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FINITE ELEMENT-BASED COMPARATIVE ANALYSIS OF MULTI-MATERIAL SHEET METAL BENDING UNDER VARIABLE CONTACT AND MESH CONDITIONS

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Abstract— **Sheet metal bending is one of the most widely used forming processes in the automotive, aerospace, railway, shipbuilding, and consumer-product industries. Component quality is governed by material properties, tool–workpiece contact interaction, mesh quality, friction, and boundary conditions, so accurate prediction of stress, strain, and deformation is essential for reliable design. This paper presents a comparative finite element investigation of sheet metal bending for three engineering materials — Mild Steel, Stainless Steel, and Aluminum Alloy — performed in ANSYS Workbench Static Structural. A punch-sheet-die assembly was modeled and analyzed under Bonded, Frictionless, and Frictional contact formulations, and under Coarse, Medium, and Fine mesh refinement levels. Results are compared in terms of Equivalent (Von-Mises) Stress, Total Deformation, Equivalent Elastic Strain, Contact Pressure, Reaction Force, and computational time. Stainless Steel produced the highest stress, contact pressure, and reaction force but the least deformation, while Aluminum Alloy showed the lowest stress and stiffness but the greatest deformation; Mild Steel exhibited balanced, intermediate behavior. Frictional contact predicted the highest, most realistic stresses, and the medium mesh offered the best accuracy-to-cost ratio. The findings provide practical guidelines for selecting materials, contact formulations, and mesh density in finite element simulation of sheet metal bending.**

Keywords— **Sheet Metal Bending; Finite Element Analysis; ANSYS Workbench; Contact Interaction; Mesh Refinement; Multi-Material Comparison; Static Structural Analysis.**

I. INTRODUCTION

Sheet metal forming is among the most important manufacturing processes used to produce lightweight, dimensionally accurate components for the automotive, aerospace, railway, shipbuilding, and consumer-product sectors [1], [2]. Bending, one of the most fundamental forming operations, subjects the sheet to combined tensile and compressive deformation about a neutral axis as a punch forces it into a die cavity [3]. Bending accuracy depends on material properties, sheet thickness, punch radius, die geometry, and friction conditions, and poor prediction of these parameters can cause springback, wrinkling, thinning, or cracking [4].

The growing use of advanced high-strength steels, stainless steels, and aluminum alloys to reduce structural weight has made accurate prediction of elastic–plastic behavior increasingly important, since these materials respond very differently under identical loading [5]. Physical trial-and-error testing is reliable but costly and time-consuming when many material, contact, and process combinations must be evaluated [9]. Finite Element Analysis (FEA) has therefore become the standard numerical approach for simulating sheet metal forming, allowing engineers to visualize stress distribution, strain localization, and contact pressure prior to manufacturing [10], [11].

Two modeling choices most strongly influence the reliability of an FEA prediction: mesh quality and contact formulation. A coarse mesh reduces computation time but can miss localized stress concentration near the punch radius, while an excessively fine mesh adds computational cost with diminishing accuracy gains, making a mesh convergence study necessary [12]–[14]. Likewise, the contact interaction between punch, sheet, and die — commonly idealized as bonded, frictionless, or frictional — governs force transfer and material flow, with frictional contact regarded as the most realistic representation of practical forming [15]–[17].

Although sheet metal bending has been widely studied numerically, relatively few investigations simultaneously examine the combined effect of multiple materials, contact formulations, and mesh refinement levels within one unified framework. This paper addresses that gap by presenting a comparative finite element study of Mild Steel, Stainless Steel, and Aluminum Alloy sheets under three contact conditions and three mesh densities, using ANSYS Workbench Static Structural, and reports the resulting stress, deformation, strain, contact pressure, reaction force, and computational-efficiency trends.

