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Selection of Optimal Bending Types in Die Process of L-Shaped Panels Considering the Springback Behaviours

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ABSTRACT
In die design, one of the most crucial decisions is selecting the appropriate die process to produce panels. The challenge for die designers is to understand the behaviour of the panel material in relation to the die processes. If the die process is not correctly determined before die fabrication, severe panel spring back may occur, which can be difficult and require additional time and effort to rectify. This paper presents research aimed at understanding the behaviour of different bending process combinations concerning springback occurrence during the stamping process of an L-shaped design intent panel. Using simulation and experimentation, three types of materials with different tensile properties 270 MPa, 440 MPa and 590 MPa with the similar thickness of 1.8 mm, were selected. The results were compared, analysed and optimized using Response Surface Methodology (RSM). The findings demonstrate that one-process bending with full bending (compress type) approach is the most suitable for producing L-shaped panels from the three material types. The study provides guidelines for die design engineers, industrial practitioners and researchers to decide on the best approach for die process decisions when dealing with specific panels properties, shape and thickness.

Keywords: Springback, Die Process, Bending, L-shaped

1 INTRODUCTION

Die manufacturing is a crucial industry worldwide, which cover a broad range of activities, including acquisition, design, work preparation, mechanical manufacturing, assembly and try-out [24]. It is an integral part of the sheet metal stamping industry, widely recognized for its ability to produce diverse shapes and parts [23]. Die manufacturing applications can be found in various industrial sectors, such as the automobile, aerospace, and defense sectors, due to its cost-effectiveness and ability to yield high-quality surfaces [1].

The design and manufacturing of dies and molds are critical links to the entire production chain, as most customized products require die or mold for their manufacturing. The quality of the dies and molds directly affects the quality of the produced parts [2]. Despite its long-established presence, the die manufacturing process requires careful study to avoid any mistakes that could impact project completion duration, quality standards and delivery schedules. Stamping technology is essential for improving product efficiency [30]. During the sheet metal stamping process, the shape undergoes permanent deformation, as it is formed beyond the material's yield point [26]. This process involves applying strain to flat panel material around a linear axis in forms like L, U, or V bending [1]. To achieve successful outcomes, it is essential to precisely control the parameters—such as material, design, tribological aspects, and lubrication [23]. The die punch and die are intersecting with the material's yield point during bending and causing the panel material to retains it bent shape, unable to return to its initial form. This bending deviation becomes a permanent feature of the manufactured panel, emphasizing the criticality of tightly controlled stamping parameters [26].

In recent years, the availability of CAD (Computer Aided Design) and Computer Aided Manufacturing (CAM) software has enabled the development of complex surface geometries for panels, elevating the importance of shape

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and stamping tolerance control [9]. However, despite advancements, the design of die processes, particularly in multi-stage stamping, still heavily relies on experience and industrial knowledge [20]. Creating a suitable die design for achieving the desired shape remains challenging, largely due to the issue of springback [11]. Many researchers are addressing the springback issues related to stamping [17]. Therefore, determining the optimal combination of die processes to minimize the springback occurrence is critical

Springback is considered undesirable as it can compromise panel accuracy, increase panel rejection costs and escalate overall manufacturing expenses [4]. Due to elastic deformation, the panel tends to springback when the tools are removed from the die sets [3]. An additional challenge linked to springback is the growing trend of using high-strength steel in sheet metal stamping, particularly in automotive applications. This material often presents shape deviation issues that are challenging to troubleshoot compared to conventional materials [9]. Producing parts from high-strength steel proves difficult and necessitates expensive and time-consuming try-out series [19]. Despite the challenges, this high-strength material is in high demand due to its ability to achieve lightweight products and meet safety regulations [20]. However, it also poses formability challenges and springback difficulties [16].

Springback refers to the change in the intended shape of the panel compared to the shape of the die after the stamping process. This is particularly challenging, especially with high-tensile materials [25]. Tensile strength is the maximum stress a material can bear before it deforms, while yield strength is the maximum stress along the axis before permanent deformation occurs. Higher tensile and yield strength make forming in the die more difficult and lead to an increase in springback effects [5].

Obtaining accurate dimensions for the final panel presents difficulties in die design since the final shape may not align with the die shape. Consequently, several die tryout iterations are necessary to compensate for springback [28]. Springback contributions arise from factores such as die design, sheet metal properties, processing conditions and bending methods [26]. Addressing springback is a primary concern in the sheet metal stamping forming industry, as failing to do so can result in wasted time, increased investment, decreased quality, higher manpower usage, and increased material consumption [8]. Springback studies that explore bending type of sheet metal stamping have garnered significant attention from researchers [27]. Since bending in metal stamping is unavoidable, the best solution lies in minimizing panel bending springback to achieve the desired tolerance levels. To tackle this common defect in sheet metal stamping, several approaches have been developed by researchers. The first involves adjusting stamping parameters such as cushion pin, blank holder force, contact friction or die radius. The second approach is springback compensation, which entails modifying the die surface to achieve optimal springback solutions [5]. Both approaches are widely used in the industry.

Additional researchers also have explored numerous approaches to improve springback, including studying deformed die shapes through structural analysis as a reference for springback compensation, instead of using the original design die shape [14]. While this approach shows promise, the die manufacturing lead time for each cycle—from trial to die analysis, followed by springback compensation, re-machining, and re-trial—brings challenges for real industrial applications. The lead time required to adjust the springback surface to meet the next process of Computer Numerical Control (CNC) machining of the die surface cannot be ignored [7]. Longer analysis lead times will contribution to longer lead times for die completion. Numerous springback analysis using simulation and finite element analysis have been conducted by researchers, demonstrating the potential to reduce die tryout times [20]. Computer-Aided Engineering (CAE) is frequently used to estimate springback amounts during die design before the machining process [25]. However, a similar concern has been raised that the long lead time for analysis, particularly with several iterations for complex products, which presents a challenge [6]. Another method for springback compensation is the “displacement adjustment method” using both Finite Element Analysis (FEA) and an experimental approach [11]. The approach involves producing the die surface in the opposite direction of the springback displacements. The results show that this method can eliminate the trial and error in actual dies. However, the research does not focus on the impact of changes in the die process on springback occurrence. Furthermore, the reliance on the iteration method requires FEA capability, which may become a limitation due to its expensive application investments.

A recent study has integrated computer-aided geometric design (CAGD) theory, process design, optimization and layout systems [15]. These systems provide advantages in die process decision making through automatic recognition. However, the investment costs of the software may be a limitation for most of die makers. With the correct methods and analysis approaches using simulation and FEA, it becomes possible to address springback issues during trials [20]. FEA in stamping method is considered as fast computation and is capable to produce as mass production [12]. The use of simulation and FEA allows die design engineers to analyze, investigate, and adjust parameters for optimal results [1], avoiding hasty decision-making in die manufacturing [10]. Recent studies by Liu et al., (2022) demonstrate that new methods of post-forming, such as the electro-plastic effect (PFEPE) are being explored to reduce stress and springback in aluminum panel materials using electric current. Although this research indicates a positive impact on reducing stress in panel materials, it does not establish a direct correlation with springback reduction.

Hot stamping is one of process that is able to eliminate springback [29] [22] [18]. The study related to the tensile properties of aluminum materials involves heating the blank panel prior to hot stamping [13]. This approach has shown promising results in lowering the tensile strength of the material; however, it does not further explore its relationship to reduce springback formation. Titanium alloy material also facing similar springback challenge, and researcher is using hot stamping to enhance the formability [21].

The ultimate goal is to ensure that the panels produced by the die during sheet metal stamping fall within allowable industrial tolerance bands, which are typically calculated based on shape deviation of 80% and above [9]. Confirmation of correct shape performance can be achieved through checking fixtures, Coordinate Measuring Machine (CMM) and panel scanning which are widely used in the automotive industry [5]. Although this research is moving toward automation and intelligent die designing, the cost of purchasing the software remains a challenge for small players in the industry. To successfully implement springback compensation through simulation and FEA, the setup of the die process needs to be completed, stress-strain analysis must be robust, forming settings must be well-defined, software adaptation to die surface modifications must be smooth, and the ability to transfer to CAD/CAM software is essential [19]. This approach requires a clear method and is time consuming.

As the trial-and-error method is not preferred in the industry due to its cost and timeline impact, industries have explored the potential of simulations for springback predictions. An alternative way is to conduct a pre-emptive study on the best approach of a common shape that can provide guidelines for the future die process approach. Therefore, this paper presents research work aimed at understanding the behavior of different types of bending combinations and radius concerning springback occurrence during the stamping simulation of an L-shaped design intent panel with different type of material tensile. The research significance is to provide guidelines for design engineers, industrial practitioners and researchers in choosing the best die process for L-shaped panel against material tensile, to minimize springback occurrence.

In the next section, the methodology of this research, including the process flow and the research procedures, is detailed. Following this, Section 3 presents the results from the experimental trials and simulations. A discussion of these findings is offered in Section 4. The paper concludes in Section 5 with the insights and conclusions drawn from the research.

2 METHODOLOGY

2.1 Process Flow

Figure 1 provides a visual representation of the research process flow. To understand the behavior of different bending-type springbacks, industry experts from an established automotive metal stamping company determined the panel shape design, die design, panel material and thickness. Subsequently, the process sequence selections, simulation and experimental set up were conducted. The simulation and experiment activities and their results were collected and assessed, followed by a discussion and final conclusion on the selection of optimal bending types in the die process of L- shaped panels.

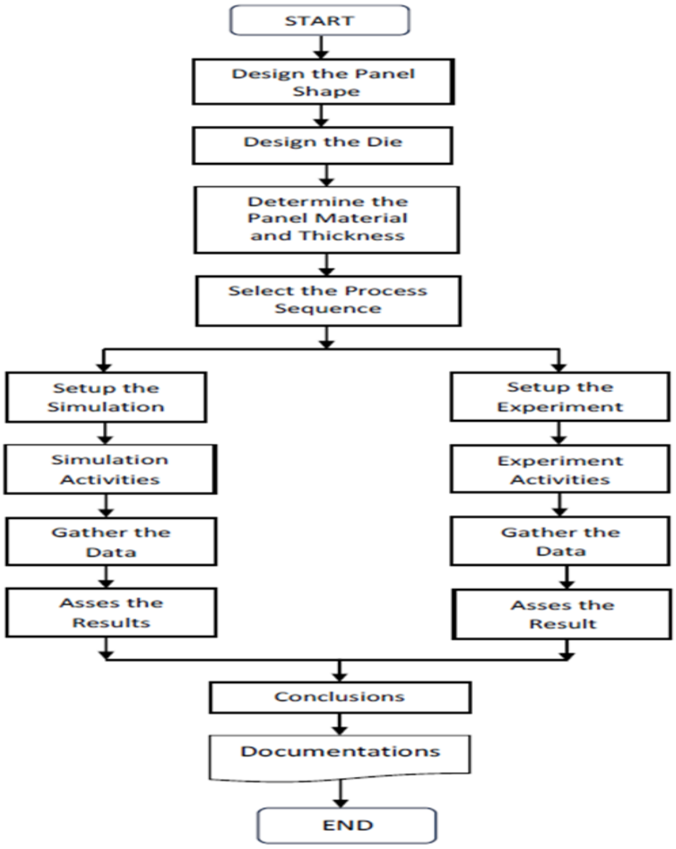


Figure 1: Selection of Optimal Bending Types Process Flow

2.2 Design the Panel Shape

To conduct the simulation and analyze the springback effect on product shape and material, the targeted panel shape was designed using CATIA V5 2021, as depicted in Figure 2. This L-shaped design, characterized by a straight bending type with a 90-degree angle, was proposed by a group of expert die engineers.

