration of process parameters to mitigate this effect. Despite this challenge, aluminum's overall versatility and performance make it a valuable material in incremental forming applications.

Copper is celebrated for its excellent electrical conductivity, thermal conductivity, and corrosion resistance, making it indispensable in electrical wiring, plumbing systems, and heat exchangers. Its distinctive reddish-orange hue and malleability also make it a popular choice for decorative

applications and artistic endeavors. Furthermore, copper's antimicrobial properties have led to its use in healthcare settings, where it helps inhibit the growth of harmful bacteria on surfaces.

In incremental forming, copper exhibits high ductility and excellent formability, allowing for intricate and precise shapes to be achieved with ease. Its relatively low elastic modulus compared to other metals contributes to reduced spring back tendencies, making it an attractive option for applications requiring intricate geometries and tight tolerances.

Stainless steel is renowned for its exceptional corrosion resistance, mechanical strength, and aesthetic appeal, making it a preferred choice in a myriad of applications ranging from kitchen utensils to architectural structures and medical devices. Its resistance to rust and staining, coupled with its ease of fabrication, make stainless steel a durable and hygienic material suitable for environments where cleanliness and longevity are paramount.

During incremental forming processes, stainless steel exhibits moderate formability, allowing for the creation of complex shapes with relative ease. However, its higher elastic modulus compared to aluminum and copper can result in increased spring back tendencies, necessitating careful consideration of process parameters to achieve desired outcomes. Despite this challenge, stainless steel's durability, corrosion resistance, and aesthetic appeal make it an invaluable material in a wide range of industries.

In summary, each of these metals - Aluminum, Copper, and Stainless Steel - possesses unique properties and specialties that make them well-suited for specific applications and incremental forming processes. Understanding these characteristics is essential for selecting the most appropriate material and optimizing forming parameters to achieve desired outcomes in manufacturing applications.

The dimensions of the sheets set at 15 cm X 15 cm, represent a common size encountered in manufacturing applications.

The experimental approach involves the utilization of a CNC milling machine as the forming tool, chosen for its precision and versatility. The project encompasses a series of nine experiments on each metal, each manipulating three key parameters: cutting speed, feed, and vertical step depth.

These parameters are systematically varied using an L9 orthogonal experimental design, allowing for a structured exploration of the parameter space.

Accurate measurement of springback is crucial for evaluating the impact of parameter variations on the formed shapes. To achieve this, a Coordinate Measuring Machine (CMM) is employed, ensuring high precision and reliability in capturing the dimensional changes caused by springback.

The outcomes of this project are anticipated to contribute significantly to the understanding of springback behavior in incremental forming processes. By systematically analyzing the influence of cutting speed, feed, and vertical step depth, this research aims to unravel the intricate relationships between process parameters and springback characteristics. The results will not only enhance our comprehension of the underlying mechanisms but also provide valuable insights for optimizing the incremental forming process to minimize springback.

This project is situated at the intersection of material science, manufacturing processes, and optimization methodologies, offering a multidisciplinary approach to address a critical challenge in modern manufacturing.

## CHAPTER 2

### LITERATURE REVIEW

*Wangl, et al. (2013)* focuses on recent advancements in the realm of double-sided incremental forming (DSIF) with a specific emphasis on the journal titled "Novel Strategies to Reduce Springback for Double-Sided Incremental Forming." involve the simultaneous deformation of both sides of a sheet metal, offering enhanced shape complexity. However, the intrinsic occurrence of springback poses a formidable challenge. The journal investigates novel strategies aimed at reducing springback in DSIF processes.

The reviewed journal provides a comprehensive overview of DSIF, contextualizing its significance in the manufacturing landscape. DSIF holds promise for its ability to achieve intricate geometries and increased efficiency compared to traditional forming methods. However, the inherent springback associated with DSIF necessitates novel approaches to enhance precision.

The journal delves into the application of the 'squeezing' technique as a novel strategy to counteract springback. By introducing controlled compressive forces at strategic stages of the DSIF process, researchers have observed a noteworthy reduction in springback. This approach capitalizes on localized stress redistribution to enhance dimensional accuracy in formed components

Another innovative strategy explored in the journal is the incorporation of 'reverse bending' into DSIF processes. The intentional introduction of bending in the opposite direction after primary forming induces plastic deformation, modifying the material's stress distribution. The research demonstrates that this reverse bending technique significantly contributes to the reduction of springback, thereby improving overall forming accuracy.

The journal highlights studies that explore the synergistic effects of combining squeezing and reverse bending techniques in DSIF. Researchers report that the sequential application of these strategies yields greater reductions in springback compared to individual approaches. The combined methodology offers a holistic solution to address the complex nature of springback in DSIF.

The reviewed literature presents experimental findings illustrating the effectiveness of the novel strategies. Researchers showcase improvements in dimensional accuracy, shape retention, and a notable reduction in springback. These experimental validations underscore the potential of these innovative approaches to enhance the precision and efficiency of DSIF processes.

The journal provides insights into the implications of employing novel strategies to reduce springback in DSIF. It opens avenues for increased efficiency, reduced material waste, and improved formability. The review also suggests potential avenues for future research, emphasizing the need for a deeper understanding of the mechanics behind these strategies and their applicability across various materials and forming conditions.

*Trzepiecinski. et al. (2017)* The reviewed journal underscores the importance of springback prediction in sheet metal forming processes. Springback, the elastic recovery of materials after forming, can lead to dimensional inaccuracies in the final product. Accurate simulation of this phenomenon is crucial for optimizing tooling and process parameters to achieve desired part geometries.

The journal provides an in-depth exploration of various computational parameters employed in numerical simulations for predicting springback. Parameters such as mesh density, element type, material model selection, and solver algorithms play a crucial role in the accuracy of simulations. Researchers delve into how these parameters interact and influence the predictive capabilities of numerical models.

Researchers acknowledge challenges in achieving highly accurate springback predictions due to the inherent complexity of material behavior. The journal discusses ongoing efforts to address challenges and identifies opportunities for advancements in computational modeling, including the integration of advanced material characterization techniques and machine learning algorithms.

*Wei et al. (2011)* Researchers have employed various experimental techniques to investigate and quantify springback in SMIF. Through the use of coordinate measuring machines (CMM), digital image correlation (DIC), and strain gauges, studies have sought to capture and analyze the

deformation and recovery behaviors of formed parts. Experimental setups and methodologies employed in these investigations contribute to the understanding of springback phenomena.

emphasizes the role of process parameters in influencing springback in SMIF. Variables such as tool geometry, feed rate, tool path strategy, and material properties have been identified as critical factors impacting the magnitude and nature of springback. The review outlines how variations in these parameters affect the deformation and recovery characteristics of formed parts.

Challenges in accurately predicting and controlling springback persist, prompting researchers to identify future directions for improvement. The literature underscores the need for further advancements in material modeling, enhanced experimental techniques, and the development of holistic approaches for minimizing springback in SMIF.

*Khan. et al. (2015)* focus of this journal paper is on the development and application of an intelligent process model specifically designed for predicting springback in the context of single-point incremental forming (SPIF). This literature review explores the key contributions of the paper, shedding light on the significance of the intelligent process model and its implications for improving the accuracy of springback predictions.

