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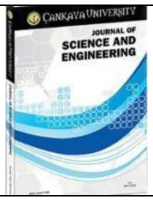

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Effect of Punch Strike Application Strategies on Forming of Fuselage Panel Lay-Up Mold

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Keywords

Invar FeNi36, Finite Element Analysis, Punch Strike Strategy, Cold-Forming.

Abstract

This study examines how three distinct punch strike application techniques affect the cold forming of a 25 mm thick Invar FeNi36 plate into a lay-up mold for an aviation fuselage panel. In each technique, the same number of punch strikes were delivered at various plate positions in varied sequences. The Finite Element Method (FEM) was employed to evaluate the effectiveness of the aforementioned strategies. The most effective approach was the one that produced a form that was most similar to the intended plate form. Additionally, for each stroke of the strategies, the temperature rise, equivalent plastic strain, and maximum stress values of the plate under the punch were compared when the plate was in contact with the mold.

1. Introduction

Composite materials are now used in the manufacture of airplane fuselage panels. A critical step in the production process is the lay-up mold's fabrication, which directly impacts the fuselage panel's final quality. The final panel quality is greatly influenced by the mold's surface quality and the mold materials' behavior at elevated temperatures, particularly the expansion-contraction properties during firing, autoclaving, or curing [1, 2]. When producing many composite fuselage panels, it is essential to employ a long-lasting lay-up mold. Determining a suitable mold production process is crucial because of the possibility of mold damage or its subsequent unavailability for reuse during the separation of the manufactured composite panel. Choosing a suitable mold production method that complies with the requirements is an important economic factor, given the possibility of damage to the mold or its subsequent unavailability for reuse during the separation of the produced composite panel.

Male and female molds make up a mold; the male mold shapes the structure's interior, while the female mold shapes its exterior. Because convex surfaces, such wings and fuselage panels, are more common in aviation and space structures because of their aerodynamic qualities, female molds are employed more often in these applications [3]. One of two methods may be used since the outer surface quality is the most important factor in forming the pieces. Making a male model one-to-one is the initial step, after which a female mold is made from the model. The second method involves using CNC and comparable equipment to process the mold material directly, much like a female mold.

The fabric fibers are usually deposited on the mold, while several methods are used for the ultimate shape of the composite structure. The material is injected with resin and then allowed to cure in an autoclave furnace.

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The plate material is first cold formed into the appropriate near-net shape to produce a thick fuselage lay-up mold. This is usually accomplished by applying successive punches as a solid cylindrical shape at various plate positions or using a 3D-shaped punch in a deep drawing process. Using a cylindrical punch, the second technique fits the various plate positions into the bottom female mold shape (Figure 1). Only a few Turkish firms use the process above for cold-forming thick (about 25 mm) Invar plates with a considerable area. A small, localized surface deformation (penetration) on the plate is also seen following each punch impact (Figure 1). The phenomenon that happens when the punch is retracted is called springback. Punch strikes are negatively correlated with the number of strikes needed to cause damage to the plate surface and prolong the life of the female mold. Proper placement and arrangement of punch strikes in a minimum number of steps will yield a cold-forming procedure that is quicker, more economical, and geometrically reliable (i.e., nearly identical to the intended shape). To improve dimensional accuracy and lay-up surface roughness, the cold-formed plate is machined (milled) at the end of the production process. A fixture (Figure 2) holds the machined lay-up mold in place and prevents it from moving during composite lay-up. The nickel-iron alloy known as Invar is commonly utilized as a lay-up mold material for producing composite fuselage panels for aircraft cabins because of its low coefficient of thermal expansion.

Few investigations have been done on the cold-forming of thick plates (about 25 mm thick) with a high surface area (usually more than one square meter), according to a literature survey. Shahare et al.'s [4] "incremental sheet forming process" describes how sheet material is cold-formed into an uneven concave down shape. Using a linear path on the x- or y-axis, the die (hammer) travels down the z-axis at a constant speed in this manner. The plate is formed incrementally by the hammer applying strikes (hits) concurrently. This approach is unsuitable for cold-forming heavy plates, as it is only viable for thin sheets (about 1 mm thick). The male and female molds for a subsequent investigation on the spring-back of three-dimensionally curved metal plates formed by cold-forming were created by combining several tiny punches. This process of forming is called a "multi-point forming process." The findings showed that as plate thickness grew, spring-back increased and plate-making got more complex [5]. Ultrasonic vibration was used in Li and Hu's work [6] to improve sheet material cold-forming in the multi-point forming process. The finite element analysis (FEA) findings showed that, in comparison to the no-vibration condition, forming the sheet with vibration improved forming accuracy (reduced spring back). A 25 mm thick plate was created in the work by Bojahr et al. [7] by combining the rolling and bending procedures with numerous rolls. The ultimate form of the plates was not in three-dimensional curvatures since the resulting forms were continuous.