The L-shaped design is very common in stamping products, generally as part of a more complex shape, as shown in Figure 3. The bending height is 55 mm and the thickness is 1.8 mm. This configuration was chosen because it is categorized as one of the high stroke and thickness panel types produced in the automotive industry. Such panels are usually difficult to stamp and the high bending value, bending angle, and thickness were identified as the main key factors contributing to the expected springback challenge, as suggested by the industrial experts.

2.3 Design the Die

After determining the desired shape, the die for the experiment was designed using CATIA V5 2021. The completed die design is depicted in Figure 4. The die employs the concept of interchangeable bending blocks for the upper and lower sections. The concept involves changing the shapes of the upper and lower bending blocks while retaining the main structure of the die. This ensures that the variables in the die design are related only to the bending method and its working blocks. This die design was created for both simulation and experimental purposes in this research.

2.4 Determine the Panel Material and Thickness

For the springback simulation, three widely used materials in the stamping industry were selected, as listed in Table 1. All the materials have the same thickness, ensuring that the variable for each material is solely due to the material properties.

The Stress-Strain curves for these three materials, based on simulation software Altair Aspire Form 2022 database, are presented in Figure 5. As evident from Figure 5, JSC270C material exhibits the lowest yield stress and tensile strength, while JSC590R material demonstrates the highest yield strength and tensile strength.

Table 2 shows the materials selected for the experiment. These materials are equivalent to those selected for the simulation and are based on commonly available materials used in the industry.

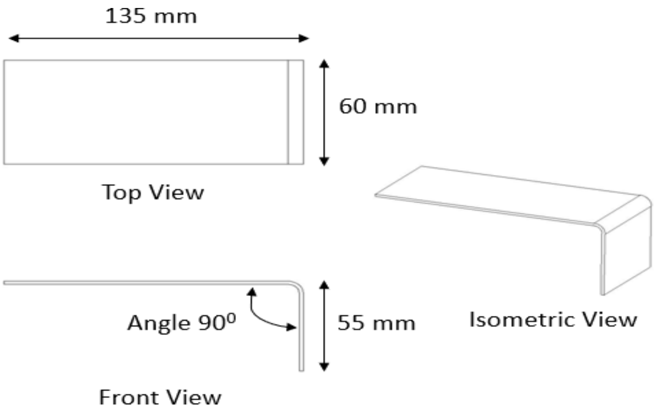


Figure 2: Panel Shape Design

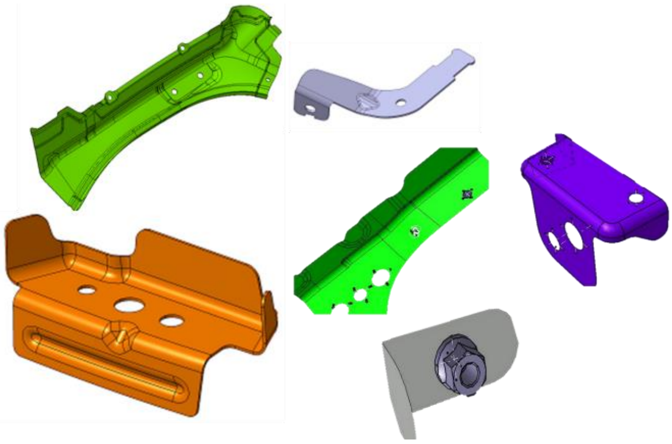


Figure 3: Example of automotive stamping product with L-shaped design

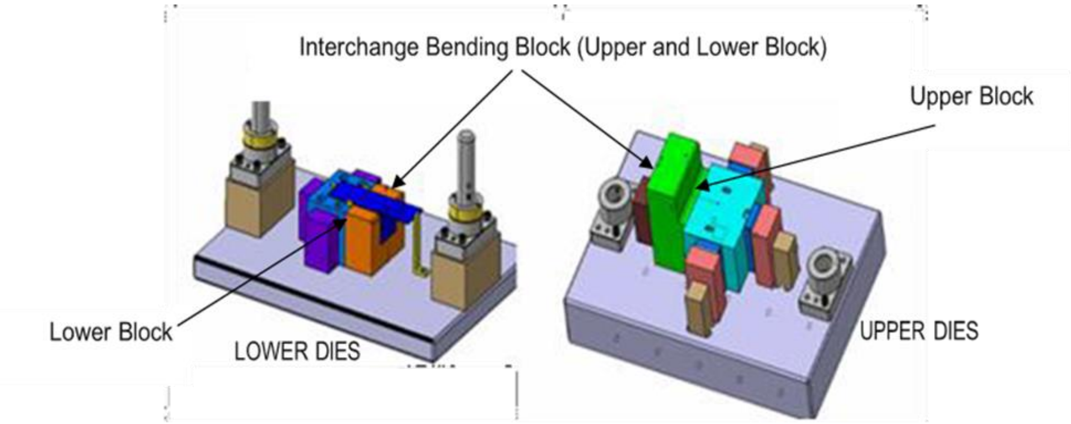


Figure 4: Die Design

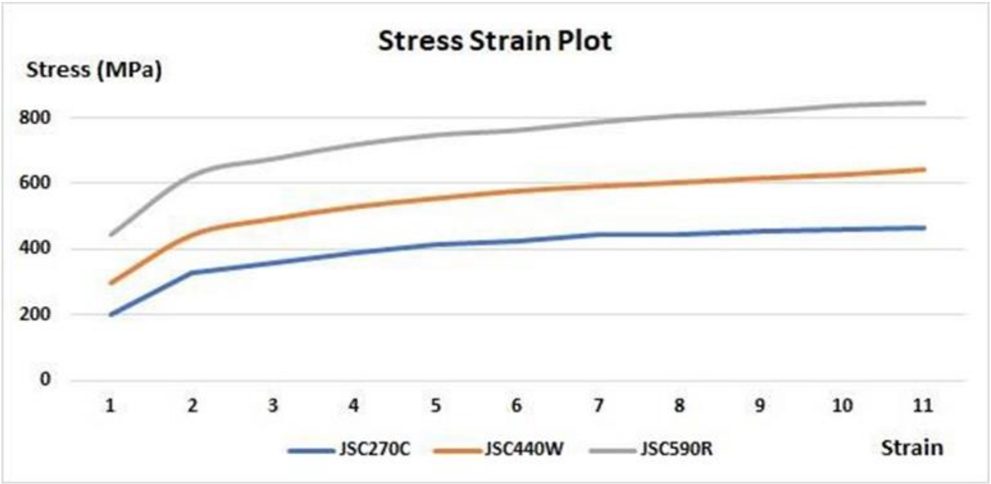


Figure 5: Stress Strain Curve for JSC 270C, JSC 440W and JSC 590R

Table 1: Process Sequence, Panel Material Selection and Die Type Selections

No	Process Sequence		Panel Material	Die Type
	1	2		
1	AR5	-	JSC 270C	One Process Bending
2	ARM5	-	1.8t	One Process Bending
3	B21	B2		Two Process Bending
4	B115A	B2		Two Process Bending
5	AR5	-	JSC440W	One Process Bending
6	ARM5	-	1.8t	One Process Bending
7	B21	B2		Two Process Bending
8	B115A	B2		Two Process Bending
9	AR5	-	JSC 590R	One Process Bending
10	ARM5	-	1.8t	One Process Bending
11	B21	B2		Two Process Bending
12	B115A	B2		Two Process Bending

Table 2: Panel Material Selection (Experiment)

Material	Thickness	Tensile Strength	Equivalent
SHGA 270C	1.8 mm	343 MPa	JSC 270C
SHGA 440-45	1.8 mm	463 MPa	JSC 440W
SPC 590	1.8 mm	624 MPa	JSC 590R

2.5 Select the Process Sequence

The list of die simulation process sequences was determined through collaboration among industry experts and members of the die finishing team. The decision-making process was guided by the challenges previously encountered in achieving the best countermeasure for the desired panel shape, especially when dealing with different types of materials. To achieve the desired panel shape as depicted in Figure 2, the selection of shape and radius options for the die surface was informed by industrial experts. The list of the die type selections is presented in Table 1.

Table 3 shows the reference codes based on bending types, radius and angle. From Table 3, AR5 is a full bending process with both radius R1 and R2 being 5 mm. For ARM, the process is similar to AR5, except for a compression curvature at the lower block. The B21-B2 processes combine R1 with a 13mm radius and R2 with a 5 mm radius, with B21 having an angle of 5 degree. Lastly, for B115A-B2, R1 as a 15 mm radius and R2 is as 5 mm radius for B115A. For B2, R1 is a 13 mm radius and R2 is a 5 mm radius, with B115A having an angle of 5 degree. The ultimate objective is to select the best combination of die processes, radius and angle to produce the L-shaped panel with minimal springback.

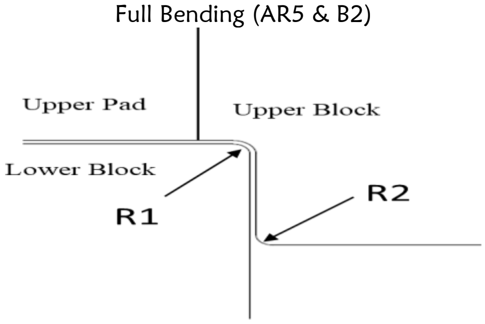
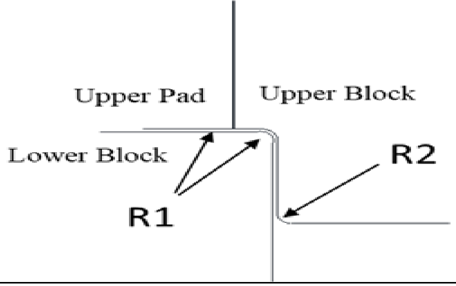
In current industrial practice, this die process selection is not documented as a formal method. Usually, the die process selection is based on the experience and know-how of die experts. Therefore, various combinations of bending types were designed to study the impact of these shapes to achieve the best desired panel shape with minimal springback. These combinations were selected based on commonly used die processes in the industry for stamping L-shaped bending. The listing starts with the process sequence, categorizing each as either a one-step or two-step bending process. For each sequence, the specific process, radius, and angle are determined, distinguishing among full bending, full bending (compression type), full bending with angle, or partial bending with angle. The combinations of the process sequence are detailed in Table 1. Figure 6 presents the descriptions of the die process sequences, selected based on the suggestions provided by the industrial experts, drawn using AutoCad 2017 software.