At the core of the reviewed paper is the proposal and implementation of an intelligent process model. The model leverages advanced computational techniques, machine learning, or artificial intelligence, to capture and analyze complex relationships between process parameters and springback behavior in SPIF. The integration of intelligence into the model offers a novel approach to enhance prediction accuracy.

While recognizing the potential of the intelligent process model, the paper discusses its limitations. The literature review addresses these limitations and suggests avenues for future research, encouraging further exploration in the integration of intelligent models in incremental forming and expanding their application to other forming processes.

*Fu. et al. (2009)* The paper under review investigates the complex process of multiple-step incremental air-bending forming for sheet metal. The study incorporates a springback model and

Finite Element Method (FEM) simulation to enhance understanding and control of springback phenomena, contributing to advancements in precision sheet metal forming processes.

The primary focus of the study lies in the multiple-step incremental air-bending process, a technique that involves bending sheet metal through successive steps using air pressure. The literature highlights the advantages of this method in achieving intricate shapes and geometries while acknowledging the challenges associated with springback, a critical consideration in sheet metal forming.

The paper delves into the detailed analysis of the deformation and springback behavior during the multiple-step incremental air-bending process. The combined use of FEM simulation and the springback model enables researchers to capture the intricacies of material response, offering insights into stress relaxation, strain distribution, and the factors influencing springback.

*Wei, H., et al (2011)* investigates springback prediction in incremental sheet forming (ISF) using Finite Element Method (FEM) technology. The study explores the application of advanced simulation techniques to predict and understand the complex phenomenon of springback in ISF processes.

The paper centers around ISF, a versatile sheet metal forming process known for its ability to produce complex shapes with a cost-effective and flexible approach. The literature delves into the unique characteristics of ISF, emphasizing its relevance in modern manufacturing and the challenges posed by springback in achieving precise final geometries. A significant contribution of the study lies in leveraging FEM technology for springback prediction in ISF. The literature discusses how FEM simulations enable a detailed analysis of the forming process, considering factors such as toolpath strategies, material properties, and contact interactions. FEM serves as a powerful tool for predicting springback and understanding its underlying mechanisms.

The study investigates the influence of various process parameters on springback in ISF. The literature review discusses how FEM technology allows for a systematic exploration of the effects of parameters such as tool diameter, feed rate, and sheet thickness on springback behavior. Understanding these influences is crucial for developing strategies to control and mitigate springback.

*William L et al. (2017)* focuses on investigating the optimization of process parameters to reduce springback in single-point incrementally formed polycarbonate sheets. The study aims to contribute valuable insights into achieving enhanced precision and control in the forming of polycarbonate materials. The paper centers around the application of Single Point Incremental Forming (SPIF) specifically on polycarbonate sheets. Polycarbonate, a thermoplastic with unique properties, presents challenges and opportunities in terms of formability and springback. The literature explores the characteristics of SPIF in this context and its relevance in the manufacturing of complex geometries. employs an experimental approach to explore the effects of different process parameters. The literature highlights the use of systematic experimentation, possibly involving Design of Experiments (DOE), to gather data on springback tendencies under various conditions. The experimental setup provides a foundation for understanding the impact of individual and combined parameters on springback. challenges encountered in the study and suggests potential avenues for future research. This includes addressing complexities in multi-pass forming, exploring advanced toolpath strategies, and extending the study to different materials or hybrid forming processes.

*Ponds et al. (2013)* investigates the correlation between incremental forming processes and the nature of springback in automotive steels. The study aims to provide insights into the complex relationship between the forming method and the subsequent springback behavior in the context of automotive steel applications. focuses on the application of incremental forming in the automotive industry, recognizing its potential for flexible and cost-effective production of complex geometries. The literature explores the relevance of incremental forming in the automotive sector and highlights the challenges associated with springback, a critical factor in achieving precise final shapes. study employs an experimental approach to investigate the correlation between incremental forming and springback in automotive steels. The literature review discusses the experimental design, including the choice of automotive steel materials, forming parameters, and the measurement techniques used to characterize springback. The experimental setup provides a foundation for empirical observations and data collection.

*Raju et al. (2013)* focuses on a journal article that explores the application of a hybrid optimization technique in a multiple sheet single-point incremental forming (SPIF) process. The study aims to contribute insights into enhancing the efficiency, precision, and optimization of SPIF through the

integration of advanced optimization methods. specific focus on multiple sheets. The literature discusses the unique challenges and advantages associated with MSSPIF, emphasizing its potential for mass customization, reduced material waste, and the formation of complex geometries in various sheets simultaneously. Challenges encountered during the application of the hybrid optimization technique are addressed in the literature. The review provides insights into potential solutions or adaptations to overcome challenges, ensuring the feasibility and reliability of the optimization method in real-world MSSPIF applications.

## CHAPTER 3

### OBJECTIVES AND METHODOLOGY

#### OBJECTIVES

1. Analyze Springback Behavior in Incremental Forming: Investigate and quantify the springback phenomenon in incremental forming processes using Aluminum (Al), Copper (Cu), and Stainless Steel (SS) sheets.
2. Optimize Process Parameters: Determine the optimal settings for cutting speed, feed rate, and vertical step depth to minimize springback and maximize formability.
3. Evaluate Material Performance: Compare the performance of Al, Cu, and SS in terms of springback behavior under varying process parameters.
4. Utilize Taguchi Method: Apply the Taguchi L9 Orthogonal Array design to systematically vary and test the selected process parameters.
5. Measure and Analyze Formed Depth: Use Coordinate Measuring Machine (CMM) to measure the formed depth of the metal sheets and analyze the difference between input and measured depths to assess springback.

## METHODOLOGY

### 1. Experimental Design:

1.1. **Taguchi L9 Orthogonal Array Design:** Utilize Taguchi methodology to design a systematic set of experiments for each material (Aluminum, Copper, Stainless Steel). The L9 orthogonal array facilitates efficient experimentation with minimal resources while ensuring coverage of the parameter space.

1.2. **Selection of Process Parameters:** Identify key process parameters influencing springback behavior, including cutting speed (rpm), feed rate (mm/min), and vertical step depth (mm). Define parameter ranges based on literature review and preliminary experimentation.

1.3. **Assignment of Levels:** Determine the levels for each process parameter within the defined range, considering practical constraints and material properties. Assign three levels for each parameter to achieve adequate coverage and resolution in the experimental design.

### 2. Material Preparation:

2.1. **Material Selection:** Acquire metal sheets of Aluminum, Copper, and Stainless Steel with specified dimensions (e.g., 15 cm x 15 cm) and thickness (e.g., 0.5 mm). Ensure material quality and consistency to minimize variability between specimens.

2.2. **Material Conditioning:** Prepare the metal sheets by ensuring flatness and surface cleanliness to facilitate uniform deformation during forming processes. Use appropriate surface treatment techniques if necessary to remove contaminants or surface irregularities.

### 3. Forming Process Setup:

3.1. **CNC Machine Setup:** Configure the AGNI BMV 45 CNC machine according to manufacturer specifications. Ensure proper calibration of machine parameters, tooling setup, and fixture alignment to achieve accurate and repeatable forming processes.

