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ABSTRACT: One of the most challenging problems faced by large-scale manufacturing engineers is the spring back (SB) of sheet metals noted after removing mold loads. This issue can affect the aerodynamic performance of manufactured automobiles, airplanes, and ships. nonetheless, this concern is not sufficiently discussed in the available literature. A lack of experimental investigations does exist. Thus, this research is performed to explore the pattern of SB issue in three mostly utilized metals, including steel, aluminum, and copper. An experimental approach was adopted through which corresponding metal specimens and metal sheets were prepared to be inspected relying on standard apparatus and testing machines. V-shape molds were exploited. Tensile stress, compressive stress, deformations, and strain rates were examined. The results revealed that the SB value (elastic recovery proportion) would rise after removing the applied mold loading as the punch die radius increases in steel and aluminum. But in copper, the rise in the punch radius would lessen the elastic recovery ratio. As the punch radius rises, the force could spread to larger plastic volume. Thus, the elastic recovery ratio would rise. Steel and copper exhibit larger elastic recovery ratios after removing the mold load than aluminum through all thicknesses. Larger punch radii of the contact area between the punch and the sheet would become greater. As a result, the bending moment would rise, resulting in a large SB angle. Steel, copper, and aluminum and could exhibit different ranges of SBP characteristics. The aluminum has lower ratios of SBP/ elastic recovery portion than steel and copper. When the SBP bending radius increases, the metal would show remarkably stability of the SB behavior than the lower bend radius.

Keywords: Spring back (SB) • aerodynamic performance • sheet metal forming (SMF) • experimental analysis • manufacturing • mold loading • steel • copper • aluminum.

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١. Introduction

In the prior stages of automotive, ship, and aircraft manufacturing, low-quality research approaches have been applied to examine and figure out critical factors and indices that affect the pattern, tendency, and behavior of critical metals, like steel, aluminum, and copper in showing their proper rates of elastic recovery after mold loading is removed when they are processed in sheet metal forming (SMF). In other words, when these metals do not exhibit optimum elastic recovery values, spring back (SB) issue can take place, contributing to low-scale mechanical distortions (cm- or mm-size deformations), which, if not efficiently treated, they may cause a reduction in the metal's performance in terms of aerodynamic effectiveness. Corresponding friction, drag force, vibrations, noise, and turbulence can be largely created around these distorted regions in the metal, resulting in an overall flaw in the end-product. These end-products are automotives, ships, and aircrafts. Thus, these tiny deformations and very low scale distortions might cause dramatic problems and failure in the mechanical system if are not carefully and efficiently resolved (Özdemir, ٢٠٢٠).

With continuous research and development (R&D) per annum, which are conducted by experimental laboratory works and numerical simulations and mathematical investigations, precise results and imperative insights are collected to overcome the SB issue whose occurrence in manufacturing has been remarkably growing because of the mushrooming demand worldwide on automobiles, ships, and aircrafts. Researchers reported that through mathematical simulations, scholars can precisely understand, figure out, and interpret relevant patterns and mechanical behaviors of SB in these metals when mold loads are applied (Broggiato, ٢٠١٢; Xu *et al.*, ٢٠٠٤).

Simply speaking, SB issue can be expressed as a common concern that frequently takes place in different SMF processes. It can affect these important end-product's aerodynamic quality, structural integrity, and serviceability. The elastic recovery of these metals when the mold loads are removed could result in deviations, changes, and few distortions in the metal as it deviate from the planned design and the needed shape. As explained above, the impacts of SB problem may become more complicated since the essential aerodynamic characteristics and stability would be largely impacted (Toros *et al.*, ٢٠١٢).

For these reasons, careful investigations of SB are crucial to help manufacturers formulate effective solutions to overcome the SB obstacle when many metals are subjected to pressure and compressive stresses to prevent any uncommon or irregular elastic recovery patterns that may influence their performance and surface integrity (Chen, ٢٠١١).

As many researchers elucidated in the available literature, many processed in the SMF rely on a punch and a die to formulate variant metal sheets, helping create proper plastic deformations to provide the necessary shape planned for automobiles, aircrafts, and shapes. It is remarkable to note that elastic materials can return to their original shape to a certain rate after removing the mold loads. Because of the SB issue and adverse effects, common metals treated with SMF might not match dimensional tolerances. Thus, they need additional types of processing and modifications. As a result, this can sure contribute to extra production cost and time (Liu *et al.*, ٢٠١٧).

To achieve the significant requirements linked to the critical needs for lightweight metals with sophisticated geometrical characteristics, enabling their flexible exploitation in automobile, aircraft, and ship manufacturing disciplines, diversified categories of SB-related indices and variable are crucial to inspect (Wu, ١٩٩٦).

٢. Short Literature Review

The SB effect was explored by conducting experimental comparisons with finite element analysis (FEA) of U-shape forming testing outcomes. A mild steel JSC٢٧٠C and dual phase steel (DP) steels JSC٥٩٠R and JSC٧٨٠Y with variant mechanical strengths were introduced. Relying on the experimental and numerical works, it was found that all material models frameworks had limited SB effect among the examined steel specimens. However, the Yoshida–Uemori model provided remarkable scales of accuracy. Simultaneously, higher-strength steel strain recovery could be best expressed by the model. Nonetheless, careful identification of the model's variables is essential. Researchers found that cyclic testing could precisely express corresponding kinematics linked to the material (Chongthairungruang *et al.*, ٢٠١٣).

Krasovskyy *et al.* (٢٠٠٦) proposed a novel experimental-numerical strategy to perform an accurate prediction of SB behavior of steel when it is processed in SMF. Stress-strain curves from tension-compression tests were figured out to obtain a collection of critical material properties. During the implementation of these tests, a special rig was exploited to prevent any buckling of the specimen during the compression process. Their SB behavior prediction strategy has shown its considerable effectiveness and practicality in providing noteworthy data and core information on the steel behavior under tensile and compressive loadings needed in the context of SMF. On the other hand, texture mathematical simulations have also proved their feasibility in identifying imperative indices and data concerning SB phenomena occurring in the steel subjected to SMF loads.

Similarly, experimental and numerical analyses of a rail part prone to wrinkling and ٢D SB was explored by Neto *et al.* (٢٠١٧). The two research approaches applied by the researchers revealed that the blank's material and numerical model symmetry conditions could strongly affect wrinkling. Moreover, it was found from the mathematical simulation procedures that the numerical outcomes have greatly matched the experimental findings. The acquisition of critical data would be better when considering overall variables of the blank model. Also, it was discovered that the numerical simulation procedures relying on the full blank model would be much more computationally expensive than using one-fourth of the blank model.

Cheraghi *et al.* (٢٠٢١) explored SB issue referring to a U-form die by a stretch bending testing on st١٢ steels in a laboratory. Critical SB variables, including die radius, pin diameters, blank holding force (BHF), and pin distance have been estimated. The stretching depth was defined to be ١٠ mm. From the laboratory analysis, it was discovered that different geometric and technical variables would have significant effects on the SB occurrence. Also, it was found that a rise in the die radius, pin diameters, and blank holder force would contribute to a reduction in the SB issue. A similar aspect would be noted when increasing pin spacing, which caused SB observation to spring-go. Figure ١ shows the SBP rate for different BHF, Rd=١٠ mm and h=٢٠ mm.

Another research has proved that with the increasing exploitation and utilization of advanced high-strength steels and lightweight metal alloys, the prevalence of the SB issue has been exponentially magnified, especially in the SMF process design according to Slota *et al.* (٢٠١٣). Those researchers forecasted how die radius value would affect the steel SB occurrence. They estimated the variation in the SB angle after implementing the first and second cycles. It was realized that Bauschinger effect has caused the SB angle to change between the two cycles. This process was numerically and experimentally examined. The static implicit FEA code Autoform was exploited for their numerical analysis.