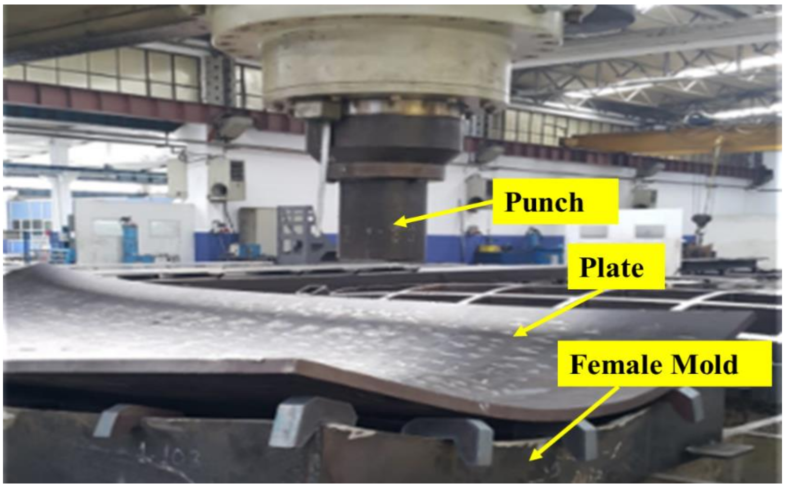


Figure 1. The Cold-Forming of the Invar Plate.

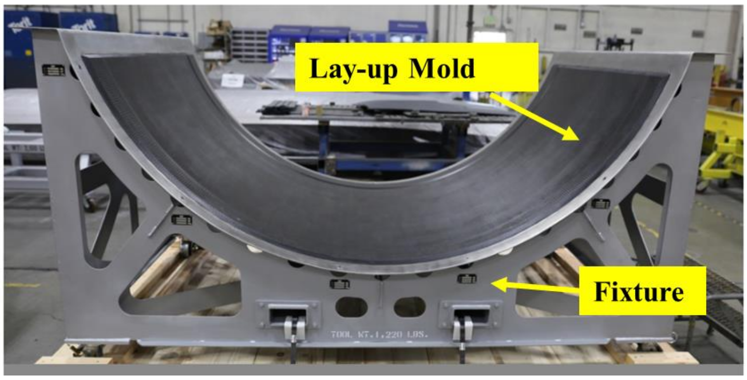


Figure 2. Lay-up Mold and Its Fixture.

As mentioned earlier, punch striking is a more cost-effective method of cold-forming lay-up molds than deep drawing since they do not require expensive, three-dimensional punches. However, the press operator's prior experience determines the application points of the punch strike on the plate surface during the cold-forming operation. Generally speaking, the operator lacks a thorough understanding of how punch application spots affect the plate's ultimate geometry. Research on the impact of punch application spots on the final shape of the cold-formed plate is therefore crucial. This study used the Finite Element Method (FEM) to simulate the cold-forming process and implemented three distinct punch strike application tactics to cold form the Invar FeNi36 plate into a fuselage panel lay-up mold in order to fill in the gaps in the literature. To ascertain the impact of punch application sites on the final geometry of the plate, the same number of punch strikes were applied at various positions on the Invar FeNi36 plate.

2. Materials and Methods

Using the QForm 10 Metal Forming Simulation Software (also known as QFform), the cold-forming process of the fuselage panel lay-up mold was simulated in this study by Finite Element Method. This section of the study provides information on the female mold, punch, and Invar plate's material qualities, modeling, punch strike techniques, boundary conditions, and motion limitations.

2.1. QForm Simulation Program

QForm is used in many metal-forming operations, such as extrusion of aluminum profiles, rolling, and hot and cold forging [8, 9]. Its design makes it easier for user-defined custom substructures, thermal process assessments, and optimization studies. The software works with both remeshing infrastructure and automatically generated meshes. The workpiece and tool geometry, the workpiece material parameters (including the material rheological model), the initial temperature and accumulated degree of deformation, the tool parameters, the lubricant properties, the type and parameters of equipment actuating the tool, the boundary conditions, and the conditions of operation completion must all be entered in order to simulate the process (with or without consideration for the heat problem). As the deformation problem is nonlinear, it is resolved with the iterative method. In the simulation, the explicit multi-step procedure organization method was employed.

Modeling

Four components made up the investigated system (Figure 3a) were: an Invar plate (1454 mm x 705 mm x 25 mm), eight plate limiters, a female mold, and a SAE1040 steel punch (250 mm diameter). All other plates except the Invar plate were deemed stiff in the analysis. Figure 3b provides the dimensions of the female mold and support structure.