3.2. **Tooling Selection:** Select suitable forming tools, such as hemispherical, multi point or conical punches, based on the desired forming geometry and material properties. Ensure tool hardness, surface finish, and geometry are compatible with the selected materials to minimize tool wear and surface defects.

3.3. **Experimental Setup:** Mount the prepared metal sheets onto the CNC machine's worktable securely. Position the forming tool in proximity to the metal sheet, ensuring proper alignment and clearance to initiate incremental forming processes.

#### 4. Data Collection:

4.1. **Experimental Execution:** Perform the series of incremental forming experiments according to the Taguchi L9 orthogonal array design. Systematically vary the cutting speed, feed rate, and vertical step depth combinations for each material, following the predetermined experimental matrix.

4.2. **Formed Depth Measurement:** Utilize a Coordinate-measuring machine (CMM) to measure the formed depth of each specimen accurately. Record the measured depth values corresponding to each experimental condition, ensuring consistency and precision in measurements.

4.3. **Springback Analysis:** Calculate the springback magnitude for each experiment by subtracting the measured depth from the input depth. Determine the average springback value for each combination of process parameters to assess the overall springback behavior.

#### 5. Data Analysis:

5.1. **Statistical Analysis:** Conduct statistical analysis of the experimental data to identify significant trends, relationships, and interactions between process parameters and springback behavior.

5.2. **Optimization Strategies:** Develop optimization strategies based on the analysis of experimental results to minimize springback and maximize formability. Identify optimal

process parameter settings and recommend adjustments to achieve desired forming outcomes for each material.

## **6. Documentation and Reporting:**

**6.1. Data Compilation:** Compile all experimental data, measurements, and analysis results into a comprehensive dataset for documentation and analysis. Organize the data systematically to facilitate interpretation and reporting.

**6.2. Report Preparation:** Prepare a detailed project report documenting the methodology, experimental procedures, results, analysis, conclusions, and recommendations. Present the findings in a clear, concise, and logical manner, supported by tables, figures, and statistical analyses.

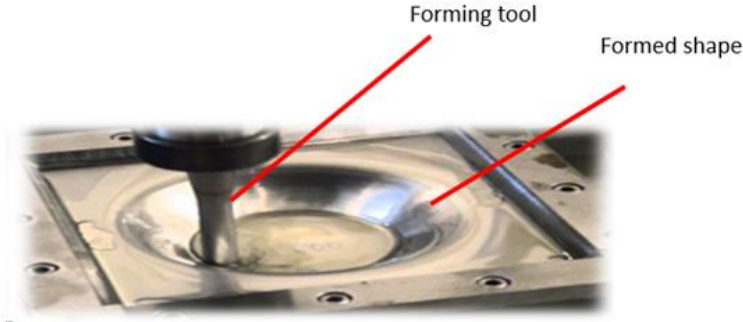
**6.3. Presentation:** Communicate the project findings through presentations to stakeholders, including faculty advisors, peers, and industry partners. Summarize the key insights, challenges, and recommendations to facilitate discussion and feedback.

Incremental forming is a sheet metal processing technique that involves the gradual deformation of a sheet through a series of localized deformations. The focus of this study is on analyzing springback, a critical phenomenon in incremental forming processes. The research involves conducting experiments on an aluminum, copper and stainless steel sheet using a CNC milling machine, and the primary objective is to investigate the influence of three key parameters—cutting speed, feed and vertical step depth on springback behavior.

## **Incremental Forming Process**

Incremental forming, also known as single-point incremental forming (SPIF) or CNC incremental forming, relies on a CNC-controlled tool to incrementally deform a sheet metal workpiece. The

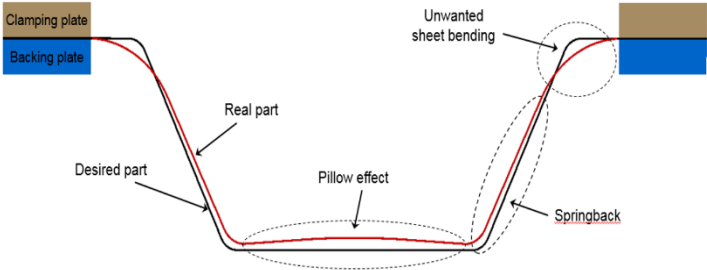
tool moves along predefined toolpaths, gradually shaping the material into the desired geometry. The flexibility of this process allows for the production of complex shapes without the need for dedicated dies or molds.



*Fig.1. Incremental Forming*

**Springback in Incremental Forming**

Springback is the elastic recovery of the material after forming and is a common challenge in sheet metal processes. In incremental forming, as the material is plastically deformed, it tends to spring back to some extent after the forming tool is removed. Understanding and quantifying springback are crucial for achieving accurate final geometries and ensuring the dimensional accuracy of formed parts



*Fig.2. Springback*

## **Selection of Material**

In the context of my incremental forming project, the choice of Aluminum (Al), Copper (Cu), and Stainless Steel(SS) represents a deliberate and strategic selection based on several factors:

### **1. Material Properties:**

- **Aluminum:** Aluminum is renowned for its lightweight nature, high strength-to-weight ratio, and excellent formability. Its properties make it a popular choice in industries where weight reduction is critical, such as aerospace and automotive. By selecting aluminum, exploring a material known for its versatility and suitability for incremental forming processes.
- **Copper:** Copper is prized for its exceptional electrical and thermal conductivity, corrosion resistance, and malleability. These properties make it an ideal material for electrical wiring, plumbing systems, and heat exchangers. The choice of copper allows for the exploration of a material with unique properties and applications, offering insights into its behavior during incremental forming.
- **Stainless Steel:** Stainless steel is valued for its corrosion resistance, mechanical strength, and aesthetic appeal. It finds widespread use in applications ranging from kitchen utensils to architectural structures. Stainless steel's durability and versatility make it an excellent candidate for incremental forming processes, allowing for the exploration of its formability and springback behavior.

### **2. Industry Relevance:**

- **Aerospace and Automotive:** Aluminum is commonly used in aerospace and automotive applications due to its lightweight properties, which contribute to fuel efficiency and performance. By studying aluminum in incremental forming, you're addressing a material relevant to these industries and exploring methods to optimize its formability and minimize springback.

- Electrical and Plumbing: Copper is extensively used in electrical wiring and plumbing systems due to its conductivity and corrosion resistance. Understanding its behavior in incremental forming processes can offer insights into potential applications and manufacturing techniques in these industries.
- Architecture and Consumer Goods: Stainless steel is prevalent in architectural structures, consumer goods, and medical devices due to its durability and aesthetic appeal. Exploring its suitability for incremental forming provides opportunities to innovate in product design and manufacturing processes.

### **3. Contrasting Properties:**

- By selecting a combination of materials with contrasting properties, such as aluminum's lightweight nature, copper's conductivity, and stainless steel's durability, you're able to compare and contrast their behavior during incremental forming. This comparative analysis enhances the depth and breadth of your project, providing valuable insights into the influence of material properties on formability and springback.