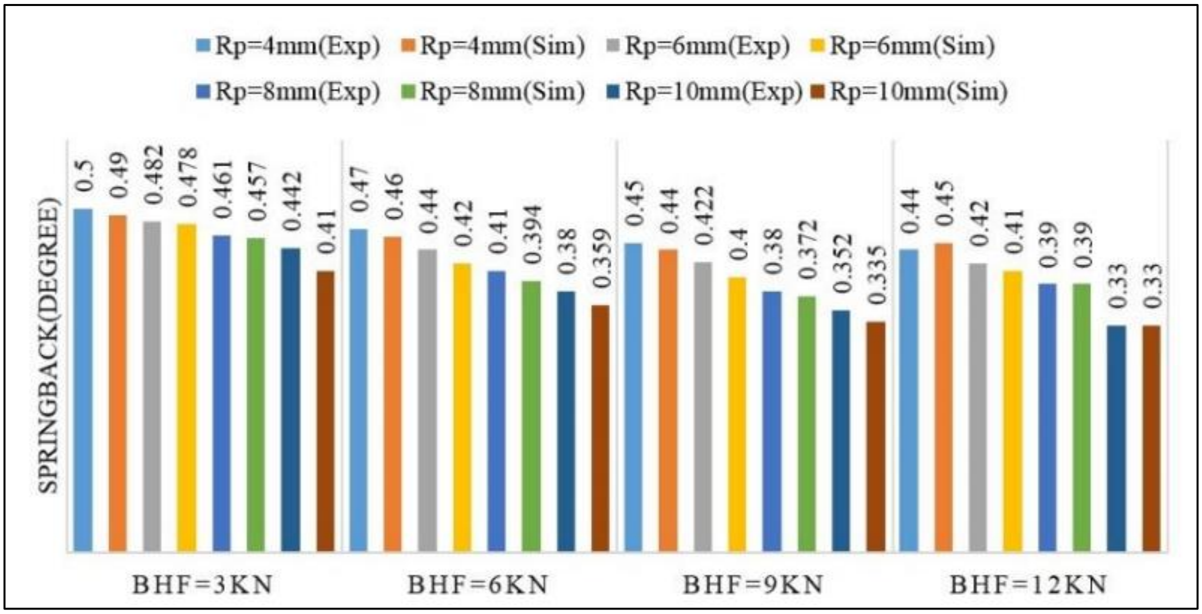


Figure ١. The SBP rate for different BHF, Rd=١٠ mm and h=٢٠ mm (Cheraghi *et al.*, ٢٠٢١).

Figure ٢ displays the experimental device prepared and harnessed to identify the SB angle.

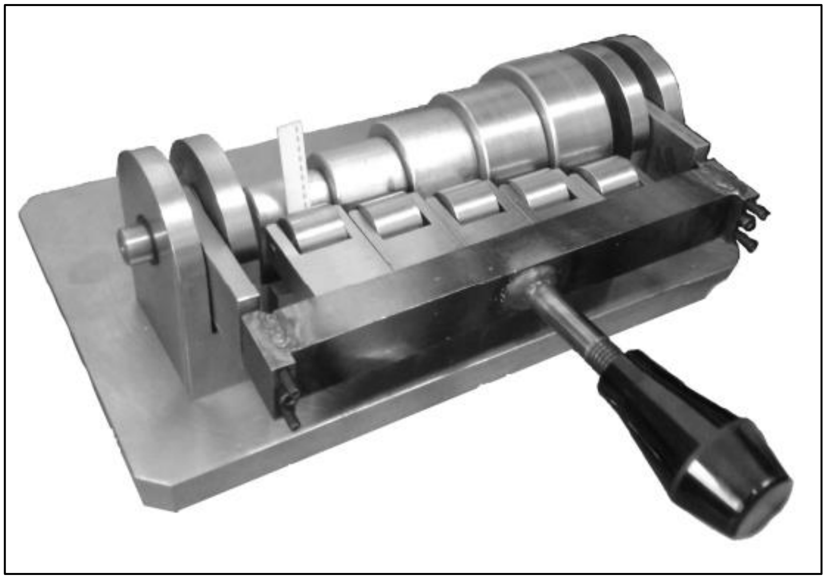


Figure ٢. The experimental device for determination of the SBP angle (Slota *et al.*, ٢٠١٣).

Özdemir (٢٠٢٠) explored the SB issue existing in the DP-٦٠٠ steel sheet when it is subjected to SMF loads relying on an air V-mold bending test. Four punch tip radii and four sheet thicknesses were exploited and studied as major bending variables. Corresponding comparisons were conducted between experimental rates of SB observations. Response Surface Method (RSM) and Taguchi (L١٦) orthogonal array were harnessed to make necessary analysis of the obtained experimental data. In addition, mathematical simulations were utilized. Relying on the two primary data collection approaches, it was found that experimental outcomes have matched with those obtained from the numerical simulation procedures. In addition, optimum values of the variables that affect the SB behavior of the steel have been identified referring to the signal-to-noise ratio (SNR). Besides, the optimal bending index combination was estimated. Relevant data analytical processes utilized the SNR and crucial design of experiment (DOE) framework. Finally, major indices and variables that affected the SB pattern in the steel under the V-mold bending test were categorized.

According to Shukla and Gautam (٢٠١٤), SB phenomena, which expresses an elastic recovery during unloading, is remarkably sensitive to SMF phases and processes, which could cause geometric changes in the end-product. Variant factors could affect the bend angle and the bend curvature. The effects of anisotropy—the rolling direction of ٠°, ٤٥°, and ٩٠°—of ultra-low carbon steel Interstitial Free (IF) Steel in V-mold bending with ٧,٥ mm punch corner radii were estimated by experimental procedures and numerical simulations. Major experimental outcomes and FEA simulation results were compared and found to be remarkably similar. Figure ٣ indicates the major sample size and dimensions according to ASTM E٨M-٠٤ tested in UTM.

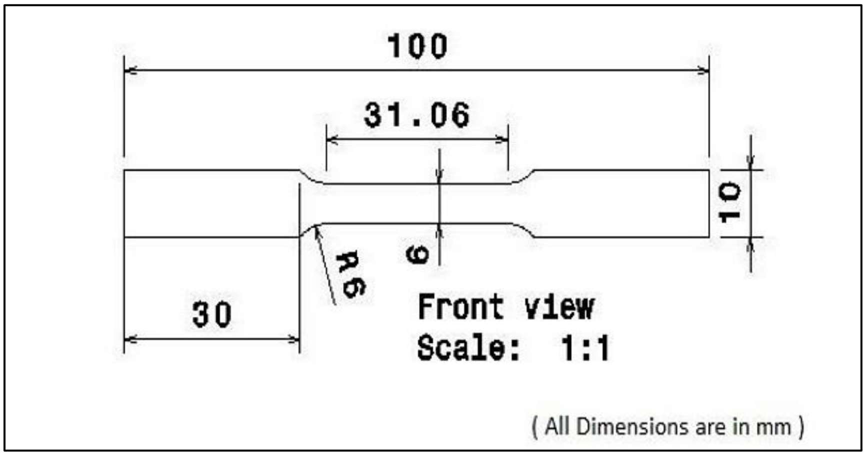


Figure ٣. The major sample size and dimensions according to ASTM E٨M-٠٤ tested in UTM (Shukla and Gautam, ٢٠١٤).

As a whole, it can be noticed from the reviewed research publications and experimental and numerical studies that the SB issue has been increasingly recorded in various manufacturing fields and factories, which handle majorly SMF. To introduce the reduction and control of this issue, scholars and mechanical engineers conducted diversified investigations through laboratory works and mathematical simulations to examine and figure out the critical reasons of this problem, aiming to alleviate its frequency and prevalence in manufacturing. Most of the research inspections revealed that a number of geometric and technical variables and indices, like the punch radius, bend angle, mold shape, type of the metal, die radius, pin diameter, and other factors would influence the elastic recovery and metal's response and behavior to the SB issue.

In conclusion, the experimental research of this article is implemented to bridge a knowledge gap, explained in section ٣.

Primary laboratory experimental data collection and analysis are adopted to supply necessary significant insights and crucial observations regarding the behavior of SP issue in three heavily exploited metals in the manufacturing context (Katre *et al.*, ٢٠١٥; Broggiato, ٢٠١٢).