To get a much closer plate form to the desired one and minimize the number of punch hits, the plate is deep drawn by a 3D male mold (Figure 4). Because the plate tended to spring back when the male mold retracted, the space between it and the female mold at the center of the plate was roughly 25 mm. This study did not cover the finite element analysis (FEA) of the plate's initial formation through the deep drawing procedure.

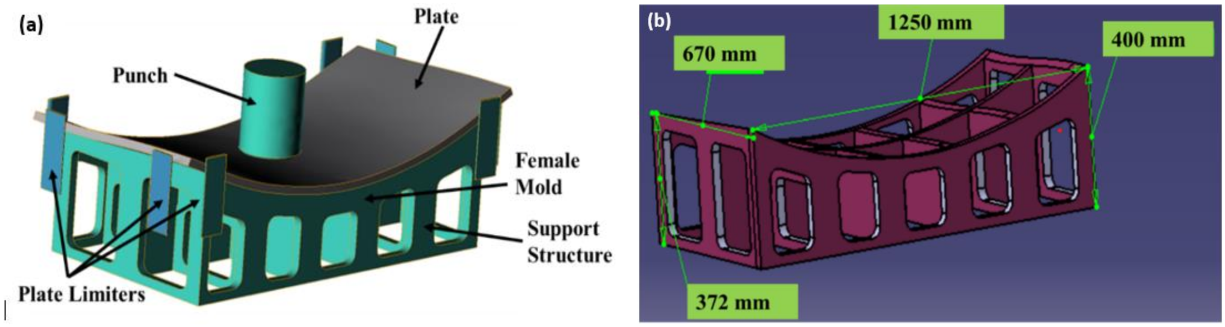


Figure 3. a) Female Mold Dimensions, b) Assembly of the System.

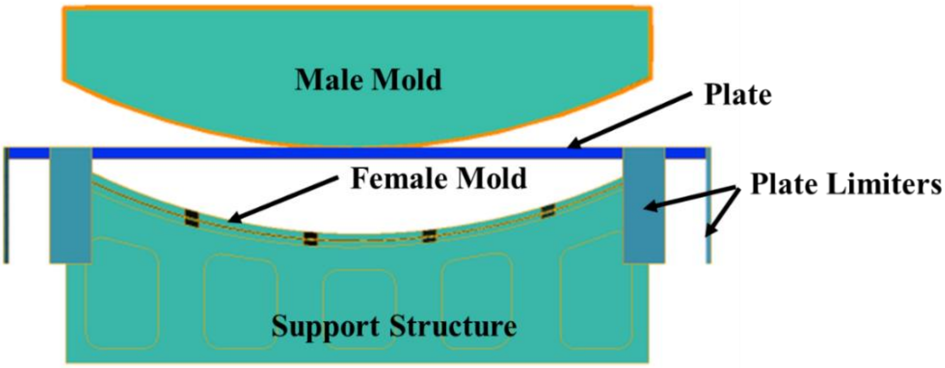


Figure 4. Plate, Male and Female Molds.

2.2. Plate Material

The study employed Invar (Nilo 36 (36% Ni, 64% Fe), UNS K93600) [10] as the plate material. It is widely utilized in the aviation sector to make reference lengths, meters, measuring instruments, and parts requiring high precision because of its low expansion coefficient. Tensile testing of five specimens from the same Invar plate yields the mechanical parameters of the material (Table 1).

Table 1. Tensile test results of the Invar material (for five specimens)

Yield Strength (at 0.2% offset), MPa	275-282
UTS, MPa	424-428
Strain at UTS, %	31-32
Fracture Strength, MPa	274-279
Fracture Strain, %	43.5-47.5
Young's Modulus, MPa	140600-141900
Energy at the break, J	338-348

2.3. Boundary Conditions and Motions

There were restrictions on the female mold's x, y, and z-axis motions. To limit the plate's movements in the x and y axes, eight plate limiters were welded to it (Figure 3a). The plate elements' rotary and linear x, y, and z motions were free. The punch's x, y, and z axes of motion are all possible. Punch retraction occurred when the punch's z-motion stopped and the distance between it and the female mold was less than 25 mm in the direction the plate touched the female mold. The punch had a maximum force of 10 MN and a maximum speed of 25 mm/s. The displacement principle was used to carry out the analytical program.

2.4. Meshing

Tetrahedral mesh geometry was employed in the investigation (Figure 5a). Data re-meshing was done automatically by the software (Figure 5b). Table 2 displays the number of nodes and elements.