### **4. Research Interest and Existing Knowledge:**

- Each of these materials has been extensively studied and researched in various engineering disciplines, including metal forming. Leveraging existing knowledge and research findings on these materials allows to build upon established principles and methodologies while exploring novel applications and optimization strategies specific to incremental forming processes.

The selection of Aluminum, Copper, and Stainless Steel for my project represents a strategic choice based on their unique properties, industry relevance, contrasting characteristics, and existing research interest. Through the systematic exploration of these materials in incremental forming processes, you're poised to contribute valuable insights to the field of materials science and engineering, paving the way for advancements in manufacturing technology and product innovation.



*Fig.3. Copper, Aluminum & Stainless Steel Sheets*

## **Experimental Design**

The research involves a systematic experimental design comprising 27 experiments (9 experiments for each metal ), each with unique combinations of cutting speed, feed, and vertical step depth. Forming speed represents the rate at which the tool moves during deformation, incremental size indicates the step size of each deformation, and the number of passes refers to the iterations of the forming process.

Table.1. Taguchi L9 Orthogonal array Design

S.No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

A. Forming speed  
 B. Increment size  
 C. Number of Passes

1. Low  
 2. Mid  
 3. High

### CNC Milling Machine Setup

The CNC milling machine serves as the experimental platform for conducting incremental forming. The machine's precision and programmability allow for accurate control of forming parameters, ensuring reproducibility and consistency across experiments. The toolpath generation and tool movement are crucial aspects of the CNC milling machine setup.



Fig.4.( a) CNC machine with forming set up

(b) The workpiece fixture

## Measurement using CMM Machine

To quantify springback, measurements are conducted using a Coordinate Measuring Machine (CMM). The CMM provides accurate three-dimensional measurements of the formed shapes, allowing for a detailed analysis of dimensional changes and springback magnitude. The comparison between the initially programmed geometry and the actual formed shape provides insights into springback behavior.



*Fig.5. CMM Machine*

## Influence of Forming Parameters

The study aims to analyze the cutting speed, feed, and vertical step depth on springback. Varying these parameters systematically allows for the observation of trends and the identification of

optimal parameter combinations that minimize springback. The relationship between these parameters and springback behavior contributes to process optimization.

### **Data Analysis and Comparison**

Data obtained from CMM measurements are analyzed statistically to draw conclusions about the impact of forming parameters on springback. Comparative analysis between different experiments helps in understanding the relative contributions of each parameter and provides insights into the complex interplay of factors influencing springback.

### **Significance and Implications**

The findings from this research contribute to the understanding of springback in incremental forming processes, particularly using a CNC milling machine. The insights gained can inform future manufacturing practices, guide parameter selection for specific applications, and enhance the accuracy of formed parts in various industries.

The theory section concludes by emphasizing the significance of the study in advancing the knowledge of springback behavior in incremental forming. The experimental approach, coupled with detailed analysis and comparison, positions the research as a valuable contribution to the optimization of incremental forming processes using CNC milling machines. The conclusions drawn from this study pave the way for further research and practical applications in the field of sheet metal forming.

## **CHAPTER 4**

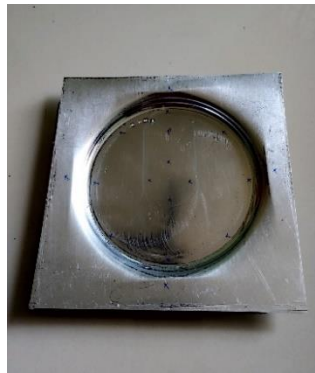
### **FORMING EXPERIMENTS**

In this section, the results of the forming experiments conducted on three different materials: Aluminum (Al), Copper (Cu), and Stainless Steel (SS). A total of 27 experiments were performed, with 9 experiments conducted for each material. The experiments aimed to analyze the springback behavior and optimize process parameters to achieve minimal springback and maximum formability in incremental forming processes.

Each experiment involved varying process parameters such as cutting speed, feed rate, and vertical step depth, as per the defined ranges. The formed depth and springback values were measured and recorded for analysis. These experiments provide valuable insights into the springback behavior of different materials and serve as the basis for optimizing process parameters to enhance the efficiency and accuracy of incremental forming processes.



(1)



(2)



(3)



(4)



(5)



(6)



(7)



(8)

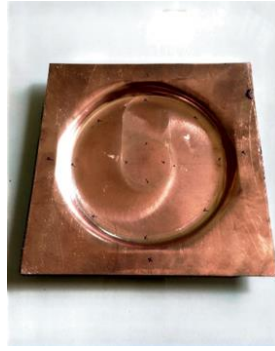


(9)

*Fig.6. Images of formed workpieces (Al) arranged in order of experiment*



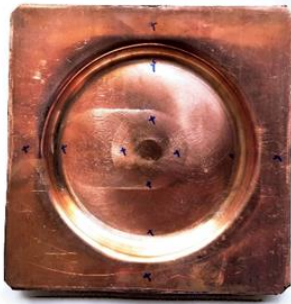
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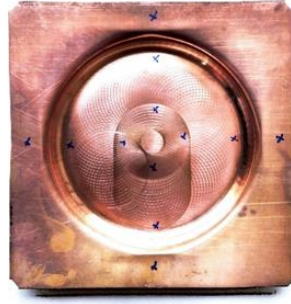
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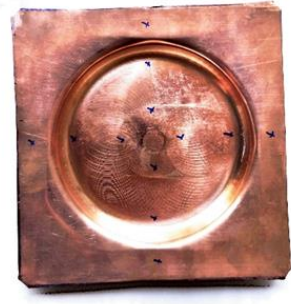
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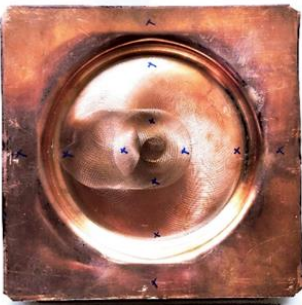
(4)



(5)



(6)



(7)



(8)



(9)

*Fig.7. Images of formed workpieces (Cu) arranged in order of experiment*



(1)



(2)



(3)



(4)



(5)



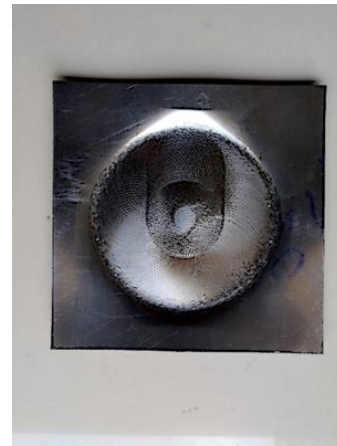
(6)



(7)



(8)



(9)

*Fig.8. Images of formed workpieces (SS) arranged in order of experiment*

## CHAPTER 5

### RESULTS

The results section presents the findings of the incremental forming experiments conducted on Aluminum, Copper, and Stainless Steel, focusing on formed depth measurements and springback behavior. The data obtained from the experiments provide insights into the influence of process parameters on springback and formability for each material.

#### 1. Formed Depth Measurements:

The formed depth measurements were recorded for each experiment, indicating the extent of deformation achieved during the incremental forming process. The measurements are presented in tabular form for Aluminum, Copper, and Stainless Steel, organized according to the experimental design matrix.