The sequence of this research can be explained in the following:

- **Section ٣** expresses the article’s **materials and methods**,
- **Section ٤** shows the paper’s **major experimental data collection and analysis phases**,
- **Section ٥** expresses the **main study outputs**,
- **Section ٦** indicates the research’s **conclusions** obtained from the substantial experimental laboratory work,
- **Section ٧** gives a number of **future work directions**.

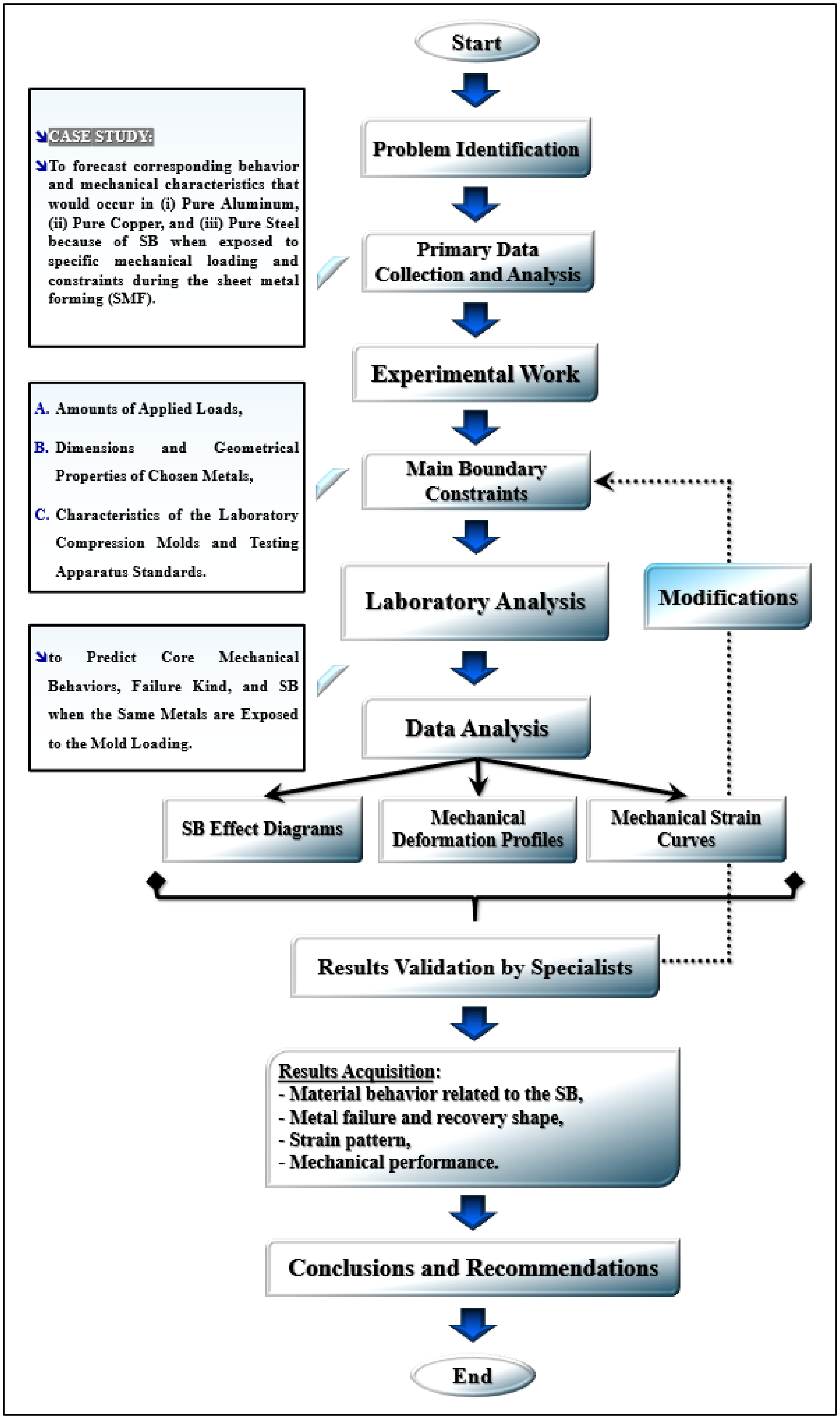
٣. Materials and Methods

As explained earlier, this study is carried out, aiming to bridge a research void translated in the need for extra experimental works, laboratory investigations, and practical estimations on the SB behavior of steel, aluminum, and copper, which are extensively exploited in different manufacturing fields when subjected to SMF processes. The provision of imperative information concerning the SB behavior of these metals is crucial to make sure that vehicles, ships, and aircrafts would have better aerodynamic performance, and sheet metals would resist various scenarios of failure, stresses, friction, and drag forces after they show ultimate scales of stability when exposed to SMF phases.

It is expected from implementing the experimental study in this paper at the mechanical engineering laboratories of The University of Babylon that the experimental results could provide sufficient answers to the following research questions, which can be expressed in the following:

- What are the significant indices, factors, and variables that largely influence the occurrence of SB issue in steel, aluminum, and copper?
- Referring to the experimental laboratory work, what may be the best approaches that can be implemented to alleviate the SB issue in these metals while they are subjected to SMF processes?
- Which metals among the three commonly utilized ones (Fe, Al, and Cu) would exhibit remarkable scales of stability and elastic recovery to their original shapes after removing mold loads?
- Which metal of these three metals would have more distortions that may create many vibrations, noise, and mechanical deformations?

The major experimental work procedures and stages across which this study will pass can be expressed in Figure ٤.



CASE STUDY:

To forecast corresponding behavior and mechanical characteristics that would occur in (i) Pure Aluminum, (ii) Pure Copper, and (iii) Pure Steel because of SB when exposed to specific mechanical loading and constraints during the sheet metal forming (SMF).

A. Amounts of Applied Loads,

B. Dimensions and Geometrical Properties of Chosen Metals,

C. Characteristics of the Laboratory Compression Molds and Testing Apparatus Standards.

to Predict Core Mechanical Behaviors, Failure Kind, and SB when the Same Metals are Exposed to the Mold Loading.

Results Acquisition:
- Material behavior related to the SB,
- Metal failure and recovery shape,
- Strain pattern,
- Mechanical performance.

Figure ٤. The experimental study stages flowchart linked to this paper (The scholar, ٢٠٢٤).

Laboratory experimental analysis includes a collection of crucial estimation activities and investigation tasks that are referred to international codes and testing standards to reach reliable outcomes that can be exploited by other researchers. Relevant variables and indices with their valid rates and optimum values are identified in the boundary conditions part. The specimens are carefully prepared, tested, and the corresponding experimental data and outcomes are obtained and recorded, aiming to provide sufficient potential of data analysis and resilient findings that can be reliable for further future works.

٤. Experimental Data Collection and Analysis Phases

٤,١ Specimens and Apparatus Preparation

To achieve the critical experimental research objectives and laboratory work, the first stages of this study were considered by preparing the fundamental specimens and their corresponding dimensions according to the the American Society of Testing Materials (ASTM) standards and values to facilitate implementing the relevant mechanical tests, including mechanical tensile stress tests, compressive stress tests, bending tests, and strain evaluations. The necessary shapes, and designs of the samples under the standard dimensions and geometric forms needed to be examined in the laboratory are prepared and formulated. Figure ٥ indicates the standard dimensions of the three specimens that need to be examined experimentally.

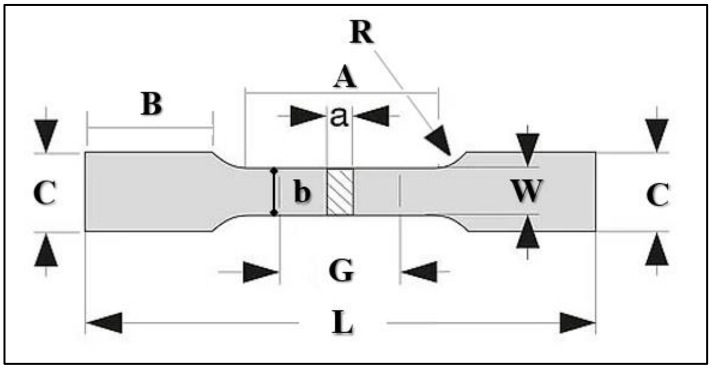


Figure ٥. The standard dimensions of the three specimens examined experimentally.