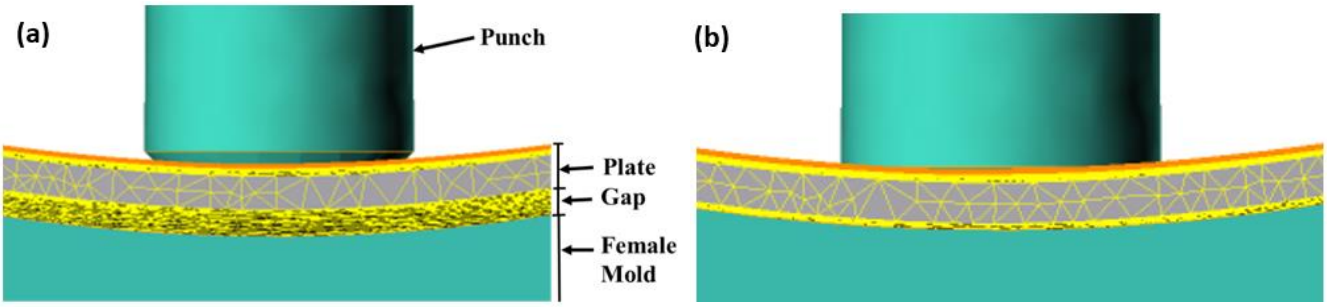


Figure 5. Mesh Structures and Re-meshing. a) Before, and b) After the Plate Contacts the Female Mold.

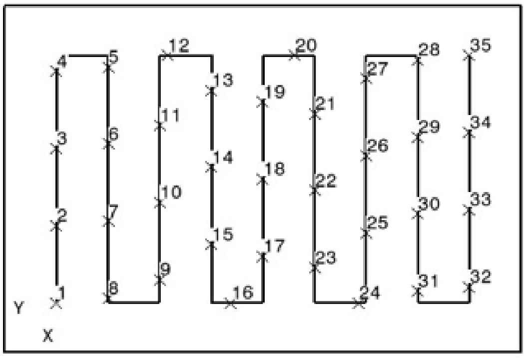
Table 2. Number of Nodes and Elements Before and After the Plate Contacts the Female Mold (for the First Strategy, S1).

Number of Nodes and Elements	Before Remeshing	After Remeshing
Nodes (on the plate surface)	7528	8810
Elements (on the plate surface)	15052	17616
Total nodes of the plate	8808	10946
Total elements of the plate	30950	40101

2.5. Punch Strike Application Strategies

Based on the authors' preliminary finite element analysis (FEA) and press operators' experience, three distinct punch striking application procedures were suggested in this study to cold shape the Invar plate into a fuselage panel lay-up mold. Figures 6-8 display the x- and y-coordinates, punch strike application sequences, and final plate shapes (after the 35th punch strike) for S1-S3 methods. A virtually identical center region of the plate surface (880 mm x 580 mm) was struck with 35 punch strikes in both methods thanks to the arrangement of the punch strike's x- and y-coordinates. Therefore, the best course of action is the one that completes the forming process with the least amount of deviance from the desired shape of the plate, that is, the shape of the female mold.

(a)



REF.	X	Y
1	0	0
2	0	15,59
3	0	31,18
4	0	46,76
5	10	47,65
6	10	32,06
7	10	16,47
8	10	0,88
9	20	4,71
10	20	20,29
11	20	35,88
12	21,47	50
13	30	42,94
14	30	27,35
15	30	11,76
16	33,82	0
17	40	9,41
18	40	25
19	40	40,59
20	46,18	50
21	50	38,24
22	50	22,65
23	50	7,06
24	58,53	0
25	60	14,12
26	60	29,71
27	60	45,29
28	70	49,12
29	70	33,53
30	70	17,94
31	70	2,35
32	80	3,24
33	80	18,82
34	80	34,41
35	80	50

(b)

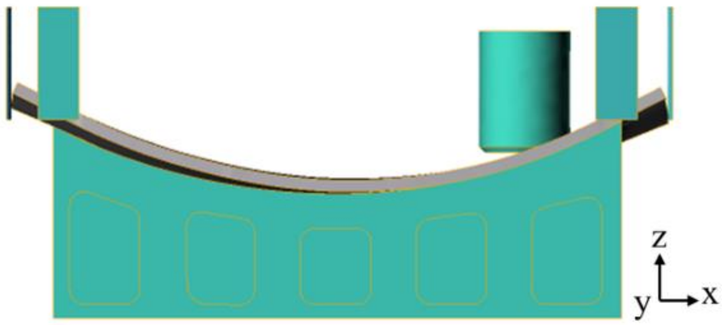
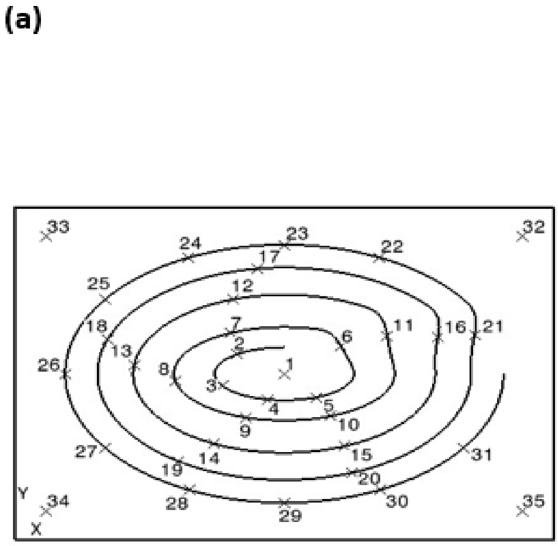