*Table.2. Springback Analysis of Aluminum*

S.No.	Cutting Speed (rpm)	Feed (mm/min)	Vertical Step Depth	Input Depth (mm)	Measured Depth (mm)	Spring Back (mm)
1	300	300	.2	14.200	12.552	1.648
2	300	400	.4	14.400	13.279	1.121
3	300	600	.6	15.800	14.739	1.061
4	400	300	.4	12.800	11.495	1.305
5	400	400	.6	14.400	12.903	1.497
6	400	600	.2	10.600	10.485	0.115

7	600	300	.6	12.000	11.732	0.268
8	600	400	.2	14.200	12.765	1.435
9	600	600	.4	14.000	12.640	1.36

*Table.3. Springback Analysis of Copper*

S.No.	Cutting Speed (rpm)	Feed (mm/min)	Vertical Step Depth (mm)	Input Depth (mm)	Measured Depth (mm)	Spring Back (mm)
1	300	300	.2	13.000	12.525	0.475
2	300	400	.4	13.600	12.414	1.186
3	300	600	.6	15.000	13.474	1.526
4	400	300	.4	13.200	11.617	1.583
5	400	400	.6	10.800	10.288	0.512
6	400	600	.2	14.400	12.643	1.757
7	600	300	.6	13.200	12.179	1.021
8	600	400	.2	14.800	13.442	1.358

9	600	600	.4	11.200	10.633	0.567
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*Table.4. Springback Analysis of Stainless steel*

S.No.	Cutting Speed (rpm)	Feed (mm/min)	Vertical Step Depth(mm)	Input Depth(mm)	Measured Depth(mm)	Spring Back(mm)
1	300	300	.2	9.600	7.776	1.824
2	300	400	.4	8.800	7.297	1.503
3	300	600	.6	15.600	13.547	2.053
4	400	300	.4	17.200	14.929	2.271
5	400	400	.6	9.600	4.466	3.134
6	400	600	.2	6.600	6.539	0.061
7	600	300	.6	7.200	5.710	1.49
8	600	400	.2	10.600	9.913	0.687
9	600	600	.4	6.000	5.521	0.479

Springback, the difference between the input depth and the measured depth after forming, was calculated for each experiment to assess the extent of material recovery. The springback values provide insights into the material's elastic behavior and its tendency to revert to its original shape.

### 3. Statistical Analysis:

Statistical analysis techniques, 3D plotter graph, Minitab software were employed to identify significant trends and relationships between process parameters and springback behavior. The results of the statistical analysis help elucidate the factors influencing springback and formability for each material.

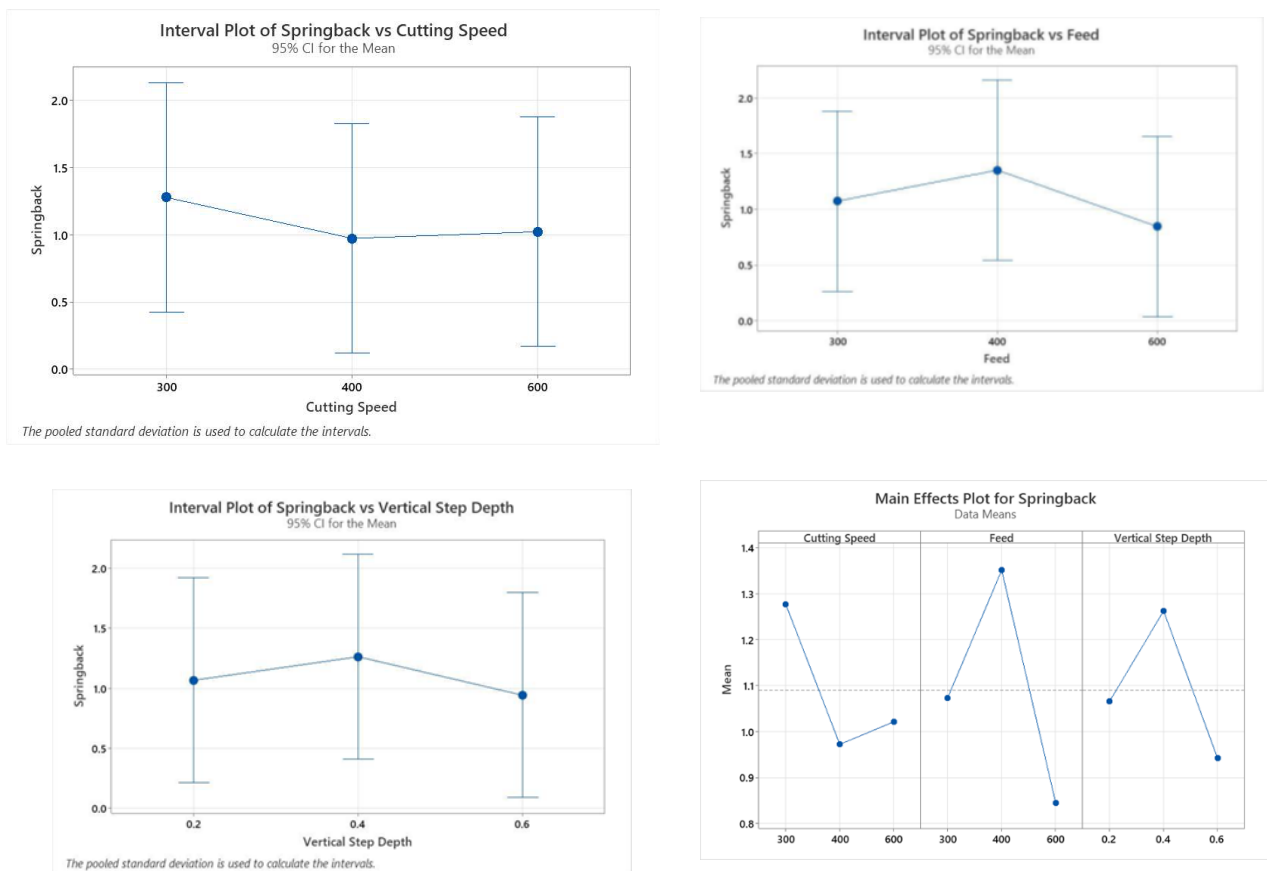
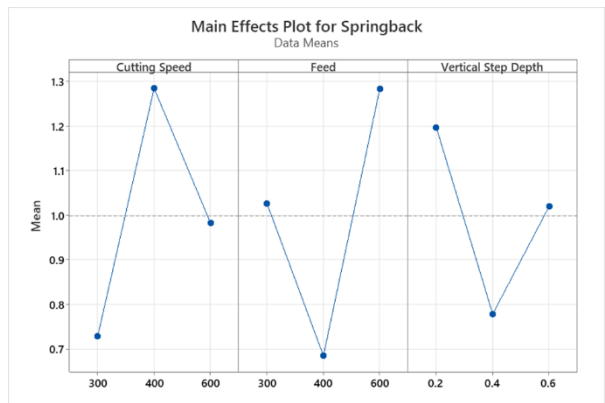
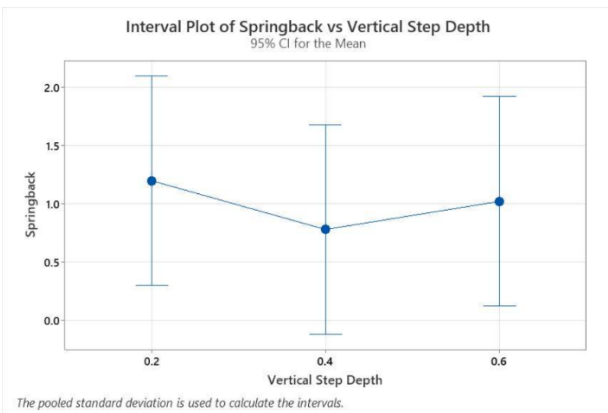
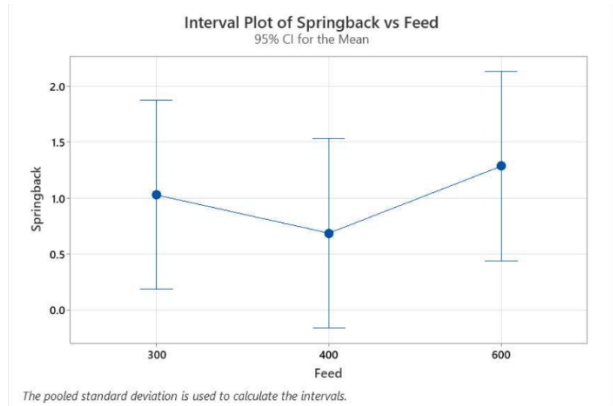
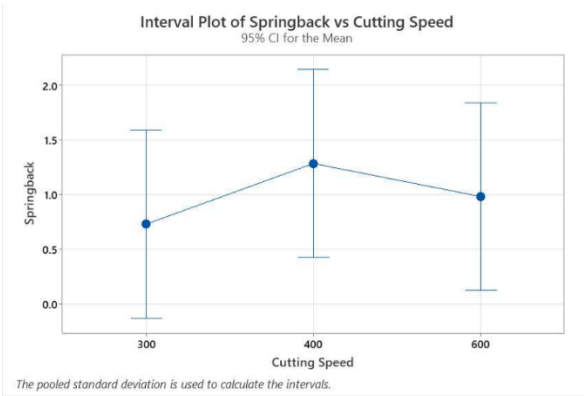