The values of the symbols shown in Figure ٥ can be explained in Table ١.

Table ١. Major dimensions of the specimen according to the ASTM standards.

Item	Maximum Dimension (mm)	Minimum Dimension (mm)
G	٥٠	٢٥
W	١٢,٥	٦,٢٥
T	٥ to ١٩	٠ to ٦
R	١٣	٦
L	٢٠٠	١٠٠
A	٦٠	٣٢
B	٥٠	٣٢
C	٢٠	١٠

For each metal, two specimens have been prepared to provide extra validation. The overall prepared specimens can be displayed in Figure ٦.

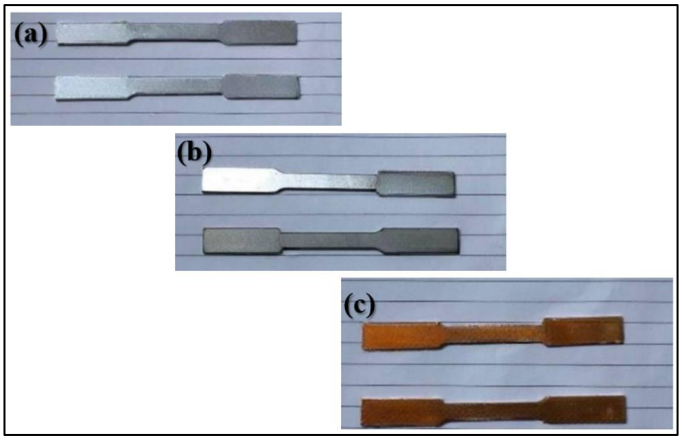


Figure ٦. The experimental samples of the three metals; (a) steel, (b) aluminum, and (c) copper.

In addition, nine plates with three major thicknesses (٢،٠ mm, ٣،٥ mm, and ٤،٠ mm) have been prepared to examine the effect of the bending force and the emergence of the SB issue in this situation. These plates can be shown in Figure ٧.

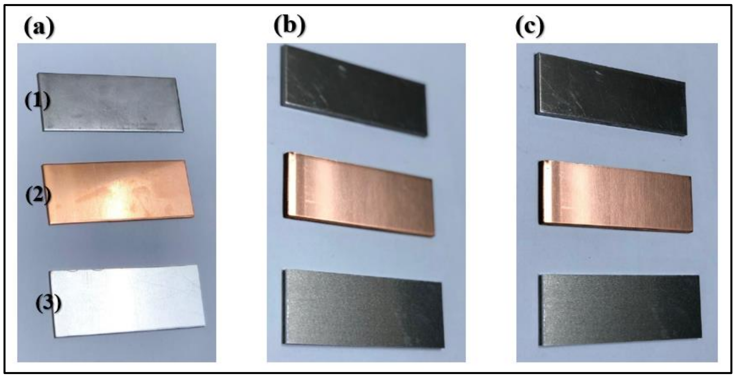


Figure ٧. The three metals examined in the laboratory work; (١) steel, (٢) copper, and (٣) aluminum with thicknesses of (a) ٢،٠ mm, (b) ٣،٥ mm, and (c) ٤،٠ mm.

After preparing these specimens, the main molds of the experimental work are utilized. Figure ٨ shows typical shapes of molds exploited in the experimental study.

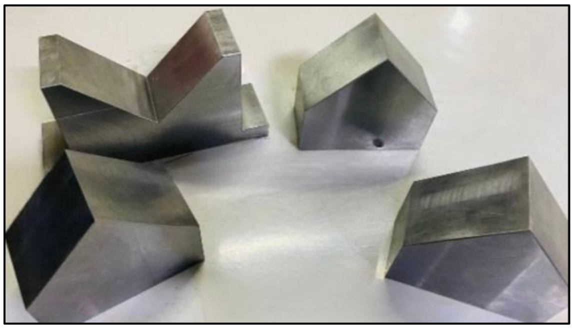


Figure ٨. Different shapes of molds utilized in the experiment.

Figure ٩ illustrates the kinds of the punch and the die of the molds in the experiment.

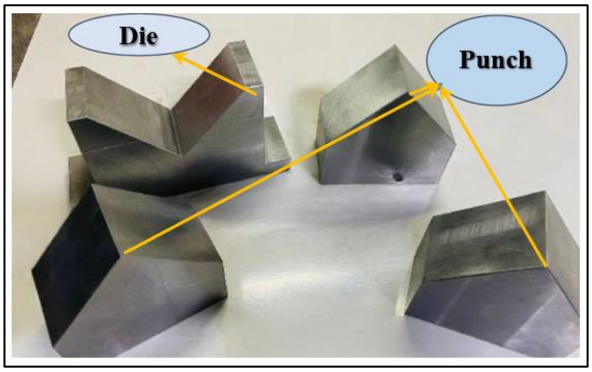


Figure ٩. The punch and die in the bending molds.

Moreover, Figure ١٠ displays the profile resulted when the V-shaped mold is completely applied.

Figure ١٠. The kind of the mold profile when the V-mold is completely applied.

As explained earlier, referring to these prepared specimens and molds, experimental forces are applied on those metals with specific dimensions until SB is realized. A collection of mechanical tests and analytical tasks are followed to confirm the occurrence of the SB issue in those metals, which do consist of tensile test, bending test, strain evaluation, and other critical mechanical tests to examine corresponding variables and indices that can predict the SB behavior in these three metals.

The SB behavior is related, majorly, to the metals' trend and tendency to change and recover to their original state, or save some/ all properties related to SB. The loading is applied with significant magnitude (in terms of kN) with time. Mold load is applied repetitively with higher frequencies/ iterations across the time. This aspect can help make more validation and emergence of the SB observation among the investigated metals under different loading conditions.

Also, extreme conditions of SB issue are explored by exposing the load to numerous number of mold fatigues and compression loads shortly to predict when SB could occur and what corresponding compression stress, strain, and deformation rates are. Bending tests are applied with a rate of ٥ mm/ min. Multiple iterations are applied until the specimen failure is realized and recorded. As a clarification, Figure ١١ displays the compression test apparatus.

Figure ١١. The compression test apparatus.

Also, Figure ١٢ indicates the tensile testing apparatus harnessed to uncover the SB behavior in the three investigated metals.

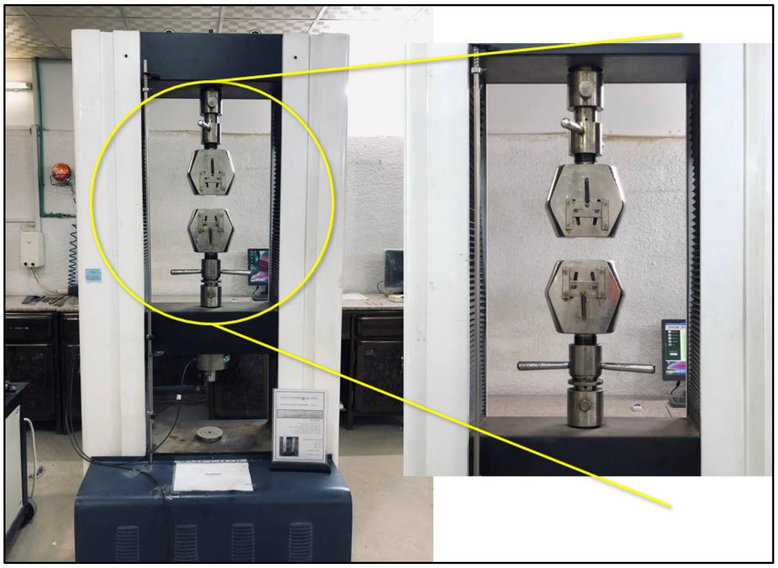


Figure ١٢. The corresponding tensile test apparatus utilized in the experimental work.

٤,٢ Main Mechanical Characteristics Linked to the Three Inspected Metals

The experimental inspection is performed to explore the SB behavior among the three heavily exploited metals (Fe, Al, and Cu). Table ٢ provides a summary of main mechanical properties of those three metals. The identified values of those mechanical features are considered in the experimental analysis.