II. MATERIALS AND METHODOLOGY

The finite element model consists of a punch, sheet, and die, developed and analyzed in ANSYS Workbench Static Structural. The sheet is positioned between the punch and die; a downward displacement is applied to the punch while the die remains fixed, producing plastic bending deformation in the sheet. The methodology follows four stages: material modeling, contact-interaction modeling, mesh generation with a convergence study, and application of boundary conditions before the nonlinear static solution is obtained.

A. Material Modeling

Three engineering materials commonly used in sheet metal components were selected for comparison: Mild Steel, Stainless Steel, and Aluminum Alloy. Their mechanical properties, obtained from standard material data, are listed in Table I.

TABLE I. Mechanical Properties of Selected Materials

Property	Mild Steel	Stainless Steel	Aluminum Alloy
Young's Modulus (GPa)	210	193	69
Density (kg/m³)	7850	8000	2700
Poisson's Ratio	0.30	0.30	0.33
Yield Strength (MPa)	250	290	95

B. Contact Interaction Modeling

Three contact formulations were investigated at the punch–sheet and sheet–die interfaces: Bonded contact, which permits no relative sliding or separation; Frictionless contact, which allows unrestricted sliding; and Frictional contact, with a coefficient of friction of 0.2, resolved using the Augmented Lagrange algorithm to represent realistic sliding resistance and material flow.

C. Mesh Generation and Convergence

Three-dimensional tetrahedral elements were used throughout for their suitability to complex contact geometry. Coarse, Medium, and Fine mesh densities were generated and compared through a mesh convergence study, in which the mesh was considered converged once further refinement produced negligible change in predicted stress and deformation.

D. Boundary Conditions and Solution Procedure

The die was fully fixed in all degrees of freedom, and a downward displacement was applied to the punch while the sheet remained free to deform between punch and die; gravity was neglected as the bending force dominates the response. The nonlinear static solver computed equivalent stress, elastic strain, contact pressure, and reaction force incrementally until full punch displacement was reached. Table II summarizes the simulation parameters common to all cases.

TABLE II. Simulation Parameters

Parameter	Value
Analysis type	Static Structural
Software	ANSYS Workbench
Punch motion	Downward displacement
Sheet thickness	2 mm
Contact types	Bonded, Frictionless, Frictional
Friction coefficient	0.2
Element type	3-D tetrahedral
Mesh levels	Coarse, Medium, Fine

III. RESULTS AND DISCUSSION

Simulations were performed for all combinations of the three materials, three contact conditions, and three mesh densities described above. Results are compared in terms of equivalent stress, total deformation, elastic strain, contact pressure, reaction force, and computational efficiency.

A. Equivalent (Von-Mises) Stress

The equivalent stress, used to predict yielding under the Von-Mises criterion, was highest around the punch radius in all cases owing to concentrated plastic deformation in that region. As shown in Fig. 1 and Table III, Stainless Steel consistently produced the highest stress because of its greater stiffness and resistance to deformation, while Aluminum Alloy showed the lowest stress due to its lower Young's modulus. Frictional contact produced marginally higher stress than bonded or frictionless contact in every material, because friction resists material flow and increases localized stress concentration.

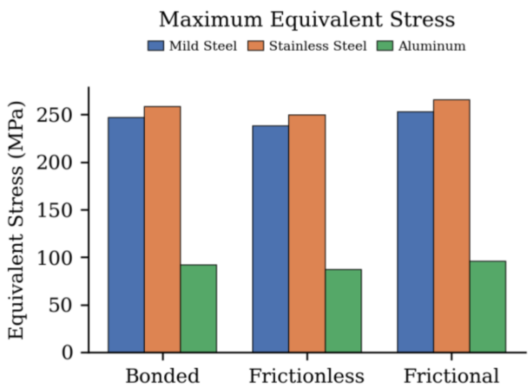

Fig. 1. Maximum equivalent (Von-Mises) stress for each material under the three contact conditions.