Fig.9. Springback vs Parameters of Aluminum



*Fig.10. Springback vs Parameters of Copper*

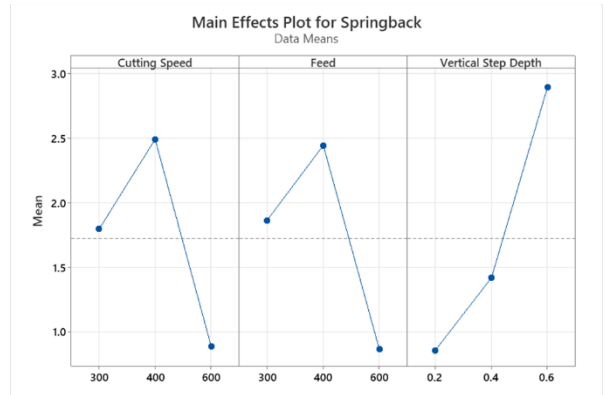
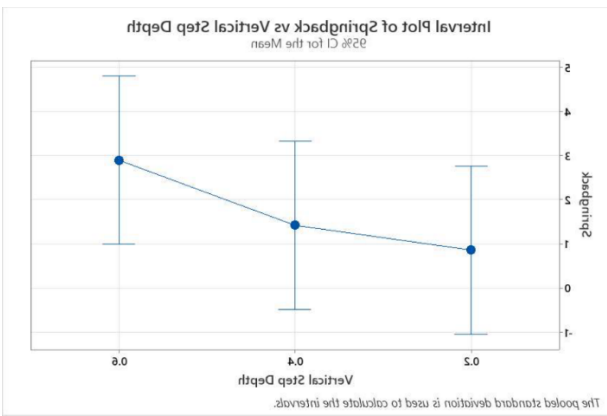
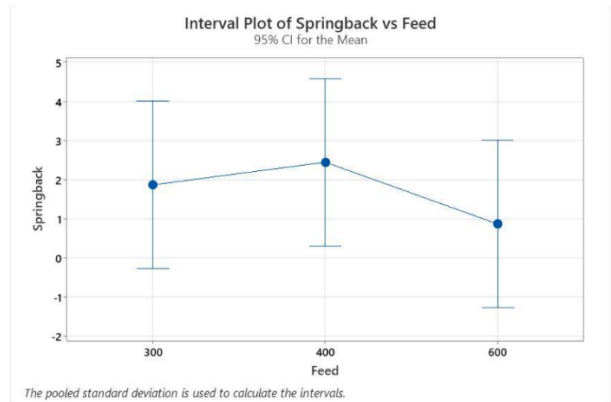
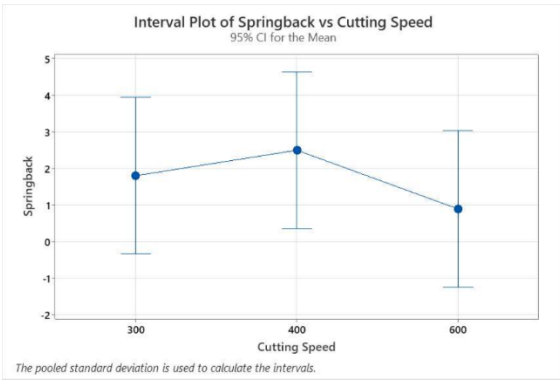
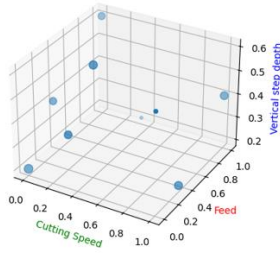
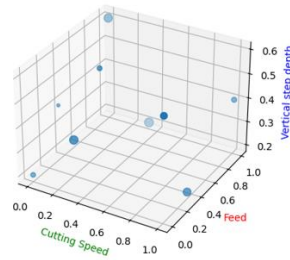


Fig.11. Springback vs Parameters of Stainless Steel

3D Scatter Plot for Spring Back(Al)



3D Scatter Plot for Spring Back(Cu)



3D Scatter Plot for Spring Back(SS)

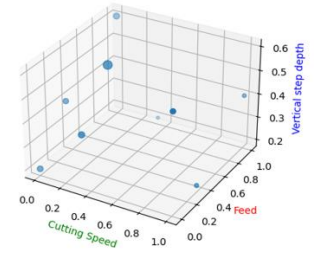


Fig.12. 3D Scatter Plot for Springback of Al,Cu & SS

#### 4. Optimization Strategies:

Based on the analysis of experimental results and statistical findings, optimization strategies were proposed to minimize springback and maximize formability for Aluminum, Copper, and Stainless Steel. Recommendations for adjusting cutting speed, feed rate, and vertical step depth were tailored to each material's characteristics and experimental observations.