Table ٢. Imperative mechanical and physical characteristics of the three explored metals.

No.	Physical and Mechanical Properties	Name of the Metal		
		Pure Steel	Pure Aluminum	Pure Copper
١	**Color**	Gray	Silvery-White	Red-Orange
٢	**Density**	٧,٨٥٠ kg/m^{٣}	٢,٧٠٠ kg/m^{٣}	٨,٩٢٠ kg/m^{٣}
٣	**Tensile Strength**	٤٢٠ MPa	٩٠ MPa	٢٠٠ to ٣٦٠ MPa
٤	**Young’s Modulus/ Modulus of Elasticity**	٢٠٠ GPa	٦٨ GPa	١٢٠ GPa
٥	**Shear Modulus**	٨٠ GPa	٢٥ GPa	٤٤ Gpa
٦	**Poisson’s Ratio**	٠,٢٥	٠,٣٦	٠,٣٥
٧	**Melting Temperature Point**	١,٢٠٥ °C to ١,٣٧٠ °C	٦٦٠ °C	١,٠٨٣ °C
٨	**Thermal Conductivity**	٤٤ to ٥٢ W/m.K	٢٣٧ W/m.K	٢٦٠ W/m.K
٩	**Vickers Hardness**	١٢٦ HV	١٥٠ to ١٦٠ HV	٤٠ to ١١٠ HV

٥. Critical Experimental Outputs

٥,١ Experimental Results of the SB Ratio

In this part, the elastic recovery ratio after removing the load and after deformations take place are recorded for the three inspected metals. Each one has three thicknesses. Thus, nine curves are obtained, which are three for each metal. Figure ١٣ indicates the SB behavior of the steel among its three specimens of thicknesses ٢,٠ mm, ٣,٥ mm, and ٤,٠ mm.

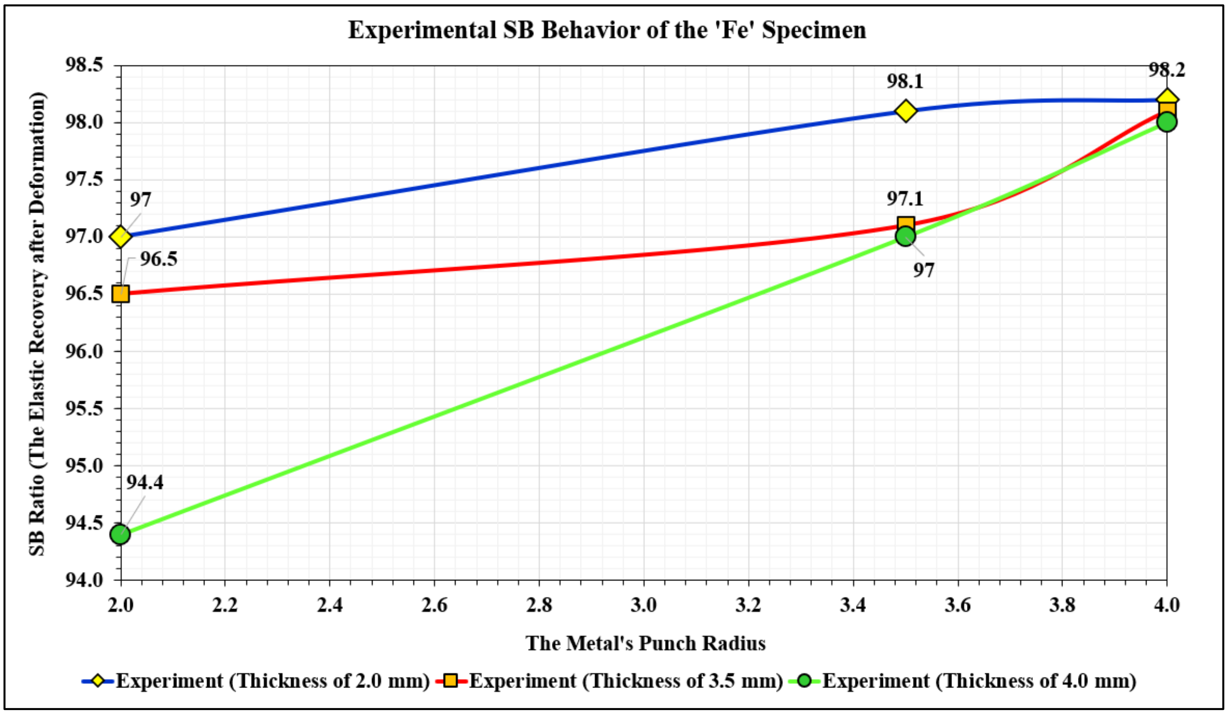


Figure ١٣. The experimental results of the SB ratio among the three steel specimens.

It can be concluded from Figure ١٣ that the steel specimen with a thickness of ٢,٠ mm did contribute to the larger SB rate (or remarkably significant elastic recovery after deformation), followed by steel specimen of thickness ٣,٥ mm, and ٤,٠ mm. Thus, it can be inferred that steel would exhibit substantial elastic recovery and higher SB percentage when its thickness would be lower.

Figure ١٤ displays the experimental results of the SB ratio among the three aluminum specimens with three thicknesses.

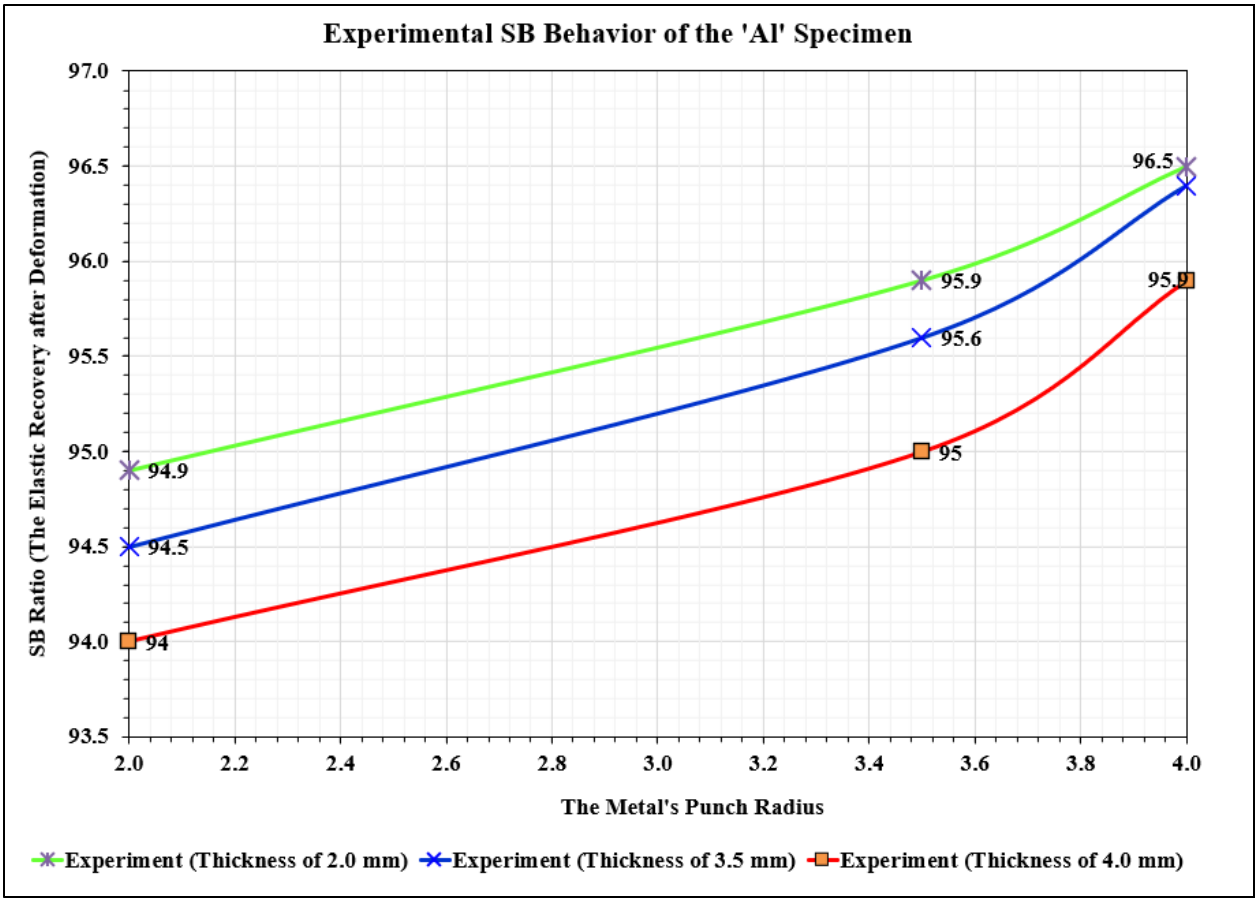


Figure ١٤. The experimental results of the SB ratio among the three aluminum specimens.