Figure 6. S1. a) Coordinates (in cm) and Sequence of Punch Strikes, b) Plate Geometry at the End of the 35th Punch Strike



REF.	X	Y
1	0	0
2	-8,88	4,06
3	-11,49	-2,56
4	-3,02	-5,44
5	6	-4,96
6	10,5	5,82
7	-10,02	8,61
8	-20,23	-1,45
9	-7,15	-9,25
10	8,64	-8,95
11	19,07	8,06
12	-9,36	15,75
13	-27,82	1,83
14	-12,93	-14,82
15	11,16	-15,33
16	28,47	7,77
17	-4,96	22,24
18	-32,73	7,29
19	-19,64	-18,5
20	12,45	-20,96
21	35,23	8,25
22	17,61	24,58
23	-0,04	27,29
24	-17,7	24,56
25	-33,15	15,74
26	-40,58	-0,03
27	-33,11	-15,78
28	-17,64	-24,57
29	0,01	-27,29
30	17,67	-24,57
31	33,13	-15,76
32	44	29
33	-44	29
34	-44	-29
35	44	-29

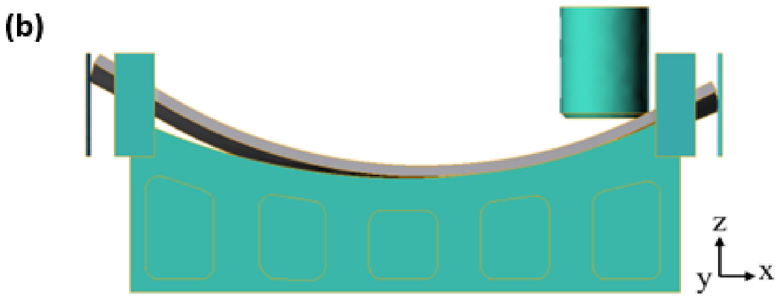


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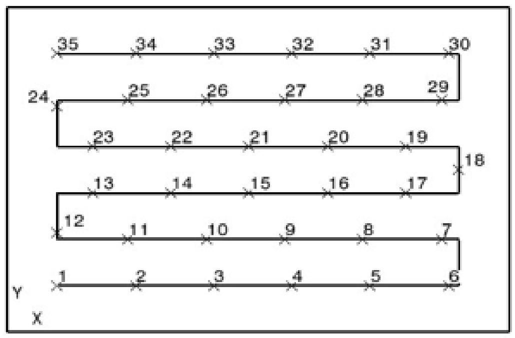
Figure 7. S2. a) Coordinates (in cm) and Sequence of Punch Strikes, b) Plate Geometry at the End of the 35th Punch Strike.

(a)



REF.	X	Y
1	0	0
2	15,59	0
3	31,18	0
4	46,76	0
5	62,35	0
6	77,94	0
7	76,47	10
8	60,88	10
9	45,29	10
10	29,71	10
11	14,12	10
12	0	11,47
13	7,06	20
14	22,65	20
15	38,24	20
16	53,82	20
17	69,41	20
18	80	25
19	69,41	30
20	53,82	30
21	38,24	30
22	22,65	30
23	7,06	30
24	0	38,53
25	14,12	40
26	29,71	40
27	45,29	40
28	60,88	40
29	76,47	40
30	77,94	50
31	62,35	50
32	46,76	50
33	31,18	50
34	15,59	50
35	0	50

(b)

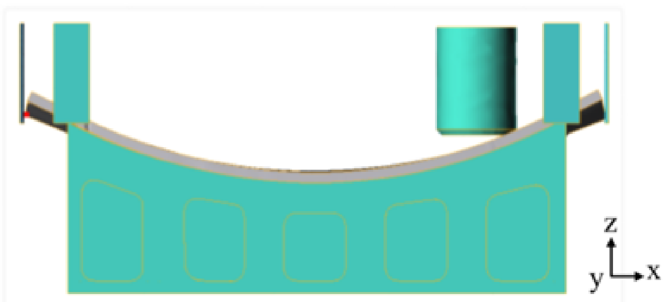


Figure 8. S3. a) Coordinates (in cm) and Sequence of Punch Strikes, b) Plate Geometry at the End of the 35th Punch Strike.