2.6 Setup the Simulation

A total of 12 simulations were created for the analysis using Altair Aspire Form 2022 software. The settings used in the simulation are depicted in Figure 7. Table 4 illustrates the force applied during the simulation process and the force obtained during the simulation process.

Table 3: Panel Material Selection (Experiment)

Reference Code	Bending Type	Radius (R1)	Radius (R2)	Angle
AR5	Full Bending	R5	R5	-
B2	Full Bending	R13	R5	-
ARM5	Full Bending (Compress Type)	R5	R5	
B21	Full Bending with Angle	R13	R5	5^0
B115A	Partial Bending with Angle	R15	R5	5^0

Die Quantity	Process Sequence
One Process Bending	Full Bending (AR5 & B2) 
One Process Bending	Full Bending (Compress Type) (ARM5) 

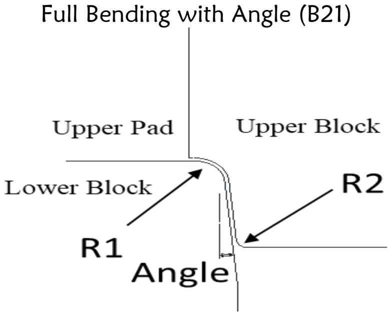
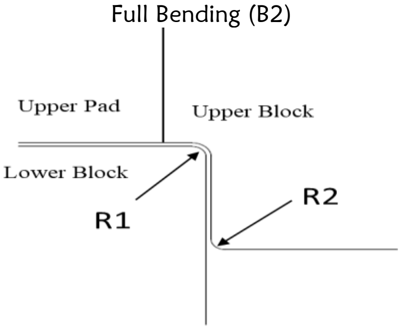
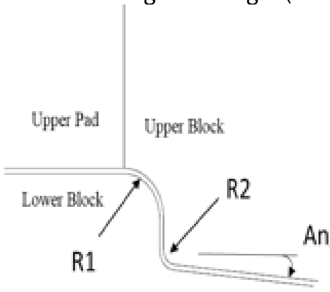
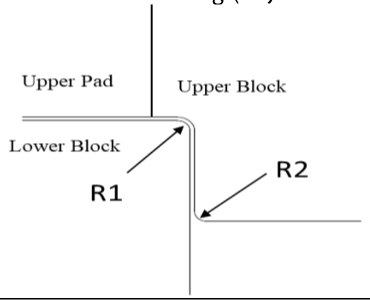
Two Process Bending	Process Sequence 1 Full Bending with Angle (B21) 	Process Sequence 2 Full Bending (B2) 
	Process Sequence 1 Partial Bending with Angle (B115A) 	Process Sequence 2 Full Bending (B2) 

Figure 6: Selected Process Sequences

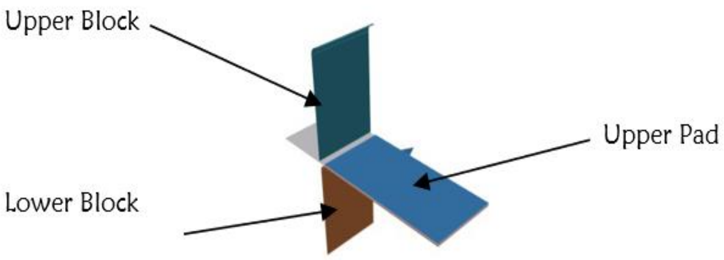


Figure 7: Simulation Setting for Process Shape Selections Descriptions

Table 4: Applied & Obtained Force (Simulation)

No	Process Sequence		Applied Force (N)	Obtained Force (N)
	1	2		
1	AR5	-	38 100	190 288
2	ARM5	-	38 100	57 466
3	B21	B2	73 938	84 123
4	B115A	B2	76 050	105 088
5	AR5	-	38 100	190 360
6	ARM5	-	38 100	46 684
7	B21	B2	73 938	80 064
8	B115A	B2	76 050	91 371
9	AR5	-	38 100	176 374
10	ARM5	-	38 100	268 310
11	B21	B2	73 938	80 064
12	B115A	B2	76 050	94 937

2.7 Setup the Experiment

Figure 8 shows the completed die set for the experimental setup. The die design was fabricated and tested using Asai Press 100 Tonne machine, as shown in Figure 9. A total of 12 experiments were created for the springback analysis. The settings used in the experiments are as depicted in Figure 10. The press holding time during stamping is 10 seconds. Figure 12 illustrates the force applied during the experimental process, which is 190 kgf/cm².

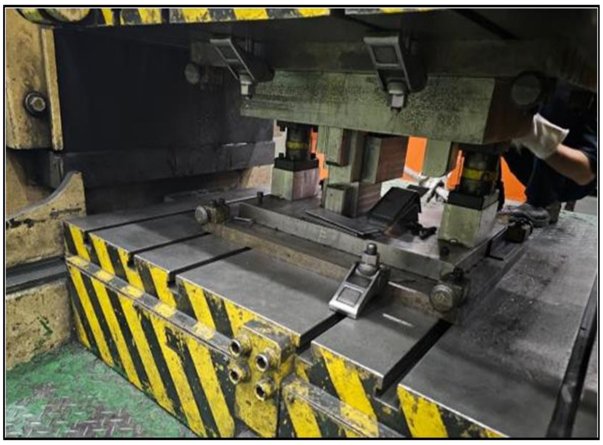


Figure 8: Completed die set for experiment

Figure 9: Press machine for experiment

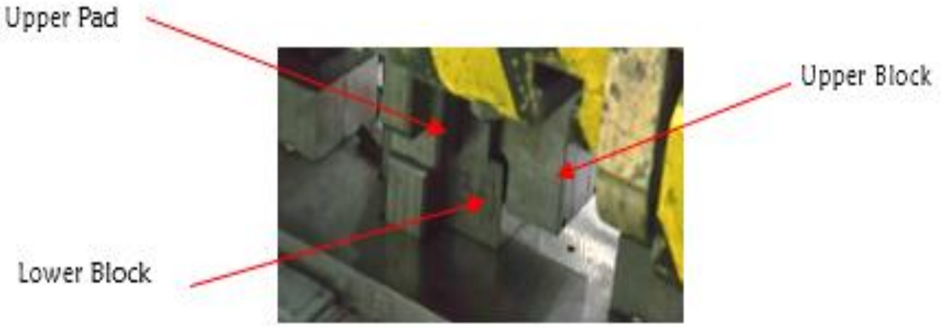


Figure 10: Experimental Setting for Process Shape Selections Descriptions

Figure 11: Applied Force (Experiment)

2.7 Result Judgements

The springback result was determined based on displacement, as illustrated in Figure 12. This method was chosen for its clear depiction on the impact of the bending method and sequence on the desired panel shape. Moreover, its replicates a common practice in industries where a panel's quality is assessed based on surface displacement from a reference surface, using a checking fixture for quality inspection. For simulation purposes, the displacements results were determined by visual color representation and the displacement values provided in the simulation report. For the experimental activities, the displacement results were measured using a taper gauge and a Teclock thickness gauge, as shown in Figure 14.

3 RESULTS

3.1 Simulation Results

Each process shape selection was simulated and repeated using different materials to observe the simulation visual color results and the displacement values. The springback displacement values were recorded based on measurements generated in the simulation software. These results demonstrate various panel behaviours due to different types of bending, materials, and die shapes.

The displacement values from the 12 simulations were tabulated in Table 5 for JSC270C material, Table 6 for JSC 440W material and Table 7 for JSC 590R material. The graphs and the visual display of the results are shown in Figure 14 for JSC270C material, Figure 15 for JSC 440W material and Figure 16 for JSC 590R material. In the visual displays, the red color indicates the maximum springback displacement value from the original panel shape, while the blue color represents values within the simulation displacement tolerance.

3.2 Experimental Results

The overall experimental results comparison is shown in Figure 17, comparing the three panels results for AR5, ARM5, B21-B2 and B115A-B2. These results are based on measurements taken with the taper gauge and thickness gauge. The comparison of simulation and experimental results for all three types of material, with tensile strengths of approximately 270 MPa, 440 MPa and 590 MPa tensile strength and the selected process sequences is shown in Figures 18, 19 and 20.

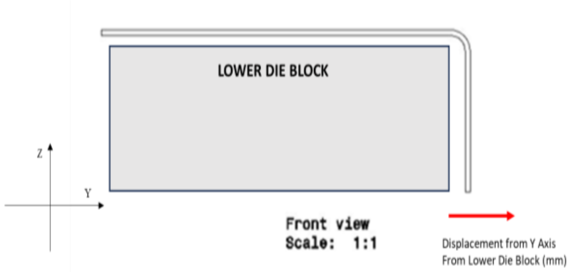


Figure 12: Displacement Determination

Figure 13: Taper Gauge and Thickness Gauge for experiment activities

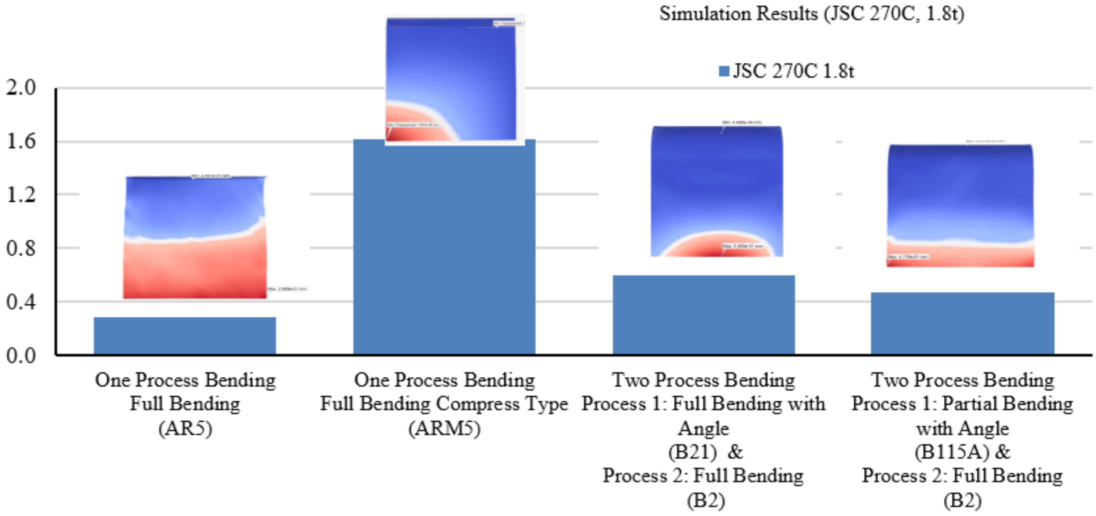


Figure 14: Simulation Result for Panel Displacements for JSC 270C, 1.8mm thickness