It can be understood from Figure ١٤ that aluminum specimens with higher thicknesses did exhibit lower SB ratios, i.e., lower elastic recovery after deformation. Thus, it can be concluded that aluminum sheets with lower thicknesses, which approximate ٢,٠ mm would provide more stable SB behavior as their elastic recovery ratio would be larger.

Similarly, Figure ١٥ shows the experimental results of the SB ratio among the three copper specimens.

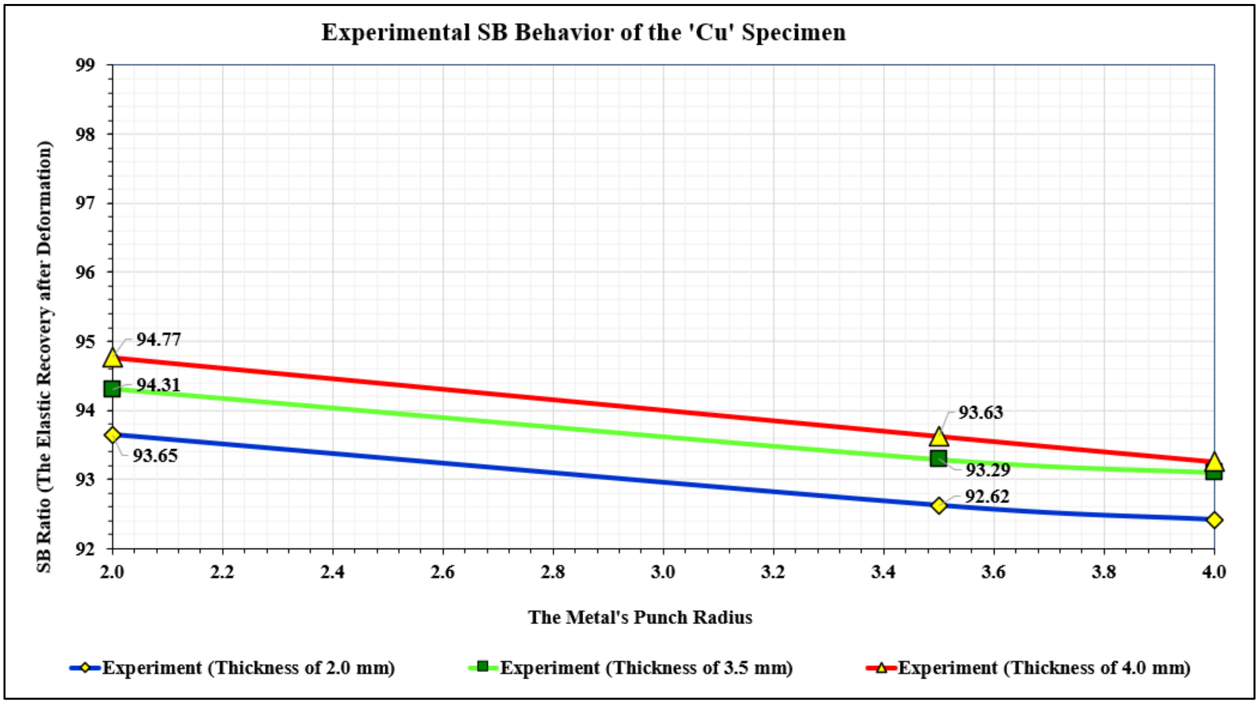


Figure ١٥. The experimental results of the SB ratio among the three copper specimens.

It can be realized from Figure ١٥ that, opposite to steel and aluminum, the copper specimens with higher thicknesses (like ٤,٠ mm) did exhibit larger elastic recovery percentage (or remarkably stable SB behavior) compared with copper specimens that have lower thicknesses (٣,٥ mm and ٢,٠ mm). Thus, it can be inferred that the copper thickness should be raised when SMF is implemented compared with steel and aluminum.

٥,٣ Comparative Analysis of the SBP between the Three Metals

To provide a tactic of comparison, enabling a better interpretation and understanding regarding which metal among the three did exhibit the best elastic recovery ratio and offered the best SB stability under mold loading, a comparative analysis was created in a single diagram that combines the SB behavior of the three metals. Figure ١٦ explains the ratio of the SB behavior (or the elastic recovery percentage) among the three metals with a thickness of ٢,٠ mm.

It can be concluded from Figure ١٦ that, in terms of better elastic recovery ratio achieved after deformation (or enhanced SB behavior), the steel specimens did consistently provide the best percentages of this index compared with the two metals.

Copper did follow the steel by higher elastic recovery ratio. Thus, the three aluminum specimens have the lowest elastic recovery and lower SB stability. For this reason, careful considerations of aluminum thickness estimations and identifications should be taken into account to avoid mechanical distortions, harmful SB behavior, and very low percentages of elastic recovery after deformations.