TABLE III. Maximum Equivalent Stress

Material	Bonded (MPa)	Frictionless (MPa)	Frictional (MPa)
Mild Steel	246.8	238.4	252.7
Stainless Steel	258.6	249.5	265.3
Aluminum	91.7	87.2	95.6

B. Total Deformation

Total deformation represents the maximum displacement of the sheet during bending. As Fig. 2 and Table IV show, Aluminum Alloy exhibited the greatest deformation because of its markedly lower elastic modulus, whereas Stainless Steel showed the least deformation, confirming its superior stiffness. Frictional contact slightly reduced deformation relative to bonded and frictionless contact because of the added resistance at the sliding interface.

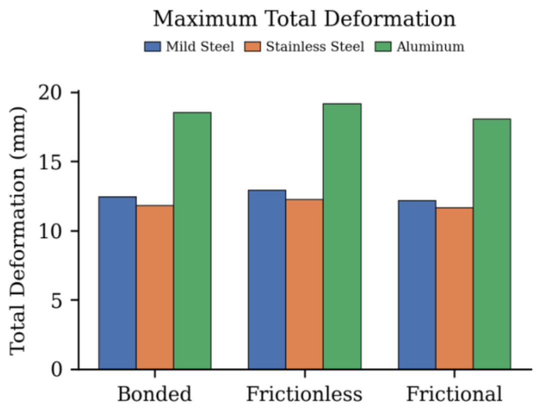

Fig. 2. Maximum total deformation for each material under the three contact conditions.

TABLE IV. Maximum Total Deformation

Material	Bonded (mm)	Frictionless (mm)	Frictional (mm)
Mild Steel	12.45	12.91	12.18
Stainless Steel	11.83	12.26	11.64
Aluminum	18.52	19.17	18.05

C. Elastic Strain, Contact Pressure, and Reaction Force

Equivalent elastic strain follows the same trend as deformation, with Aluminum Alloy showing the highest recoverable strain and Stainless Steel the lowest, consistent with their relative stiffness. Contact pressure and reaction force, by contrast, are governed by material stiffness in the opposite sense: Stainless Steel developed the highest contact pressure and reaction force due to its greater resistance to deformation at the tool–sheet interface, while Aluminum required the lowest reaction force to reach the same punch displacement. These parameters are summarized in Fig. 3 and Table V.

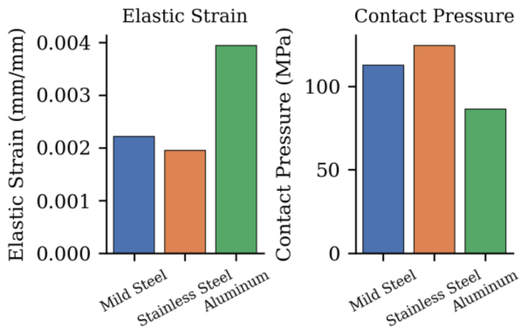

Fig. 3. Equivalent elastic strain and maximum contact pressure by material.

TABLE V. Elastic Strain, Contact Pressure, and Reaction Force

Material	Elastic Strain (mm/mm)	Contact Pressure (MPa)	Reaction Force (N)
Mild Steel	0.00221	112.5	4256
Stainless Steel	0.00195	124.3	4518
Aluminum	0.00394	86.2	3192

D. Mesh Refinement Study

A mesh convergence study compared Coarse (18,540 elements), Medium (46,360 elements), and Fine (102,870 elements) meshes. As shown in Fig. 4 and Table VI, the coarse mesh under-predicted maximum stress and required the least computational time, while the fine mesh gave the highest accuracy at nearly six times the computational cost of the coarse mesh for only a marginal (≈2%) improvement in predicted stress over the medium mesh. The medium mesh is therefore considered the optimum choice, balancing accuracy and computational efficiency.