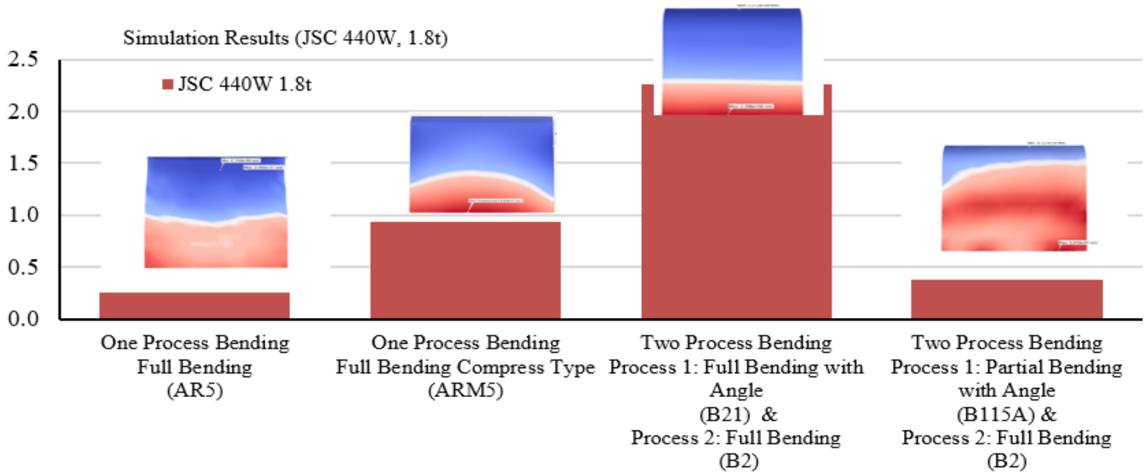


Figure 15: Simulation Result for Panel Displacements for JSC 440W ,1.8mm thickness

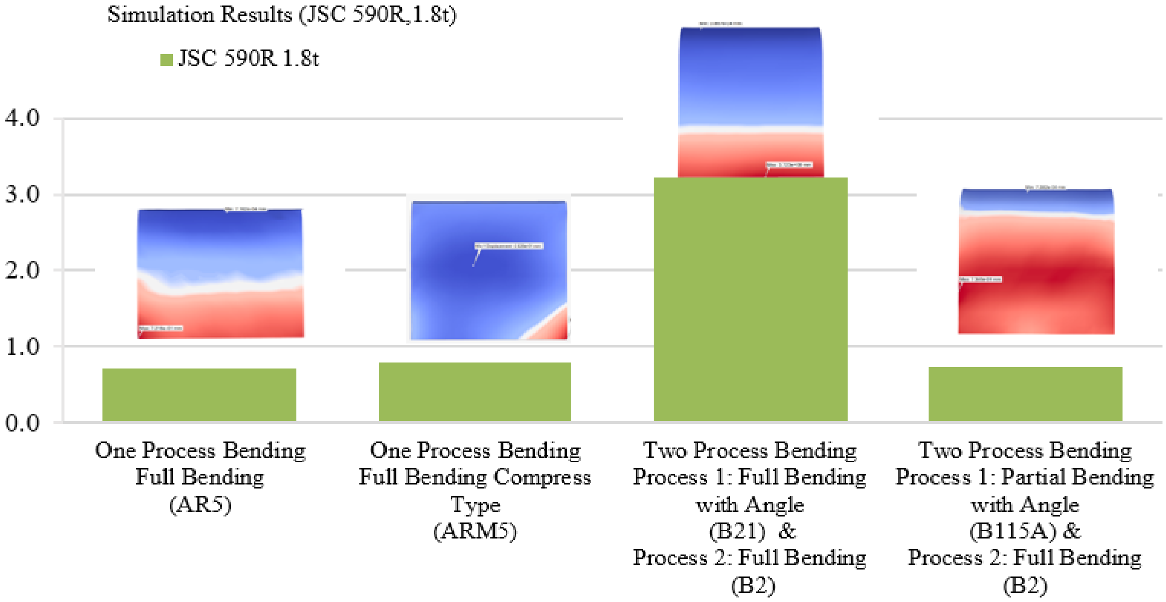


Figure 16: Simulation Result for Panel Displacements for JSC 590R,1.8mm thickness

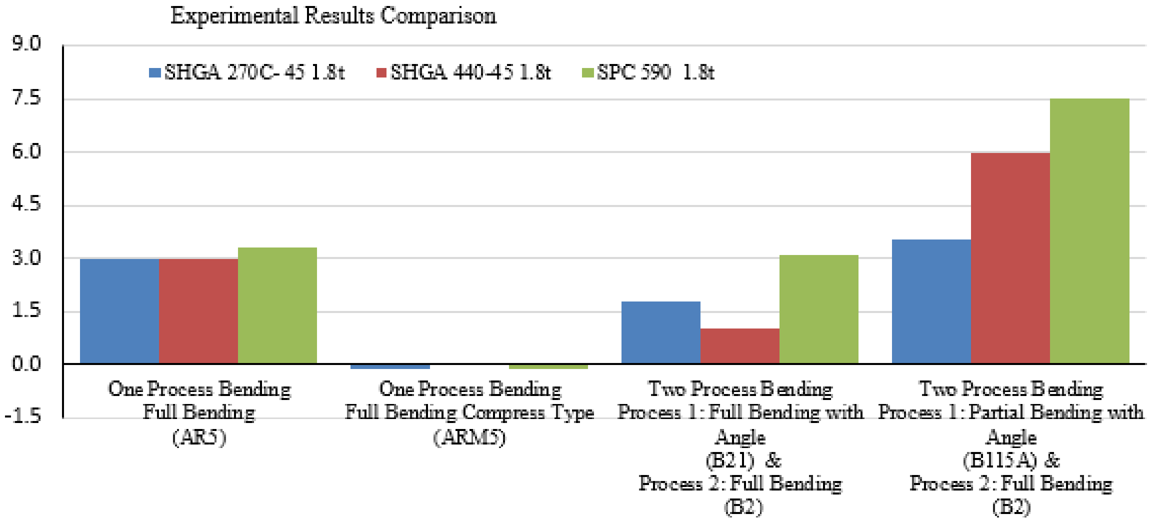


Figure 17: Experimental Result Comparison for combination of three different panel tensile material

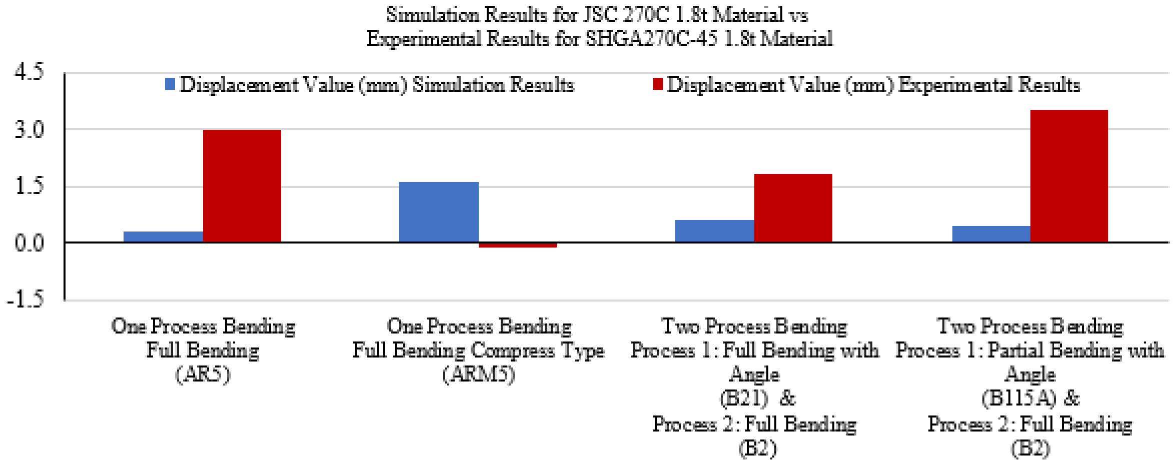


Figure 18: Simulation Results for JSC 270C 1.8t Material vs Experimental Results for SPC270C 1.8t Material

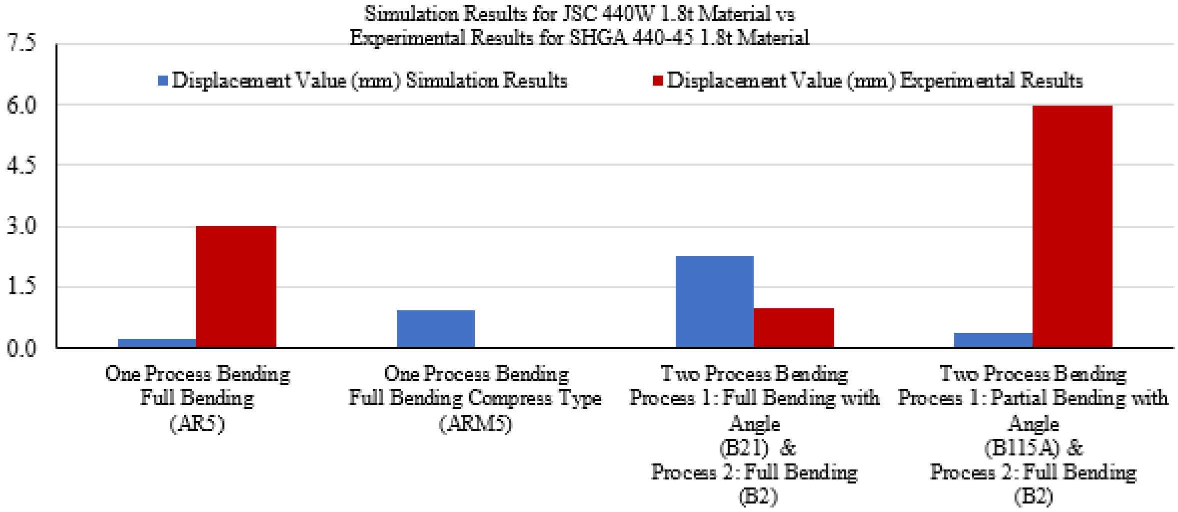


Figure 19: Simulation Results for JSC 440W 1.8t Material vs Experimental Results for SCGA 440-45C 1.8t Material

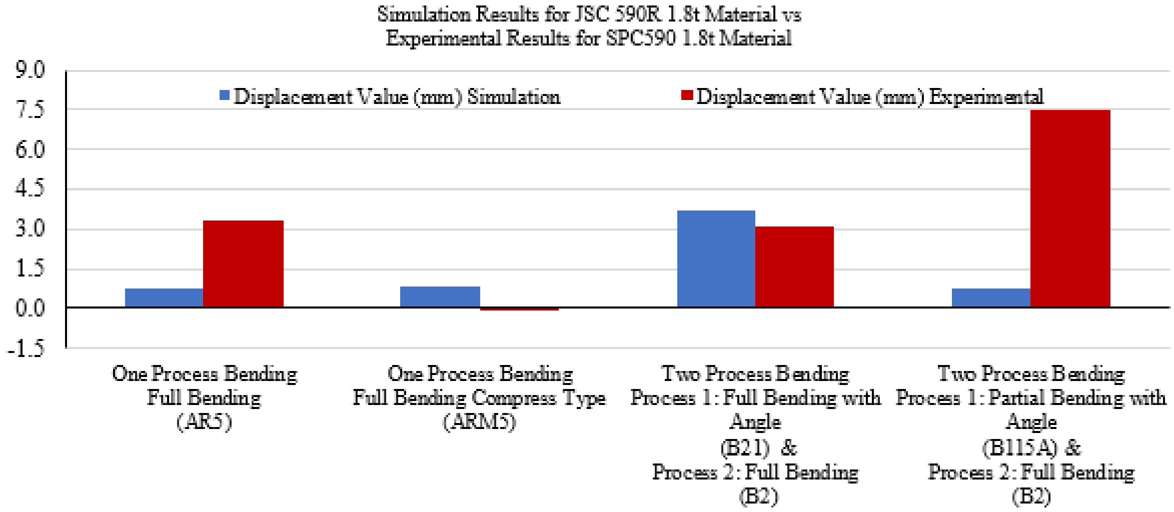


Figure 20: Simulation Results for JSC 590R 1.8t Material vs Experimental Results for SPC 590 1.8t Material

4 DISCUSSIONS

The results were analyzed based on both simulation and experimental conditions. The analysis considered both the panel material perspective and from the die process perspective, depending on industrial needs. The panel material perspective is relevant when the panel material is selected by the customer, and the die maker does not have the capability to choose the panel material. The die process perspective is applicable if the die maker can produce a panel with their own design, allowing them to select the suitable panel material according to the die process, investment and fabrication timeline. The findings suggest that careful consideration of both perspectives is required to optimize the selection of panel materials for various industrial requirements.