2.6. Plate's Shape Deviation, Maximum Temperature (T_{max}), Equivalent Plastic Strain ($\bar{\varepsilon}^p$) and Maximum Stress (σ_{max}) Calculations

In this study, the volume between the cold-formed plate form and the female mold form (Figure 9) was proposed as the deviation metric. The strategy with minimum volume indicated the best strategy. The volume calculations were done using the QForm analysis results. The mean distance between the final plate shape and the female mold form, calculated by dividing the volume by the plate area (0.838 m^2), provided information for comparing distances between the center of the actual and ideal plate forms.

The maximum temperature (T_{max}) of the plate under the punch at the moment of contact with the female mold was also examined in this investigation. The plastic deformation of the plate in the bending and squeezing modes was the cause of the plate's temperature rise under the punch.

Moreover, FEA was used to determine the equivalent plastic strain $\bar{\varepsilon}^p$ values for each punch strike when the plate made contact with the female mold. Equation (1) was used to calculate the increment of equivalent plastic strain, $d\bar{\varepsilon}^p$

$$d\bar{\varepsilon}^p = \sqrt{\frac{2}{3}\sum_{i=1}^{3}\sum_{j=1}^{3} d\varepsilon_{ij}^p d\varepsilon_{ij}^p} \quad (1)$$

Here, de_{ij}^p is the plastic strain incremental tensor components in the principal direction.

Maximum stress s_{max} (Von Misses-based) values of the plate under the punch at the instant of contact with the female mold were also calculated.

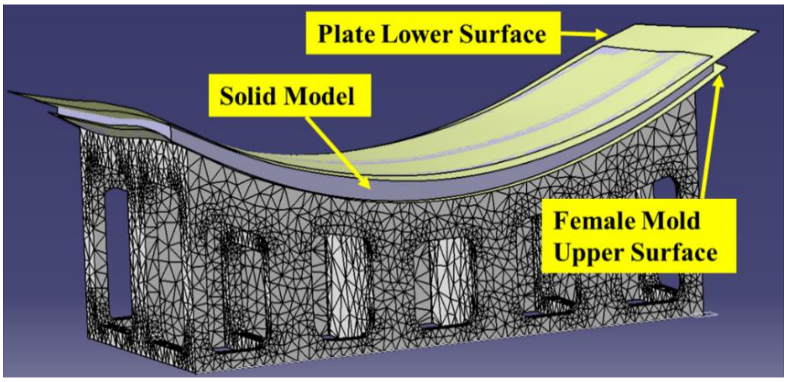


Figure 9. The Solid Model Created Between the Bottom (Lower Surface) of the Cold-Formed Plate and the Upper Surface of Female Mold.

3. Results and Discussion

In the S1 and S2, the solid model volumes generated between the female mold and the cold-formed plate (Figure 9) were larger than those of the S3 (Table 3). Volumes from the S1 and S2 were 216% and 333% greater than those from the S3. S3 was the approach that produced the plate form that was most closely aligned with the female mold form. The distances between the center point of the cold-formed plate (from the bottom surface) and the female mold were 0.042 m for S1, 0.063 m for S2, and 0.022 m for S3. As a result, it was found that the S2 method was the least successful in reaching the ideal plate form, while the S3 technique was the most successful.

The strategies (Figure 10) showed $\bar{\varepsilon}^p$ values ranging from 0.0065 to 0.016, which were sufficiently high (over 0.2% offset strain) to generate plastic deformation of the plate. For S1 and S3, the $\bar{\varepsilon}^p$ values were extremely near to one another. S2 produced significantly greater $\bar{\varepsilon}^p$ values than the other two strategies. The plate surface's localized plastic deformation (penetration) markings (Figure 1) were due to the sharp side of the cylindrical punch's localized high compressive stress.

Figure 11 showed that, except a few punch striking positions, the plate's T_{max} ranged from 22^o C to 50^o C. Compared to the other techniques, the S2 produced higher temperatures during the first 15 strikes. The plate's plastic deformation brought on by the downward punch movement was the cause of this temperature spike that was noticed.

The variations of s_{max} with punch strike sequence for the S1-S3 are shown in Figure 12. The s_{max} values, which ranged from 260 MPa to 500 MPa, were generally higher than the yield strength of the Invar material (276 MPa to 280 MPa) in all strategies, resulting in penetration marks on the plate surface.

Table 3. The volume and center distance between the cold-formed plate and the female mold for the strategies.