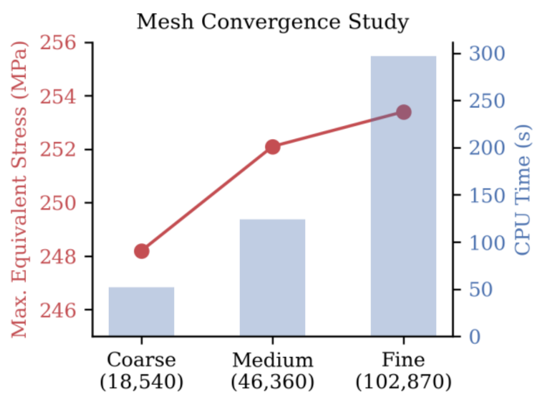

Fig. 4. Mesh convergence study: maximum equivalent stress and CPU time versus mesh density.

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TABLE VI. Mesh Statistics

Mesh	**Elements**	**Max. Stress (MPa)**	**CPU Time (s)**
Coarse	18,540	248.2	52
Medium	46,360	252.1	124
Fine	102,870	253.4	297

E. Effect of Contact Interaction

Table VII compares the three contact formulations qualitatively. Bonded contact assumes no relative motion and is numerically the most stable but does not realistically represent the bending process. Frictionless contact allows unrestricted sliding, producing lower stress but larger deformation than observed in practice. Frictional contact most closely represents actual manufacturing conditions, accounting for sliding resistance and material flow, and is therefore the most suitable contact model despite its modestly higher computational demand.

TABLE VII. Comparison of Contact Conditions

Contact Type	**Stress**	**Deformation**	**Comp. Stability**
Bonded	Moderate	Low	Excellent
Frictionless	Low	High	Excellent
Frictional	Highest	Moderate	Good

F. Comparative Material Performance

Table VIII summarizes the overall comparative performance of the three materials across all evaluated parameters. Stainless Steel offers the highest structural rigidity and load-carrying capability, making it suitable where dimensional accuracy and strength are critical. Mild Steel offers a balanced combination of strength, ductility, and cost, suiting general engineering applications. Aluminum Alloy, despite greater deformation and lower stiffness, is advantageous where light weight is required, such as in aerospace and automotive structures.

TABLE VIII. Overall Comparative Material Performance

Parameter	**Mild Steel**	**Stainless Steel**	**Aluminum**
Eq. Stress	Medium	Highest	Lowest
Total Deformation	Medium	Lowest	Highest
Elastic Strain	Medium	Lowest	Highest
Contact Pressure	Medium	Highest	Lowest
Stiffness	High	Highest	Low

IV. CONCLUSION

A comparative finite element study of sheet metal bending was carried out for Mild Steel, Stainless Steel, and Aluminum Alloy under three contact formulations and three mesh refinement levels using ANSYS Workbench Static Structural. The results show that material properties exert the strongest influence on structural response: Stainless Steel produced the highest equivalent stress, contact pressure, and reaction force but the smallest deformation, reflecting its high stiffness; Aluminum Alloy produced the lowest stress and reaction force but the largest deformation and elastic strain, owing to its lower elastic modulus; and Mild Steel provided balanced, intermediate performance suited to general engineering use.

Contact interaction was found to meaningfully affect predicted stress and deformation. Bonded contact gave stable but unrealistically stiff results, frictionless contact under-predicted stress while over-predicting deformation, and frictional contact — the most representative of practical bending — produced the highest, most realistic stress levels at moderately greater computational cost.

The mesh convergence study confirmed that stress prediction is highly sensitive to mesh density: refining from a coarse (18,540-element) to a fine (102,870-element) mesh increased predicted maximum stress by only about 2%, while computational time increased nearly six-fold. The medium mesh (46,360 elements) offered the best trade-off between accuracy and computational cost and is recommended as the optimum configuration for this class of problem.

Overall, Stainless Steel is best suited to applications demanding high structural rigidity, Aluminum Alloy is preferable where light weight is the governing requirement despite greater deformation, and Mild Steel remains an economical, versatile choice for conventional bending operations. The combination of frictional contact and medium mesh refinement is recommended as the optimum finite element modeling strategy for accurate and efficient simulation of multi-material sheet metal bending.

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