4.1 Simulation Results Discussions

The overall results shows that the simulation outcome vary according to the different die process sequences and materials used. This is an important finding, as each die processes sequence and material variation produce different result. Even when using a similar shape die, the resulting panel shape differs due to the change of the panel material.

4.1.1 From Panel Material Perspective

Table 5 and Figure 15 show the results for JSC270C material. Based on the displacement value, the Full Bending process (AR5) displays the lowest springback value and the Full Bending Compress Type (ARM5) shows the highest displacement value. However, in terms of visual representations, AR5 shows the largest red colour visual area, compared to other die process.

For JSC 440W material, Table 6 and Figure 16 shows that AR5 displays the lowest springback value, while Full Bending with Angle followed by Full Bending (B21-B2) processes show the highest displacement value. For the visual display, the red colour visual area is almost similar for ARM5, AR5 and B21-B2 processes. The most visible red colour visualization area is for the Partial Bending with Angle followed by Full Bending process (B115A-B2).

As for JSC 590R material, Table 7 and Figure 17 show that ARM5, AR5 and B115A-B2 process produce almost similar results, with B21-B2 processes showing the highest displacements values. For the visual representation, ARM5 shows a good visual, with minimum red visual area.

From the panel material perspective, based on the simulation results, the best process to produce an L-shaped design for each material needs to be evaluated in both displacement value and visual area representation.

For JSC290C, even though the visual representation shows process AR5 has a major red area, the displacement value is only 0.29 mm. Furthermore, AR5 requires only one process, which is an advantage in terms of die investment and die lead time completion. A similar displacement value was obtained for JSC 440W material with a value of 0.26 mm. Therefore, JSC270C and JSC 440W materials are most preferably produced by the AR5 die process, according to the simulation results.

For JSC 590R material, three die processes have almost similar displacement values. Among the three materials, the ARM5 process produce the least red visual area, and is therefore suitable for JSC 590R material. ARM5 also requires only one die process, along with the compress curvature to control springback.

4.1.2 From Die Process Perspective

From Figure 18, in the case of AR5 process, three types of material show variations in displacement results. Among these processes, JSC 440W material achieves the best result in terms of displacement value. This displacement location is lower compared to JSC270C and JSC 590R materials. The visual representation area is almost similar for all three types of materials.

For ARM5 process, JSC 590R material shows the best results in terms of visual representation area and the displacement value in the simulation.

For B21-B2 processes, results show a significant effect of the two- process sequence for bending the L-shaped panel. Based on the displacement, the results of JSC 440W and JSC590R materials are at a higher value, which is not preferable for springback troubleshooting. Among the three materials, JSC270C material achieves the best result in terms of displacement value and visual area representation.

As for B115A-B2 processes, JSC 440W material achieves the best result in terms of displacement value, but JSC270C achieves the best result in terms of red visual area representation.

These results provide an options to die design engineers, practitioners and researchers to choose the best die process for the panel material. However, the simulation results need to be compared to the actual experimental results for validation.

4.2 Discussion of the Experimental Results

The overall results show that the experimental outcomes produce less variation among different die processes sequences and materials used. The results indicate a similar pattern across the three material types.

4.2.1 From Panel Material Perspective

Table 8 and Figure 19 show the experimental results for SHGA270C-45 material. Based on the displacement value, ARM5 display the lowest springback value of -0.1 mm, while B115A-B2 shows the highest displacement value of 3.5 mm. A similar pattern is observed for SCGA 440-45C and SPC 590 materials in Figure 20 and 21, with the lowest values of 0.0 mm and – 0.1 mm for ARM5 respectively, and displacement values of 6.0 mm and 7.5 mm for B115A-B2. From the panel material perspective, based on experimental results, the best process to produce an L-shaped design and consistently for SHGA270C-45, SCGA 440-45C and SPC 590 panel materials is ARM5.

4.2.2 From Die Process Perspective

From the die process perspective, Figure 22 indicates that when AR5 is used, minimal variations are obtained in the displacement value results for all the three types of material. SHGA270C-45 and SCGA 440-45C panel materials have similar displacements values, followed by a slightly higher result for SPC 590 panel material. For the ARM5 die process, all material types show the best results in terms of displacement value during the experiments.

For B21-B2 processes, results show that significant effect of the two-process sequence for bending the L-shaped panel. JSC 440W material shows a less displacement value compared to the other two other materials. As for B115A-B2 processes, visual results show the highest springback effect for all three materials. Therefore, ARM5 is the most preferable process for all three types of panel materials, based on the displacement values obtained in the experimental activities.

4.3 Comparison Simulation and Experimental Results

Figure 23 shows the comparison of simulation and experimental results for panel material with tensile strengths around 270 MPa. The comparison displays a significance difference and similarities between simulation and experimental results.

For the panel material with tensile strength of approximately 270 MPa, both simulation and experimental results demonstrate favorable outcomes. In the simulation, Figure 23 shows that AR5 produces a good result with minimum displacement value while in the experiments, ARM5 also shows good result with minimum displacement value. The difference between simulation and experimental outcome highlights the importance of validating simulation predictions through experiments.

For the material with a tensile strength of around 440 MPa, Figure 24 shows the comparison of simulation and experimental results. The simulation provides a favorable result with a minimum displacement value for AR5. In the experimental results, ARM5 shows the best result for the 440 MPa material in terms of minimizing the springback displacements. Similar to the material with a tensile strength of around 270 MPa, the difference between simulation and experimental outcomes shows the necessity to validate the simulation predictions through experiments.

Figure 25 shows the comparison of simulation and experimental results for material with a tensile strength of around 590 MPa. Three options project good displacement values for the 590 MPa simulation: AR5, ARM5 and B115A-B2. For the experimental results, the minimum displacement value was achieved with the ARM5 die process, emphasizing the importance of validating simulation predictions to ensure the reliability of the die process selection.

Based on the comparison results, it can be observed that although experimental displacement values a higher value compared to the simulation results, the pattern of the optimal bending process is almost similar. The preferences are for one die process, either AR5 or ARM5.

However, if selecting one die for the process is not permissible due to the next process requirement for a trimming die, the option for a two die process need to be considered. Considering the stability of experimental results, the next suitable die process, if requiring two unit of die process, is B21-B2.

The discrepancies between the simulation and experimental values are primarily due to four main reasons. First, there were differences in the applied force and outcomes. As shown in Table 4, the applied and obtained forces during simulation were different from the applied force used in the experiment, as illustrated in Figure 11. Second, the press holding time used in the actual experiment was not applied in the simulation. Third, the simplified simulation setups, shown in Figure 7, did not consider press line factors, whereas the actual experimental setup involved mounting the sample on a press machine, as shown in Figure 10, which could affect the results due to press alignment. Finally, discrepancies also arose from differences in the tensile strength of the panel materials used in the simulation and the experiment, as shown in Figure 5 and Table 2, respectively.

4.4 Response Surface Methodology

To further understand the simulation and experimental data, an additional analysis using Response Surface Methodology (RSM) was conducted utilizing a multilevel-categorical design through Design Expert 13 (DX13) software. RSM serves as an analytical approach to analyze simulation and experimental data. By investigating the effects of various factors, it enables the optimal die process selection to minimize springback.

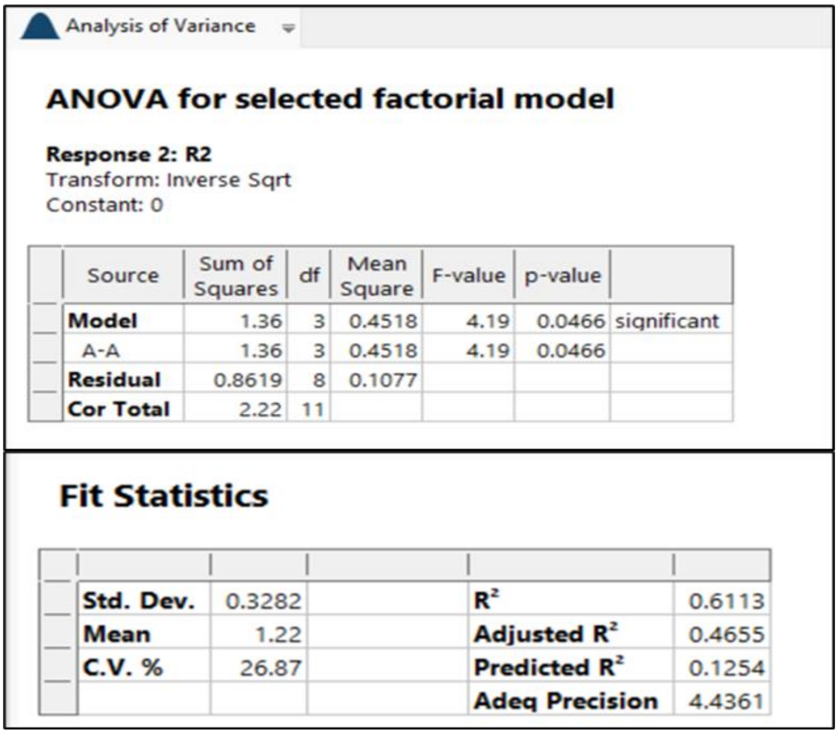
In this analytical approach, Factor 1 (A) was assigned as the die process, while Factor 2 (B) represents the material type. Both factors are categorized as Multilevel Categoric or General Factorial. The response variables are the experimental results, denoted as Response 1 (R1) and simulation results, as Response 2 (R2).