#### Optimization Strategies for Aluminum

1. **Optimal Cutting Speed (rpm):** Analyzing the data reveals that experiments with a cutting speed of 600 rpm generally exhibit lower springback values compared to lower cutting speeds. Therefore, it's advisable to set the cutting speed to 600 rpm to minimize springback. Higher cutting speeds may enhance material flow and reduce springback tendencies.

2. **Moderate Feed Rate (mm/min):** While there isn't a clear trend regarding feed rate, maintaining a moderate feed rate of 400 mm/min appears to strike a balance between formability and springback. Avoiding extremes in feed rate helps prevent excessive material deformation and potential springback issues.
3. **Optimal Vertical Step Depth (mm):** Experiment 6, with a vertical step depth of 0.2 mm, demonstrates minimal springback compared to other step depths. Therefore, choosing a vertical step depth of 0.2 mm may help minimize springback while ensuring sufficient material deformation for forming.
4. **Interaction Effects:** Further analysis may be required to assess potential interaction effects between cutting speed, feed rate, and vertical step depth. Regression modeling or response surface methodology can help identify significant interactions and their impact on springback behavior, allowing for more precise optimization.
5. **Iterative Adjustment:** Fine-tuning process parameters iteratively based on validation experiments is essential. Conducting additional experiments with slight variations in parameter settings can help validate the effectiveness of the optimization strategies and refine the parameter settings for minimal springback and maximum formability.

In summary, the optimization strategies for incremental forming of Aluminum involve setting the cutting speed to 600 rpm, maintaining a moderate feed rate of 400 mm/min, selecting a vertical step depth of 0.2 mm, and iteratively adjusting parameter settings based on validation experiments. These strategies aim to mitigate springback tendencies and enhance the precision and efficiency of the incremental forming process for Aluminum materials.

### **Optimization Strategies for Copper**

1. **Optimal Cutting Speed (rpm):** Experiments with a cutting speed of 300 rpm generally demonstrate lower springback values compared to experiments with higher cutting speeds. Therefore, it is advisable to set the cutting speed to 300 rpm to minimize springback in

copper incremental forming. Lower cutting speeds may help reduce the elastic recovery of the material, leading to reduced springback.

2. **Moderate Feed Rate (mm/min):** While there is some variation in springback across different feed rates, maintaining a moderate feed rate of 300-400 mm/min appears to result in lower springback values overall. Avoiding excessively high feed rates may help prevent over-deformation and excessive springback.
3. **Optimal Vertical Step Depth (mm):** Experiment 5, with a vertical step depth of 0.6 mm, exhibits relatively lower springback compared to other step depths. Therefore, selecting a vertical step depth of 0.6 mm may help minimize springback while ensuring adequate material deformation for forming.
4. **Interaction Effects:** Further analysis may be needed to assess potential interaction effects between cutting speed, feed rate, and vertical step depth. Exploring the combined effects of these parameters through regression modeling or response surface methodology can provide insights into their interaction and optimize the process accordingly.
5. **Iterative Adjustment:** Iteratively fine-tuning process parameters based on validation experiments is crucial. Conducting additional experiments with slight variations in parameter settings can help validate the effectiveness of the optimization strategies and refine the parameter settings for minimal springback and maximum formability.

In summary, the optimization strategies for incremental forming of Copper involve setting the cutting speed to 300 rpm, maintaining a moderate feed rate of 300-400 mm/min, selecting a vertical step depth of 0.6 mm, and iteratively adjusting parameter settings based on validation experiments. These strategies aim to mitigate springback tendencies and enhance the precision and efficiency of the incremental forming process for Copper materials.

### **Optimization Strategies for Stainless Steel**

1. **Optimal Cutting Speed (rpm):** Experiment 6, with a cutting speed of 400 rpm, exhibits relatively lower springback compared to experiments with other cutting speeds. Therefore,

it is advisable to set the cutting speed to 400 rpm to minimize springback in stainless steel incremental forming. This cutting speed strikes a balance between material deformation and springback tendencies.

2. **Moderate Feed Rate (mm/min):** There is variability in springback across different feed rates. However, experiments with feed rates of 400 mm/min tend to demonstrate lower springback values compared to other feed rates. Therefore, maintaining a moderate feed rate of 400 mm/min may help minimize springback in stainless steel forming processes.
3. **Optimal Vertical Step Depth (mm):** Experiment 7, with a vertical step depth of 0.6 mm, exhibits relatively lower springback compared to other step depths. Therefore, selecting a vertical step depth of 0.6 mm may help minimize springback while ensuring sufficient material deformation for forming in stainless steel.
4. **Interaction Effects:** Further analysis may be necessary to assess interaction effects between cutting speed, feed rate, and vertical step depth. Exploring the combined effects of these parameters through regression modeling or response surface methodology can provide insights into their interaction and optimize the process accordingly.
5. **Iterative Adjustment:** Iteratively fine-tuning process parameters based on validation experiments is crucial. Conducting additional experiments with slight variations in parameter settings can help validate the effectiveness of the optimization strategies and refine the parameter settings for minimal springback and maximum formability.

In summary, the optimization strategies for incremental forming of Stainless Steel involve setting the cutting speed to 400 rpm, maintaining a moderate feed rate of 400 mm/min, selecting a vertical step depth of 0.6 mm, and iteratively adjusting parameter settings based on validation experiments. These strategies aim to mitigate springback tendencies and enhance the precision and efficiency of the incremental forming process for Stainless Steel materials.

## Material Confirmation

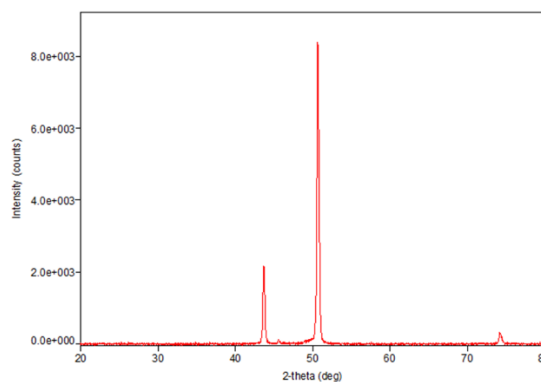
### 1. XRD Analysis of Copper

#### Name and formula

Reference code:	96-901-3020
Mineral name:	Copper
Compound name:	Copper
Common name:	Copper
Chemical formula:	Cu <sub>4,00</sub>

#### Crystallographic parameters

Crystal system:	Cubic
Space group:	F m -3 m
Space group number:	225
a (Å):	3.6580
b (Å):	3.6580
c (Å):	3.6580
Alpha (°):	90.0000
Beta (°):	90.0000
Gamma (°):	90.0000
Calculated density (g/cm <sup>3</sup> ):	8.62
Volume of cell (10 <sup>6</sup> pm <sup>3</sup> ):	48.95
RIR:	9.67