Strategy	Volume difference (m^3)	Center distance (m)
S1	0.026	0.042
S2	0.040	0.063
S3	0.012	0.022

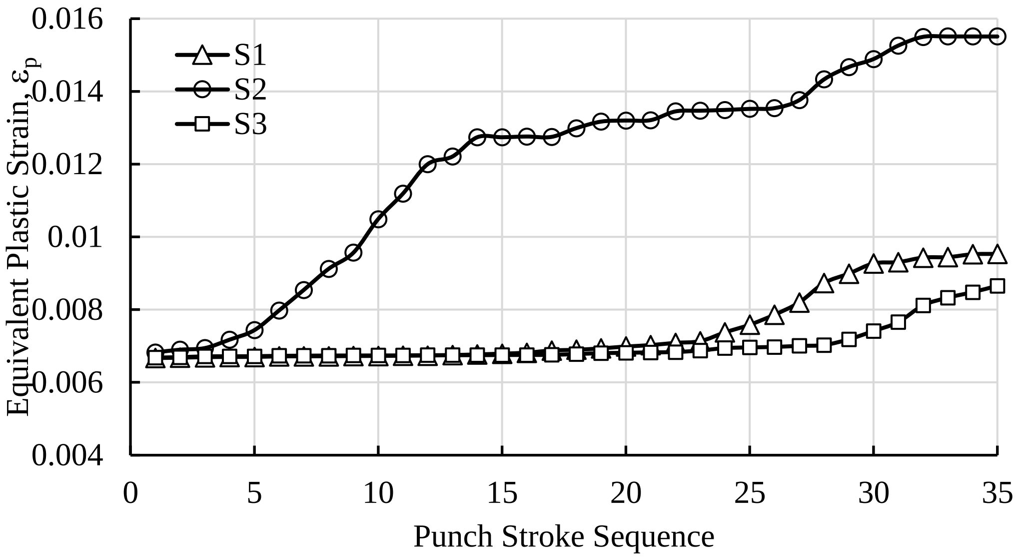


Figure 10. Variation of $\bar{\varepsilon}^p$ with Punch Strike Sequence for the S1-S3.