4.4.1 Analysis of Variance (ANOVA) of Simulation Results

Figure 21 shows the revised Linear Regression to Inverse Sqrt model. The “F-value” of 4.19 suggests a 4.66% probability that such a large “F-value” could arise due to noise. Despite this, the model remains significant as all “P-values” are below 0.0500. However, the “Predicted R2” of 0.1254 deviates from the “Adjusted R2” of 0.4655.

The “Adeq Precision” ratio, standing at 4.436, surpasses the desirable value of 4, indicating an adequate signal. Consequently, the model is deemed suitable for navigating the design space. In the model depicted in Figure 29, die process (A) emerges as a significant model term, while material type (B) does not. Further insights into the diagnostic results of the ANOVA post-transformation are presented in Figure 22.

In the Normal Plot in Figure 22, the data aligns along a straight line, in contrast to the previous results. In the Residual vs Run Plot, all data points are within the calculated limits at the 95% confidence level, indicating more consistent distribution. Additionally, the most recent transformation displayed in the Box Cox Plot reveals a Lambda value of 0.5.



ANOVA for selected factorial model

Response 2: R2
Transform: Inverse Sqrt
Constant: 0

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.36	3	0.4518	4.19	0.0466	significant
A-A	1.36	3	0.4518	4.19	0.0466	
Residual	0.8619	8	0.1077			
Cor Total	2.22	11				

Fit Statistics

Std. Dev.	0.3282		**R^2**	0.6113
Mean	1.22		**Adjusted R^2**	0.4655
C.V. %	26.87		**Predicted R^2**	0.1254
			Adeq Precision	4.4361

Figure 21: ANOVA for Simulation Result (after Transformation)

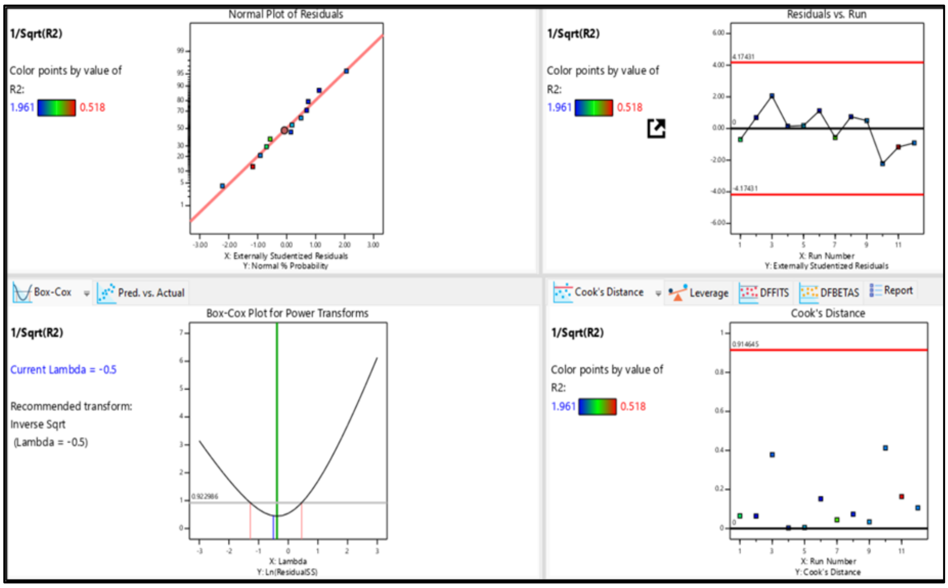


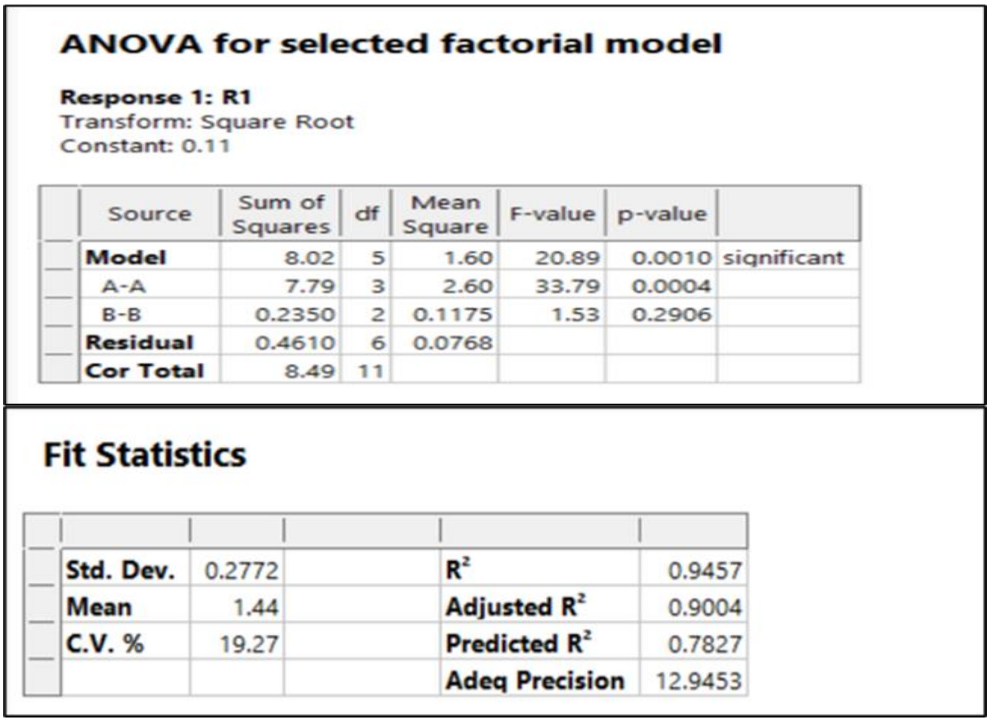
Figure 22: Diagnostic for the Simulation Results (after transformation)

4.4.2 Analysis of Variance (ANOVA) of Experimental Results

Figure 23 presents the revised Linear Regression to Square Root. The “F-value” of 20.89 suggests a mere 0.10% probability that such a large “F-value” could arise due to random variation. The model’s significance is supported by all “P-values” being below 0.0500. The “Predicted R2” of 0.7827 closely aligns with the “Adjusted R2” of 0.9004, with the difference being less than 0.2, indicating a reasonable fit of the model.

The “Adeq Precision” ratio, which ideally exceeds 4, stands at 12.945 in this model, signifying adequate signal strength. The model is suitable for navigating the design space. In the model depicted in Figure 33, the die process (A) emerges as a significant model term, whereas the material type (B) is considered a less significant model term. Further insights into the diagnostic results of the ANOVA post-transformation are presented in Figure 24.

In the Residual vs Run Plot, all data points fall within the calculated limits at the 95% confidence level, which shows a more consistent distribution. Moreover, the transformation indicated in the Box Cox Plot reveals a Lambda value of 0.5. From the ANOVA result, for both simulation and experimental data, die process (A) is a significant model term while the material type (B) is less significant model term. This finding highlights the importance of the die process and its selection in mitigating the springback effect.



ANOVA for selected factorial model

Response 1: R1
Transform: Square Root
Constant: 0.11

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	8.02	5	1.60	20.89	0.0010	significant
A-A	7.79	3	2.60	33.79	0.0004	
B-B	0.2350	2	0.1175	1.53	0.2906	
Residual	0.4610	6	0.0768			
Cor Total	8.49	11				

Fit Statistics

Std. Dev.	0.2772	R^2	0.9457
Mean	1.44	**Adjusted R^2**	0.9004
C.V. %	19.27	**Predicted R^2**	0.7827
		Adeq Precision	12.9453

Figure 23: ANOVA for Experimental Result (after Transformation)

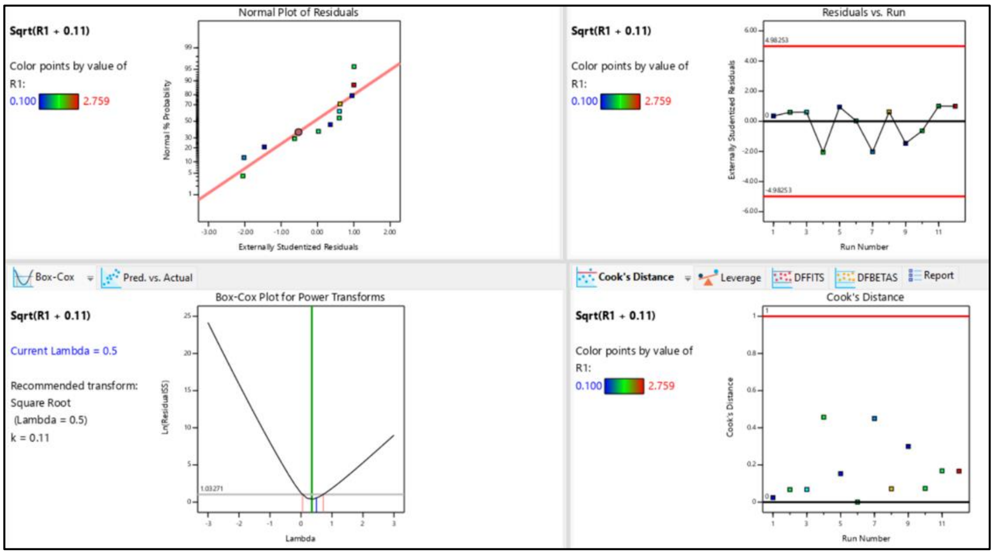


Figure 24: Diagnostic for the Experimental Results (after transformation)

4.4.3 Interaction of Experimental Results and Simulation Results

Figures 25 and 26 show the interaction for experimental results (R1) and simulation results (R2), while Figures 27 and 28 present the 3D surface results for experimental results (R1) and simulation results (R2). Figures 25 illustrates that for the experimental results, ARM5 exhibits significantly lower springback across all material types. The outcomes for AR5 and B21-B2 processes are nearly identical, with no distinct superiority of one die process over another based on the overlapping LSD bar. However, B115A-B2 yields higher results compared to all other data points. In terms of material interactions, panel material with tensile strength of 590 shows higher springback values compared to other panel materials.

In contrast, Figure 26 demonstrates that the simulation results show relatively similar outcomes across all material types and die processes, with no particular material or die process standing out based on the overlapping LSD bar. This difference in results can be attributed to the variations in material properties between the simulation and experimental materials. Additionally, variations may exist between the experimental and simulation conditions, such as press holding time and the actual press tonnage, due to the experimental setup being conducted in an actual industrial setting.

The 3D Surface for experiment and simulation presented in Figure 27 and 28 demonstrate that effects of panel material and die process. The data for experimental results displays a wider distribution across materials and die processes, extending up to 8 mm. In contrast, simulation results indicate a narrower range, with displacements constrained to a maximum of 4 mm. This observation suggests that experimental results offer more extensive and diverse data compared to simulation results.