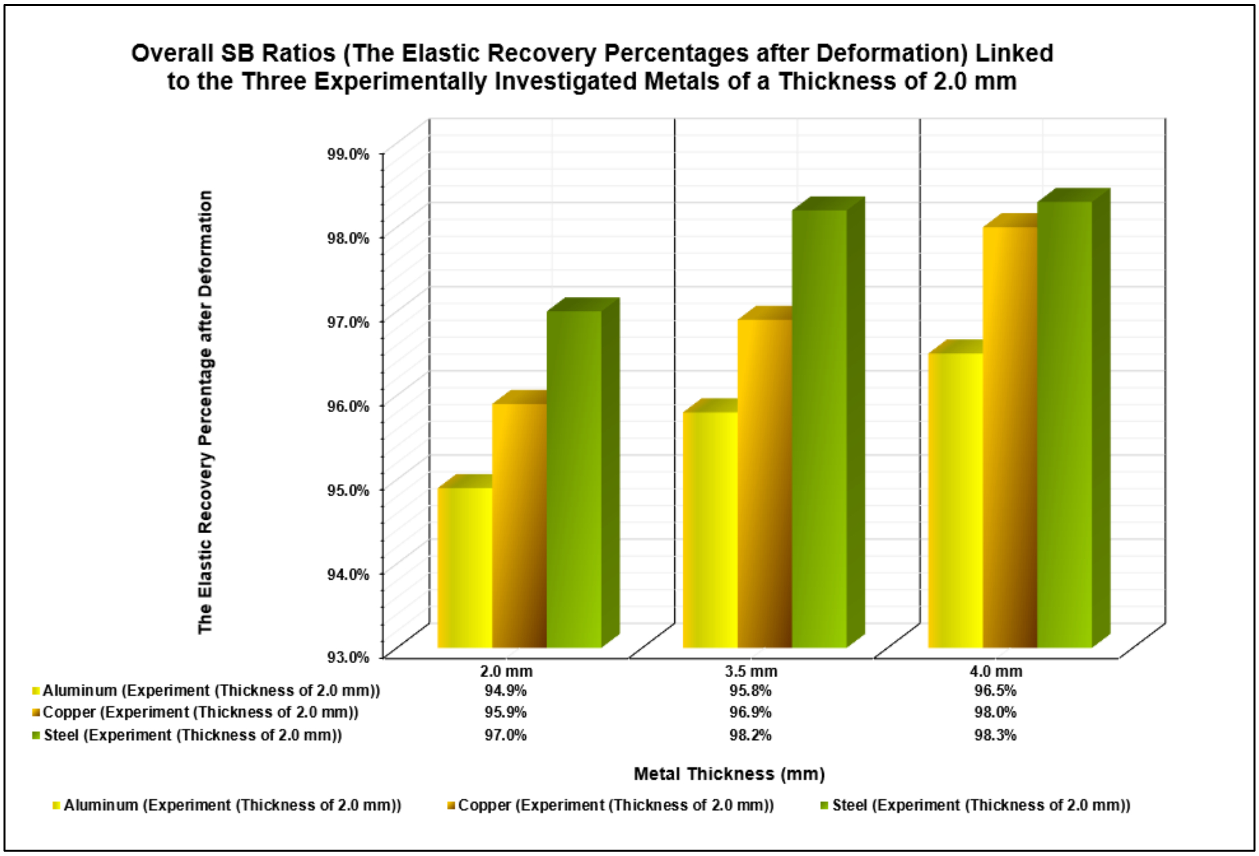


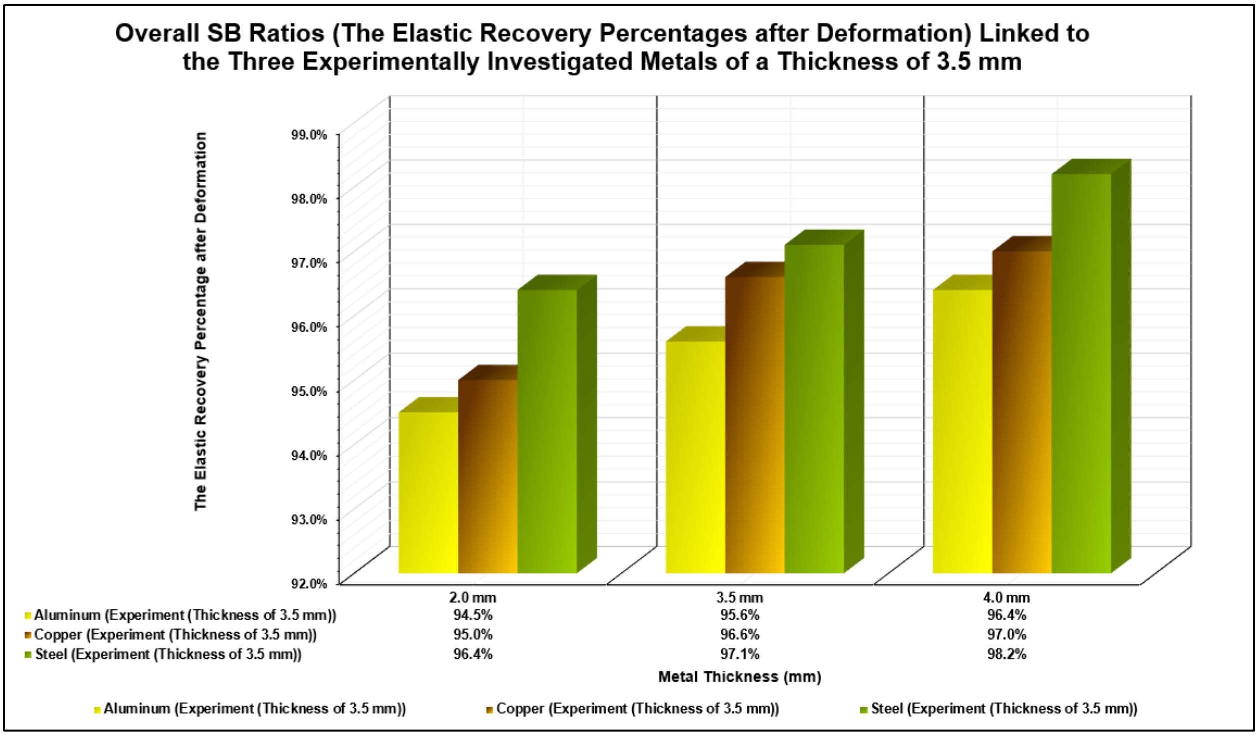
Figure ١٦. The SB behavior (the elastic recovery ratio) of the three metals of ٢,٠ mm thickness.

At the same instant, Figure ١٧ displays the SB behavior (or the elastic recovery ratios) of the three metals of ٣,٥ mm thickness.

It can be concluded from Figure ١٧ that, similar to the SB behavior and comparison of elastic recovery ratios among the three metals expressed in Figure ١٦, the steel specimens again did consistently exhibit the largest elastic recovery percentages, considering the three thicknesses.

It is followed by the copper, which does also have remarkably stable SB pattern than aluminum.

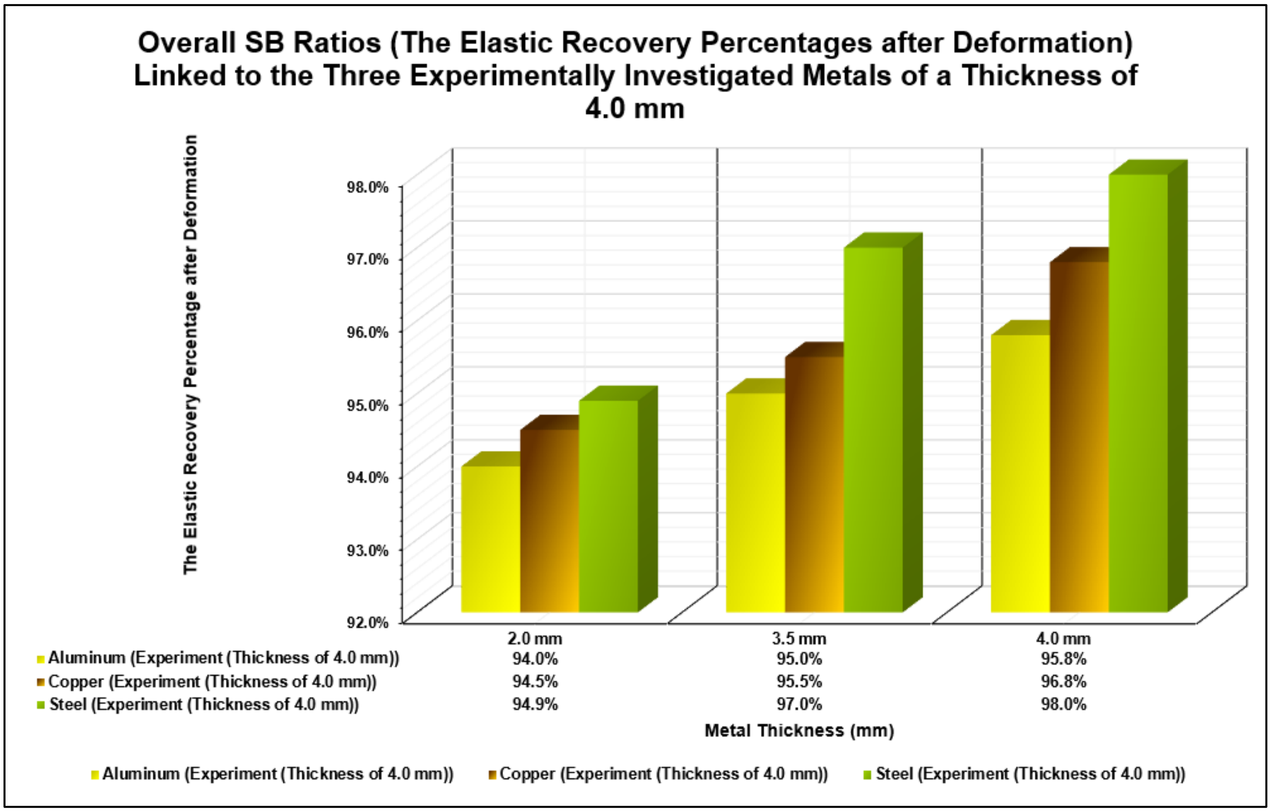
Thus, it can be inferred, another time, that careful considerations should be introduced when SMF is implemented for aluminum due to its poorer SB behavior compared with steel and copper.