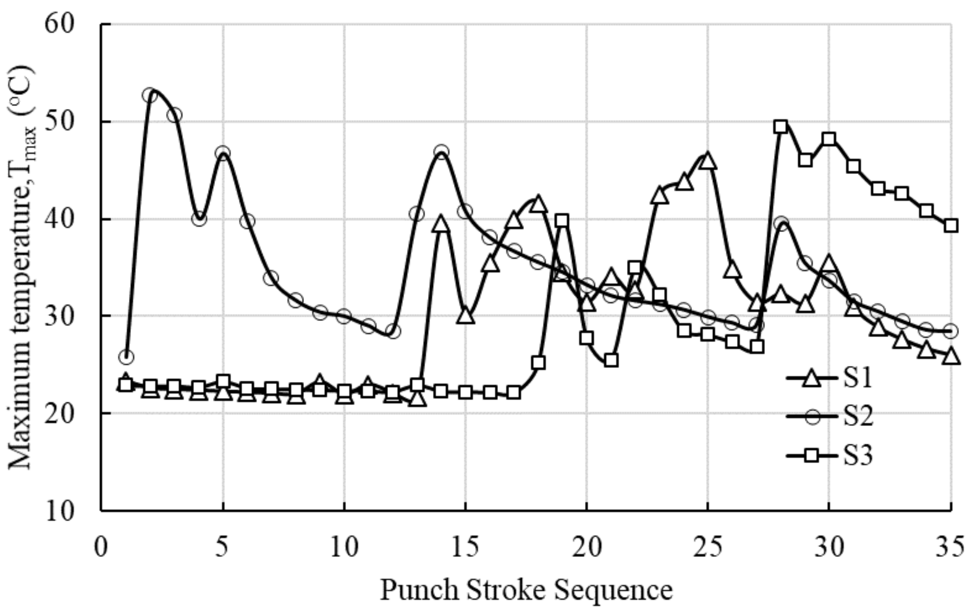


Figure 11. Variation of T_{max} with Punch Strike Sequence for the S1-S3

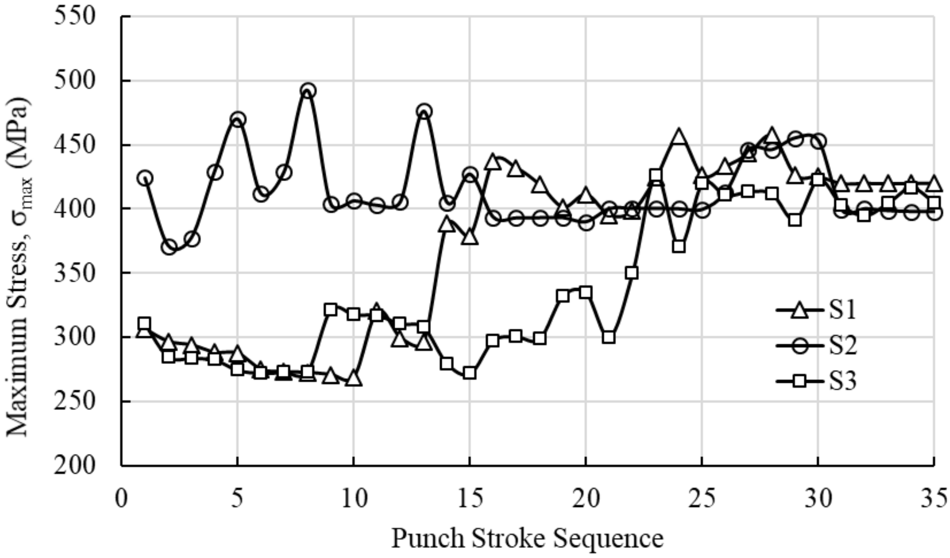


Figure 12. Variation of s_{max} with Punch Strike Sequence for the S1-S3.

4. Conclusion

This study investigated how three distinct punch striking application procedures (S1–S3) affected the Invar FeNi36 plate's ability to be cold-formed into a fuselage panel lay-up mold. The processes' finite element simulation led to the following conclusions:

Regarding volume and center distance between the cold-formed plate and the female mold, the S3 method proved to be the most successful in producing the desired plate form.

There was local plastic deformation (penetration marks) on the top surface of the plate in all strategies because the stress values of the plate under the punch at the moment of contact with the mold were higher than the yield strength of the Invar material. Moreover, the strain values were sufficiently high at the moment of plate contact with the female mold to result in plastic deformation and an increase in the Invar plate's temperature. However, despite the higher equivalent strain values in S2, no temperature increase was recorded; this could be due to localized plastic deformation on the plate surface.

Declaration of Competing Interest

No conflict of interest was declared by the authors.

Authorship Contribution Statement

Can ÇOĞUN: Writing, Reviewing, Editing.

Melis HIZARCI İBİŞ: Modelling, Data Preparation, Editing.

References

[1] A. Demircan, A. Kayran, and D. F. Kurtuluş, "Kompozit Yapılı Mini İHA'lar İçin Kalıp Üretim Teknikleri ve Aerodinamik Yüzeylerin Üretimi," *IV.UHUK, Hava Harp Okulu*, İstanbul, 2012, Eylül 12-14, pp.1-13.

[2] C. Töre, "Uçakların Yapısal Üretim Teknikleri ve İmalat Takımları (Takım=T00l, Aparat) (Konserve veya Kola Kutusundan Uçak Gövdesi İmalatı Yapılabilir mi?)" *Mühendis ve Makine,* vol. 43, no. 506, pp. 33-38, 2020.

[3] Milli Eğitim Bakanlığı, *Plastik Teknolojisi-Makina Enjeksiyon Kalıpçılığı-2*, MEGEP, Ankara, 2008.

[4] H. Y. Shahare, A. K. Dubey, P. Kumar, H. Yu, A. Pesin, D. Pustovoytov, and P. Tandon, “A Comparative Investigation of Conventional and Hammering-Assisted Incremental Sheet Forming Processes for AA1050 H14 Sheets,” *Metals*, vol. 11, no. 11, 1862, pp. 1-17, Nov. 2021, doi:10.3390/met11111862

[5] J. K. Paik, J. H. Kim, B. J. Kim, and C. H. Tak, “Analysis of spring-back behavior in the cold-forming process of three-dimensionally curved metal plates,” *ASME 29th Int. Conf. on Ocean, Offshore Arctic Eng*, pp. 929-934, Jan. 2010, doi:10.1115/OMAE2010-20759.

[6] X. Li, and S. Hu, “Research Progress of Springback in Multi-Point Forming of Sheet Metal,” *J Phys Conf Series,* vol. 2101, no. 1, 2101 012006, Nov. 2021, doi:10.1088/1742-6596/2101/1/012006

[7] M. Bojahr, H. Prommer, R. Tschullik, and P. Kaeding, “3-Dimensional Forming of Thick Plates–A Comparison of Deep Drawing and an Approach of Rolling and Bending Within a Single Process,” *8th European LSDYNA Conf.*, Straßburg, France, 2011, May 23-24, pp.1-7.

[8] A. Köken, and E. Kurt, “Nonlinear Finite Elements Analysis of Different Steel Connections Using Ansys Workbench,” Konya Technical University, 2022.

[9] QForm, ‘’Software for Simulation and Optimization of Metal Forming Processes and Metal Profile Extrusion.’’ QForm UK. Accessed: Feb. 15, 2024. [Online]. Available: https://www.qform3d.com/products/qform.

[10] Defense Metal, ‘’Invar 36 (Alloy 36, Nilo 36).’’ Defence Metal. Accessed: Feb. 20, 2020. [Online]. Available: https://www.defencemetal.com/invar-36/.