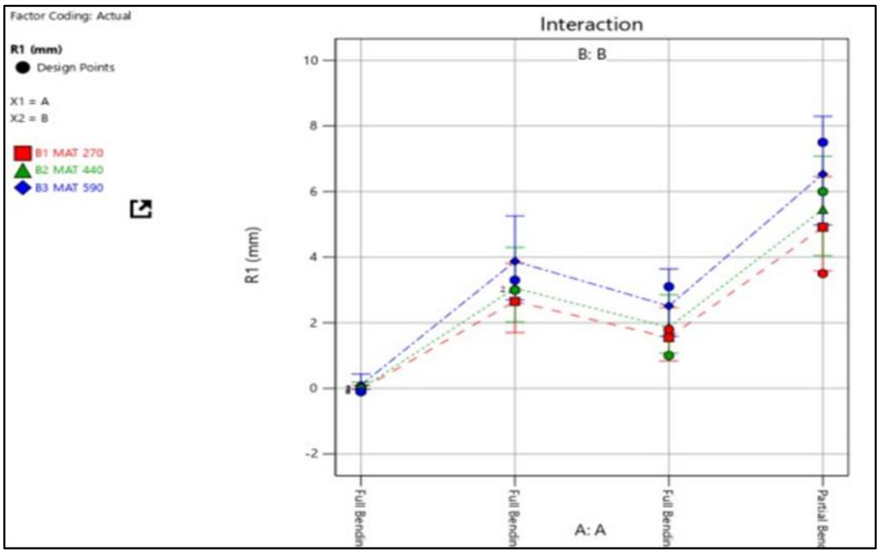


Figure 25: Interaction for Experimental Result (R1)

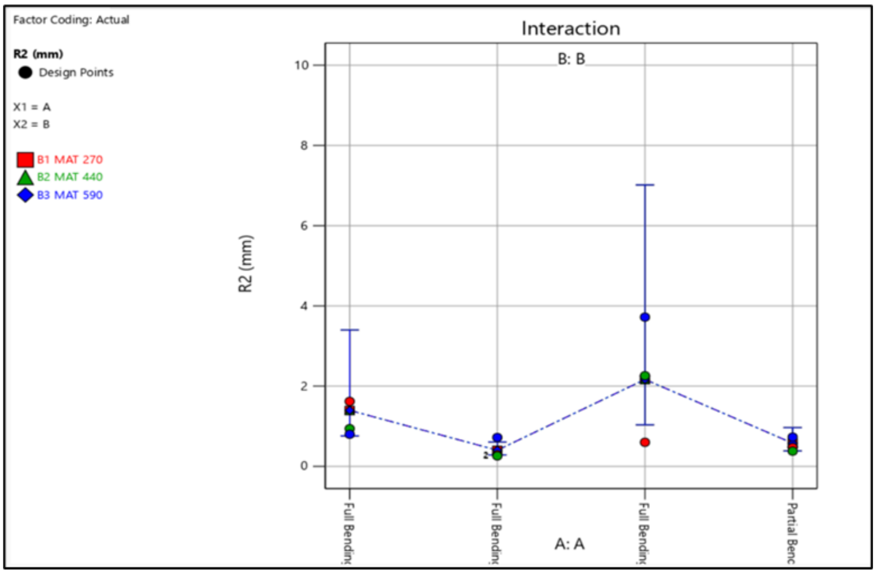


Figure 26: Interaction for Experimental Result (R2)

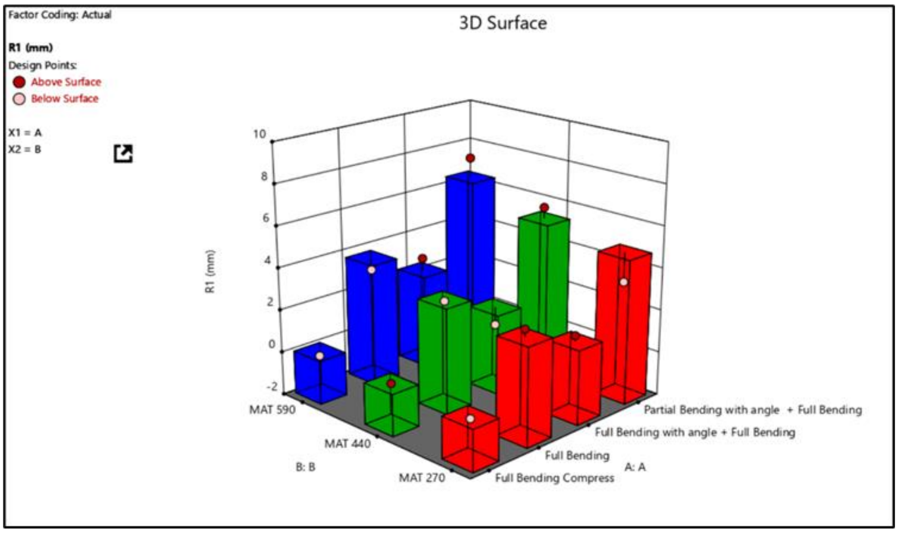


Figure 27: 3D Surface for Simulation Result (R1)

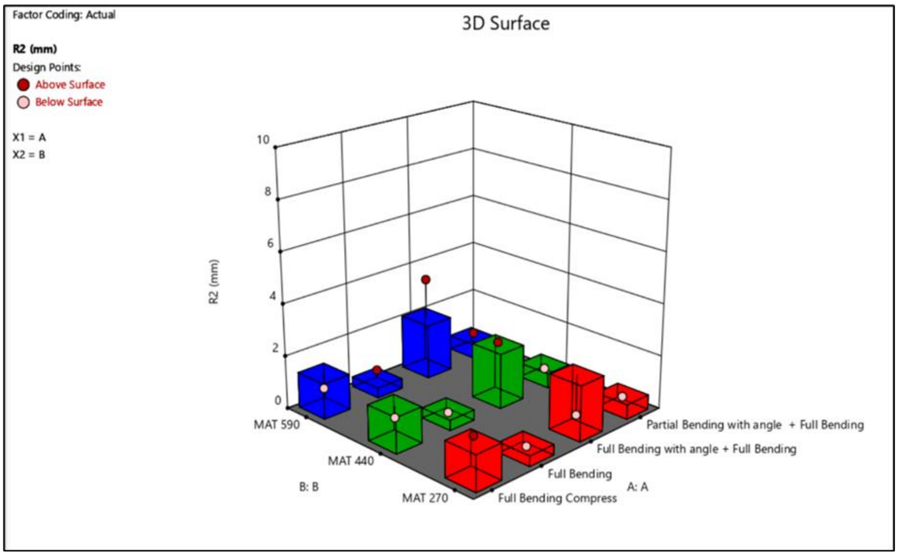


Figure 28: 3D Surface for Simulation Result (R2)

4.5 Result Optimization

The objective of the springback analysis is to identify the optimal die process that can minimize springback. In the context of RSM, the objective is to minimize the springback value for experimental results (R1) and simulation results (R2), with factor die processes (A) and material type (A) within range. Table 11 illustrates the constraints established to obtain the optimized solution.

Table 12 shows the proposed solution generated by DX 13 software. As illustrated, the recommended process is Full Bending Compress type, ARM5 for all material types, exhibiting minimal springback values ranging from -0.012 mm to 1.397 mm. Therefore, the Full Bending Compress type is deemed the most optimized choice for minimizing springback in L-shape panel fabrication.

The Full Bending Compress Type have the potential to be explored further as it is utilize the current panel radius to compress the thickness, preventing the springback occurrence. Figure 29 shows the condition of the compress element in ARM5, compared to AR5. From the Figure 29, it can be observed that ARM5 shows a visible "mark" at the panel area due to the curvature nature that differs from the AR5 process.

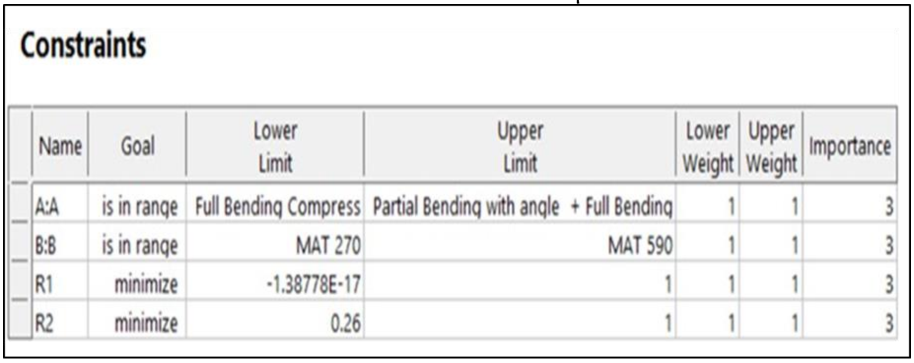
In comparison with AR5, the lower die of ARM5 is consist of a curvature that does not correspond to the thickness of the panel, causing the panel to be compressed prior to the bending process. As springback is related to the panel returning to its original shape due to elastic deformation (Anggono et al., 2011), the compress shape causes the panel flow to be "locked" at the radius, minimizing springback occurrence.

Figure 30 shows a close up of the compress area for ARM5 in comparison with AR5, using CATIA V5 2021 software. This is the primary difference between ARM and AR5, which results in a significant difference in the springback occurrence. Therefore, the compressed method in ARM5 contributes to minimizing the springback of the L-shaped panel.

Besides obtaining good L-Shape panel results and minimizing springback, the ARM5 approach relies on the die surface adjustment through surface modelling, CAM and CNC machining. Figure 31 shows an example of the surface modelling of the ARM5 lower curvature shape, using CATIA V5 2021 software. The initial lower surface of curvature, can be created using a surface modelling, which act as the "lock" for the L- shaped, followed by CAM data generation and transfer in CNC machining process. The advantage is that this curvature can be re-designed and adjusted using the re-machining and surface tuning, if the springback minimization results do not meet the desired requirements.

Furthermore, only one die process needs to be developed if the springback minimizing method follows the ARM5 approach. Typically, a two-unit die is chosen to minimize springback for L-shaped panels for a high die stroke and thickness panel material, as mention in the panel shape design selection in Section 2.2. Therefore, instead of a two process approach that can produce similar results, this approach is much more economical, cost-effective and able to reduce lead time for die development. Consequently, this research provides an alternative option for die process selection to die design engineers, industrial practitioners and researchers.