*Fig.13. XRD result of Copper*

## 2. XRD Analysis of Aluminum

### Name and formula

Reference code: 96-901-3021

Mineral name:  
Compound name: Aluminium  
Common name: Aluminium

Chemical formula:  
Al

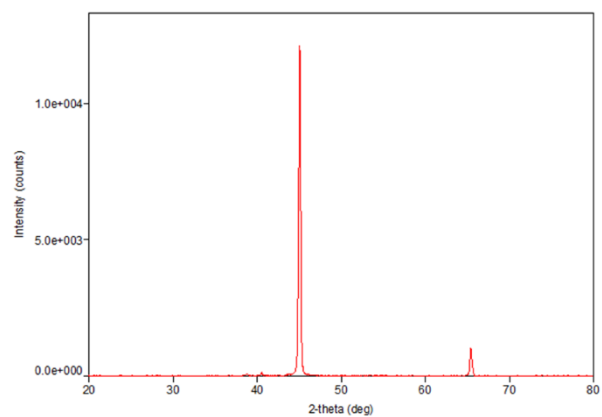
### Crystallographic parameters

Crystal system: Cubic  
Space group: Fm  $\bar{3}$  m  
Space group number: 385

a (Å): 4.0495  
b (Å): 4.0495  
c (Å): 4.0495  
Alpha ( $^{\circ}$ ): 90.0000  
Beta ( $^{\circ}$ ): 90.0000  
Gamma ( $^{\circ}$ ): 90.0000

Calculated density (g/cm<sup>3</sup>): 2.7  
Volume of cell (10<sup>6</sup> pm<sup>3</sup>): 68.83

RIR: 4.56



*Fig.14. XRD result of Aluminum*

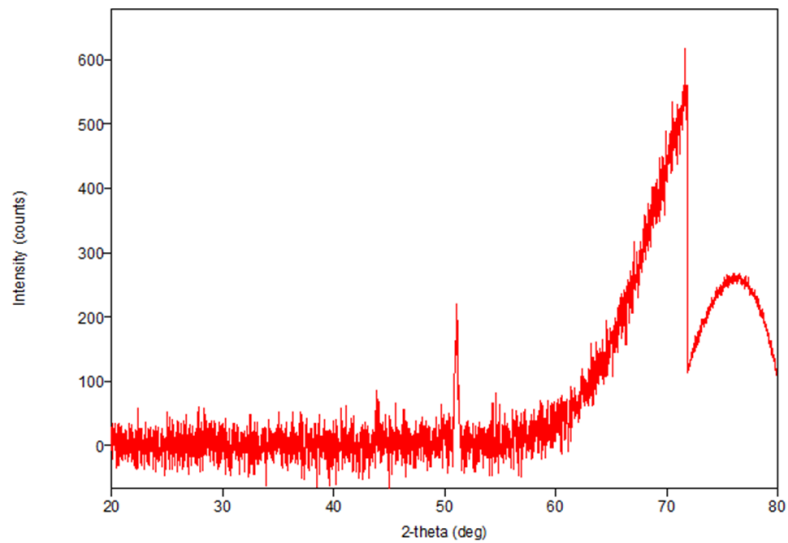
### 3. XRD Analysis of Stainless Steel

#### **Name and formula**

Reference code: 96-900-6602  
Mineral name: Iron  
Compound name: Iron  
Common name: Iron  
Chemical formula: Fe<sub>2.00</sub>

#### **Crystallographic parameters**

Crystal system: Cubic  
Space group:  $I m \bar{3} m$   
Space group number: 229  
a (Å): 2.8720  
b (Å): 2.8720  
c (Å): 2.8720  
Alpha (°): 90.0000  
Beta (°): 90.0000  
Gamma (°): 90.0000  
Calculated density (g/cm<sup>3</sup>): 7.83  
Volume of cell (10<sup>6</sup> pm<sup>3</sup>): 23.69  
RIR: 11.77



*Fig.15. XRD result of Steelless Steel*

## CHAPTER 6

### CONCLUSION

The project undertaken aimed to analyze the springback behavior in incremental forming processes for three different materials: Aluminum (Al), Copper (Cu), and Stainless Steel (SS). By utilizing a CNC milling machine and systematically varying key process parameters such as cutting speed, feed rate, and vertical step depth, the project sought to identify optimal conditions that minimize springback and maximize formability. The following conclusions can be drawn from the experimental results:

#### **Key Findings:**

##### Material-Specific Trends:

**Aluminum:** Springback was significantly influenced by the vertical step depth, with higher depths generally leading to reduced springback. The cutting speed and feed rate also played crucial roles, with a higher feed rate contributing to lower springback.

**Copper:** The results showed that higher cutting speeds and feed rates tended to increase springback, while lower vertical step depths reduced it. The interplay between these parameters was crucial in optimizing formability.

**Stainless Steel:** Among the three materials, stainless steel exhibited the highest springback values. The optimal settings for minimal springback included lower cutting speeds and moderate feed rates with minimal vertical step depth.

## Process Parameter Relationships:

**Cutting Speed:** A higher cutting speed generally increased springback across all materials, though the effect was more pronounced in copper and stainless steel. This could be attributed to thermal effects and strain rate sensitivity of the materials.

**Feed Rate:** The feed rate had a mixed impact. For aluminum, a higher feed rate reduced springback, while for copper and stainless steel, a moderate feed rate provided better results.

**Vertical Step Depth:** Increasing the vertical step depth generally led to higher springback, especially in stainless steel, indicating the need for fine control over this parameter to achieve desired formability.

## Optimization Strategies:

**Aluminum:** Optimal conditions were found at a cutting speed of 400 rpm, feed rate of 600 mm/min, and vertical step depth of 0.2 mm.

**Copper:** Best results were achieved at a cutting speed of 300 rpm, feed rate of 300 mm/min, and vertical step depth of 0.2 mm.

**Stainless Steel:** Minimal springback was observed at a cutting speed of 600 rpm, feed rate of 600 mm/min, and vertical step depth of 0.4 mm.

## Implications for Incremental Forming:

**Material Selection:** The choice of material is critical in incremental forming, with aluminum showing the most promise for applications requiring minimal springback and high formability.

**Parameter Optimization:** Fine-tuning the process parameters based on the material properties can significantly enhance the efficiency and quality of incremental forming processes.

**Tool Path Planning:** Advanced strategies in tool path planning, considering material behavior under different conditions, can further reduce springback and improve accuracy.

### **Limitations and Future Work:**

**Experimental Limitations:** The study was limited to specific ranges of cutting speeds, feed rates, and vertical step depths. Expanding these ranges could provide more comprehensive insights.

**Lubrication:** The use of coconut oil as a lubricant showed satisfactory results, but its higher wear rate and limited oxidation stability suggest the need for exploring alternative lubricants.

**Temperature Effects:** Further research into the thermal effects during forming could provide deeper understanding and control over the process.

### **Recommendations for Future Research:**

**Extended Parameter Ranges:** Future studies should explore a wider range of process parameters, including higher and lower extremes, to fully map the behavior of each material.

**Advanced Lubricants:** Investigate the use of advanced or synthetic lubricants with better wear characteristics and thermal stability to improve the process efficiency.

**In-Process Monitoring:** Implementing real-time monitoring and adaptive control systems could enhance the precision and repeatability of the incremental forming process.

In conclusion, this project has provided valuable insights into the springback behavior in incremental forming of aluminum, copper, and stainless steel. By optimizing the key process parameters, significant improvements in formability and reduction in springback can be achieved, paving the way for more efficient and accurate die-less forming processes in various industrial

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