	2.0 mm	3.5 mm	4.0 mm
Aluminum (Experiment (Thickness of 3.5 mm))	94.5%	95.6%	96.4%
Copper (Experiment (Thickness of 3.5 mm))	95.0%	96.6%	97.0%
Steel (Experiment (Thickness of 3.5 mm))	96.4%	97.1%	98.2%

Figure ١٧. The SB (the elastic recovery ratio) of the three metals of ٣,٥ mm thickness.

Figure ١٨ shows the SBP/ the elastic recovery ratio of the ٤,٠ mm-thickness metals.



	2.0 mm	3.5 mm	4.0 mm
Aluminum (Experiment (Thickness of 4.0 mm))	94.0%	95.0%	95.8%
Copper (Experiment (Thickness of 4.0 mm))	94.5%	95.5%	96.8%
Steel (Experiment (Thickness of 4.0 mm))	94.9%	97.0%	98.0%

Figure ١٨. The SBP (the elastic recovery ratio) of the three metals of ٤,٠ mm thickness.

It can be understood from Figure ١٨ that the steel did again prove its potential in offering ultimate scales of elastic recovery proportions compared with the two metals across all thicknesses. Copper follows the steel in terms of stable BP behavior and good values of elastic recovery ratios after deformation. As aluminum has the lowest rates of elastic recovery, it is advised, as explained above, to giver additional considerations of thickness and other properties when SMF is applied.

٦. Discussion

٦,١ *The Effect of Punch Radius on SB Behavior*

From the overall experimental work conducted in this article, a conclusion can be reached regarding the impact of punch radius on the SB behavior or the percentage of the elastic recovery in the metal after removing the deformation and the load.

It can be said that both steel and aluminum did exhibit larger elastic recovery, i.e., remarkably stable SB behavior with the rise of the punch radius of the metal. In contrast, copper's SB stability and elastic recovery did lessen with the rise in the punch radius. More specifically, copper with smaller and larger thicknesses (٢,٠ mm, ٣,٥ mm, and ٤,٠ mm) exhibited in the three situations lower SB stability, which contributes to less elastic recovery percentage after removing deformations/ loads.

Comparatively, steel and aluminum specimens had higher elastic recovery proportions with the rise in the punch radius. It is also noted that lower metal thickness, i.e., ٢,٠ mm did correspond to higher elastic recovery ratio compared with the two thicknesses ٣,٥ mm and ٤,٠ mm.

As an illustration, the SB behavior would rely on the volume of the plastic deformation area. Lower punch radius values could help concentrate the pressure force within a narrow zone, contributing to larger local stresses and considerably plastic deformations. When the punch radius rises, the force can spread to a large plastic regions. Thus, the SB behavior and elastic recovery percentage would increase.

Simply speaking, when the punch radius rises, the contact angle and contact region would increase. As a result, the SB phenomenon could contribute to extra friction in the surface between the punch and the sheet. Thus, it can be obvious that SB behavior and elastic recovery percentages would upgrade with raising the punch radius. Steel and copper did exhibit larger elastic recovery ratios after removing the mold load than aluminum through all thicknesses. This can occur due to larger punch radii linked to the contact region between the punch and the sheet that would become greater. Therefore, the bending moment would rise, resulting in a larger SB angle.

The outcomes obtained from this experimental analysis are consistent with Slota *et al.* (٢٠١٣), who examined carefully the effect of the metal's dimension, mainly the die radius variation on the steel SB behavior. They examined the SB profile that would change, considering the SB angle after implementing the first and second load cycles. Also, they noticed that Bauschinger impact caused the SB angle to variate between the two load cycles. The major investigated metal in their experimental and numerical work were high-strength steel and lightweight alloys.

These results are also compatible with the outcomes of Cheraghi *et al.* (٢٠٢١), who also considered the investigation of SB issue in st١٢ steels, taking into consideration various values of punch radius (which were ٤,٠ mm, ٦,٠ mm, ٨,٠ mm, and ١٠ mm). They found that a rise in the die radius, pin diameters, and blank holder force would contribute to a reduction in the SB issue. A similar aspect would be noted when increasing pin spacing, which caused SB observation to spring-go.

٦,٢ *Influence of the Type of the Sheet Metal*

From the experimental investigations, it was realized that the three sheet metals with the three thicknesses, ٢ mm, ٣,٥ mm, and ٤ mm exhibited to various SB behavior referring to the type of the inspected metal.

To explain, it was discovered that the steel had the highest SB stability and it did have the largest elastic recovery percentage compared with copper, which is followed by aluminum, respectively. After removing the loads; and thus deformations, steel did record in all three thicknesses the largest values of elastic recovery ratios.

To provide some insights on these observations, the correlation between the SB behavior and metal properties was noted to have some remarkable impacts on the materials' applicability for active production objectives. For ductile materials, the SB behavior is much lower than in hard metals, with a reliance on the modulus of elasticity of the material.

The scale of the SB pattern would rise with larger yield strength metals. For example, steel, copper, and aluminum would exhibit different ranges of SB properties. The attained analytical outcomes of SB radius linked to wiping die bending sheet metal can be considered different in these three metals. The aluminum has lower ratios of elastic recovery/ SB than the steel and copper. When the SB bending radius would rise, the material would show remarkable SB compared with the lower bending radius.

As a whole, a conclusion can be attained that the SB behavior would reduce values from steel, to copper, and to aluminum.

These findings are equal to the results of Özdemir (٢٠٢٠), who exploited experimental analysis with V-shaped bending molds to examine the SB behavior in DP٦٠٠ steel. The author found that with the rise of the punch radius, the SB behavior would increase. Also, when the sheet metal thickness increases in DP٦٠٠ steel, it was noted that the SB behavior reduce. The authors discovered that the variable that had the most largest effect on the SB behavior in the steel was the sheet thickness (contributing to ٧٨,٠٢٪), followed by the punch radius (١٥,٨٪).

Besides, the results regarding the effect of the sheet metal type were consistent with the mathematical simulation outcomes of Lafta *et al*. (٢٠٢٠), who found that Al die face and Cu punch face setting situations did experience smaller SB behavior and elastic recovery ratios. Their corresponding outcomes did confirm that SB behavior is affected by the punch radius, die radius, and sheet thickness, relying on V-shape mold bending forces.

٧. Conclusions

This study was implemented to distinguish the impact of a collection of geometric indices and mechanical variables of three common metals (steel, aluminum, and copper) on their SB behavior and the percentage of elastic recovery after the load; and thus, the deformations are removed. To achieve the study goal, an experimental approach was adopted through which corresponding metal specimens and metal sheets were prepared to be inspected relying on standard apparatus and testing machines. V-shape molds were exploited. Tensile stress, compressive stress, deformations, and strain rates were examined. Referring to the primary experimental data collection, the overall study results can be summarized in the following points:

A- The SB value (elastic recovery proportion) would rise after removing the applied mold loading as the punch die radius increases in steel and aluminum. But in copper, the rise in the punch radius would lessen the elastic recovery ratio. It relies on the volume of the plastic deformation region,
B- A punch with a smaller radius can concentrate the compressive force in a narrow volume, contributing to higher local stress and remarkably plastic deformation. As the punch radius rises, the force could spread to larger plastic volume. Thus, the elastic recovery ratio would rise,
C- As the punch radius rises, the contact angle and contact region would raise. Thus, the SB issue can create additional friction in the surface between the punch and the sheet.
D- SB ratios would rise with increasing the punch radius. Steel and copper exhibit larger elastic recovery ratios after removing the mold load than aluminum through all thicknesses.
E- Larger punch radii of the contact area between the punch and the sheet would become greater. As a result, the bending moment would rise, resulting in a large SB angle,
F- For ductile metals, the SBP ratio would be much lower than in hard metals, referring to their modulus of elasticity,
G- The amount of elastic recovery can rise with greater yield strength in metals. Steel, copper, and aluminum and could exhibit different ranges of SBP characteristics,
H- The aluminum has lower ratios of SBP/ elastic recovery portion than steel and copper. When the SBP bending radius increases, the metal would show remarkably stability of the SB behavior than the lower bend radius.

CRediT Authorship Contribution Statement:

Elham: Data Analysis, Writing, Experimental Analysis, Conceptualization, Review and Editing, Mechanical Engineering, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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