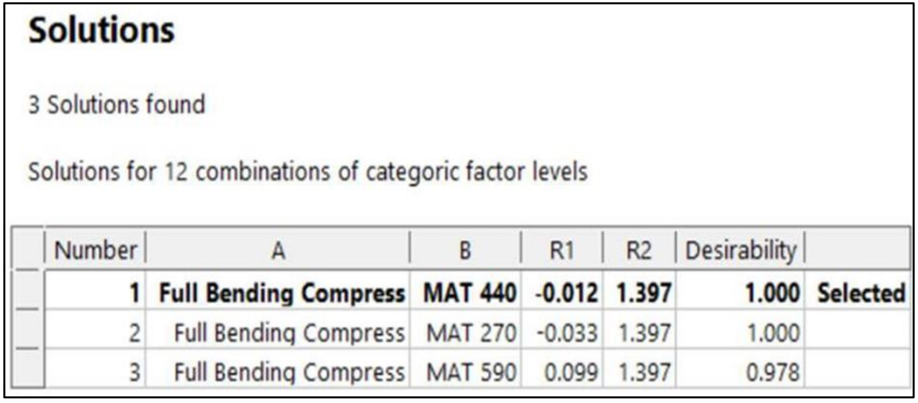
Table 11: Constraints Set for Optimization



Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:A	is in range	Full Bending Compress	Partial Bending with angle + Full Bending	1	1	3
B:B	is in range	MAT 270	MAT 590	1	1	3
R1	minimize	-1.38778E-17	1	1	1	3
R2	minimize	0.26	1	1	1	3

Table 12: Proposed Optimize Solution



Solutions

3 Solutions found

Solutions for 12 combinations of categoric factor levels

Number	A	B	R1	R2	Desirability	
1	**Full Bending Compress**	**MAT 440**	**-0.012**	**1.397**	**1.000**	**Selected**
2	Full Bending Compress	MAT 270	-0.033	1.397	1.000	
3	Full Bending Compress	MAT 590	0.099	1.397	0.978	

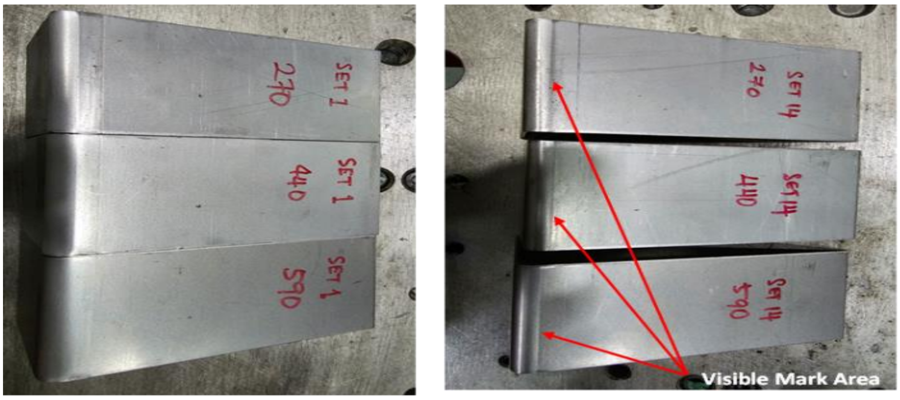


Figure 29: Difference between AR5 and ARM5 L-shaped panel

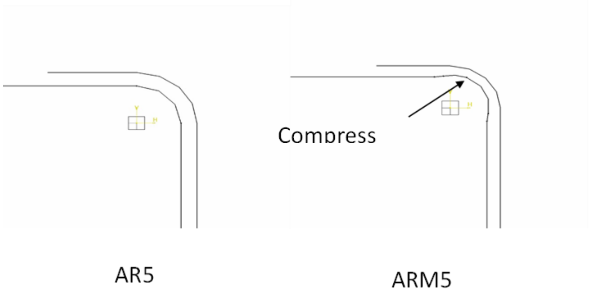


Figure 30: Difference between AR5 and ARM5 process

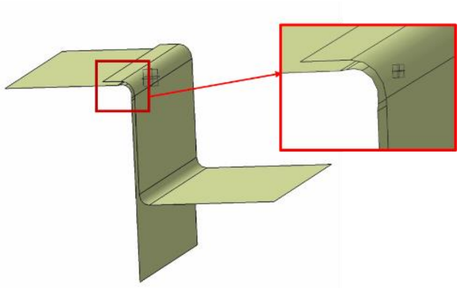


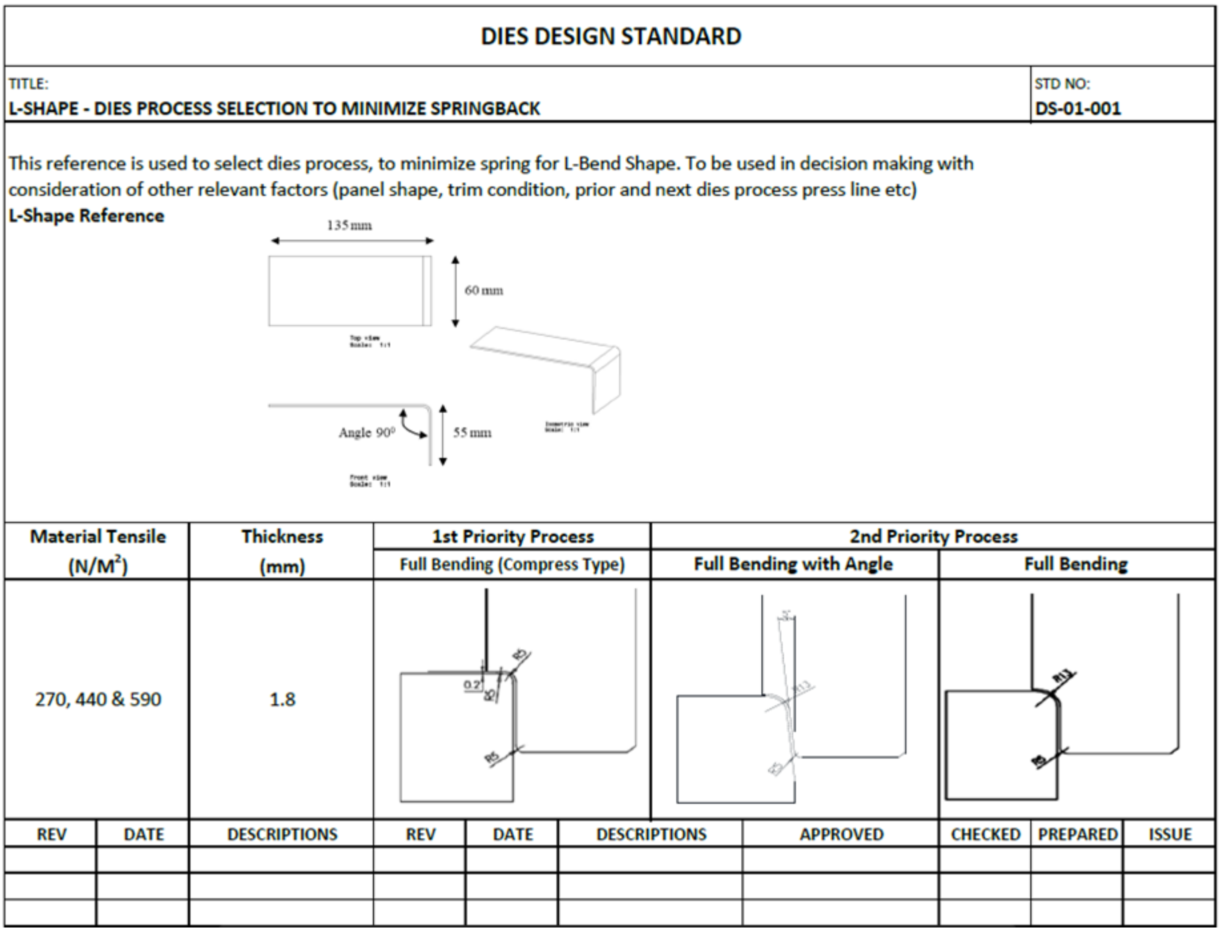
Figure 31: Surface modelling of the ARM5 lower curvature

4.5 Reference Guideline

Understanding the panel material behavior concerning the die process is crucial in die manufacturing operations. The selection of the appropriate die process is significant, as wrong choices can greatly impact panel quality and lead time for die development. Selecting an unsuitable process will cause material wastage and prolonged manufacturing lead times required to address springback issues.

This analysis provides die design engineers, industrial practitioners and researchers with valuable insights into the importance of selecting the correct die process through a combination of simulation and experimental evaluations, rather than relying solely on trial and error and past experience. The research shows the panel behaviors of multiple die process options for L-shaped bending.

Springback analysis has been undertaken by various researchers, including Baharuddin et al. (2022), Dang et al. (2017), Mertin & Hirt (2017), and Sumikawa et al. (2017). However, the previous studies have primarily focused on troubleshooting and mitigating springback occurrence. This research uniquely prioritizes identifying the optimal die process to pre-emptively minimize springback occurrence in the early stages of die design for manufacturing. Moreover, this methodology can serve as a standardization framework for junior die design engineers facing similar design problems in preliminary study of the die process.



DIES DESIGN STANDARD

TITLE:
L-SHAPE - DIES PROCESS SELECTION TO MINIMIZE SPRINGBACK

STD NO:
DS-01-001

This reference is used to select dies process, to minimize spring for L-Bend Shape. To be used in decision making with consideration of other relevant factors (panel shape, trim condition, prior and next dies process press line etc)

L-Shape Reference

Material Tensile (N/M^2)	Thickness (mm)	1st Priority Process	2nd Priority Process	
		Full Bending (Compress Type)	Full Bending with Angle	Full Bending
270, 440 & 590	1.8			

REV	DATE	DESCRIPTIONS	REV	DATE	DESCRIPTIONS	APPROVED	CHECKED	PREPARED	ISSUE

Figure 32: Reference Document for Die Process Selections to Minimize Springback

In the initial process study, the panel requirements provided by the potential customer usually comes in bulk with many design packages. The decision for the die process needs to be made in the simplest and fastest way possible with the correct judgements. This Reference Guideline is suitable as the first reference for die process decision making. The next activities are during the actual die design process will provide guidance on the suitable process for the initial die process selections. Figure 32 illustrates the Reference Guidelines generated from this research's findings. In the Reference Guidelines, the first die process option is the Full Bending Compress Type (ARM5), according to the optimized solution shown in Table 12 and the second die process option is Full Bending with Angle followed by Full Bending (B21-B2), as shown in Figure 25 and 27.

4 CONCLUSIONS

In this research, the behaviour of different types of bending combinations and radius concerning the springback occurrence during the stamping simulation of an L-shaped design intent panel with materials of different tensile strength has been studied. Through simulation and experiment activities, it was demonstrated that the L-shaped panel can be produced using several different die processes. It has been observed that for all materials, the die process that involves one-process bending- full bending compress type is the best option. The second-best option is two-process bending, which consist of Process 1 as full bending with angle and Process 2 as full bending.

This research also provides an initial insight into the outcomes of die selection decisions and provides reference guidelines for die design engineers, industrial practitioners and researchers. Die design engineers can effectively minimize springback by analyzing panel shape changes before die fabrication and selecting the optimal die process based on material tensile strength.

Alongside the past experience and knowledge of the design engineers, industrial practitioners and researchers, this information can help minimize the repetitive cycle of die improvement activities in case severe springback occurs due to mistakes in die process decisions. This reduction in time and effort contributes to more efficient manufacturing activities, enhancing productivity and competitiveness.

The L-shaped panels is the most basic shape explored in this study. Further studies are recommended to explore springback angle machining compensation of the L-shaped panel, as it presents another challenge related to machining on the vertical machine axis. Additionally, there is potential for other studies to explore the simulation and experimental results for multiple types of panel shapes and thicknesses. To understand the springback behaviour, the enhancement of multi shape panels with different type of material and thicknesses can be developed according to their complexity. The proposed further research extension can imitate the research approach presented in this paper, whereby the analysis was conducted by using simulation, experimental and RSM method with difference shapes of panels and thicknesses.

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