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# FINITE ELEMENT-BASED REVIEW OF MULTI-MATERIAL SHEET METAL BENDING UNDER VARIABLE CONTACT INTERACTION AND MESH REFINEMENT CONDITIONS

Lect. Arun S. Patait, Prof. Baswaraj S. Allurakr
Manufacturing Process Engineering
MBES COE Ambajogai, Maharashtra, India

*Abstract*—**This review paper presents a detailed comparative finite element analysis of multi-material sheet metal bending under varying contact and mesh conditions. The study critically reviews research related to bending mechanics, springback prediction, mesh sensitivity, contact modelling, and deformation analysis using finite element methods. Different materials including stainless steel, aluminium alloys, copper alloys, and high-strength steels are compared under variable contact and meshing conditions. A comprehensive literature review with twenty references and detailed contribution analysis has been included. Research gaps related to adaptive meshing, AI-based optimization, and thermo-mechanical simulation are also identified.**

*Keywords*—**Welded joints, Finite Element Analysis, Residual Stress, Structural Analysis, Weld Materials, Thermo-Mechanical Simulation**

## I. INTRODUCTION

Sheet metal bending is one of the most important deformation-based manufacturing processes used in automotive, aerospace, railway, marine, and heavy engineering industries. The process involves applying force through punches and dies to plastically deform metallic sheets into required geometries. The quality and dimensional accuracy of bent components strongly depend on material properties, bending parameters, contact conditions, frictional interaction, and mesh quality used in numerical simulations. Modern industries demand lightweight and high-strength structures, increasing the importance of accurate bending analysis. Finite Element Analysis (FEA) has become a powerful computational technique for predicting stress distribution, strain evolution, thickness variation, and springback behaviour during sheet metal bending operations. Recent industrial demand for lightweight and high-strength structures has increased the importance of multi-material sheet metal forming analysis.

Numerical simulation enables engineers to optimize weld geometry, compare different weld materials, and predict deformation before fabrication. The accuracy of numerical prediction depends on material properties, contact interaction, friction conditions, and mesh quality. Recent research has focused on multi-material sheet metal bending to improve lightweight structural design and manufacturing efficiency.

## II. DETAILED LITERATURE REVIEW

Swift [1] Swift established the theoretical basis for plastic instability and strain hardening in sheet metal forming operations. His research demonstrated that localized necking and instability strongly influence deformation behaviour during bending and stretching processes. The study introduced important analytical equations used for predicting forming limits in sheet metals. Swift's work became one of the earliest foundations for modern sheet metal bending simulations. His contribution significantly improved understanding of material flow and deformation characteristics during plastic forming.

Hill [2] Hill introduced anisotropic yield criteria for metallic sheets and proved that rolled sheet metals exhibit directional mechanical properties. His work explained that anisotropy significantly affects strain distribution, springback behaviour, and deformation characteristics during bending operations. The proposed yield criterion became widely used in finite element modelling of sheet metal forming processes. Hill's research improved prediction accuracy in bending simulations involving rolled aluminium and steel sheets. His theory remains highly important in advanced material modelling.

Marciniak and Duncan [3] Marciniak and Duncan investigated sheet metal forming mechanics and emphasized the role of friction and tooling geometry in deformation behaviour. Their research demonstrated that friction coefficient significantly affects stress distribution and punch force during bending operations. The study also analyzed strain localization and thickness variation in forming processes. Their work provided practical insights into process parameter optimization for improving forming quality. The research contributed significantly to industrial sheet metal forming applications.

Johnson and Mellor [4] Johnson and Mellor analyzed elastic-plastic bending behaviour and springback mechanisms occurring during unloading. Their study showed that residual stresses generated during bending strongly influence final component geometry. They investigated stress redistribution and neutral axis movement during bending operations. The research highlighted the importance of considering unloading effects in finite element simulations. Their work improved understanding of springback prediction in metallic sheets.

Wagoner and Chenot [5] Wagoner and Chenot reviewed finite element methods used in sheet metal forming analysis. Their research compared implicit and explicit numerical approaches for large deformation problems. The study emphasized the importance of constitutive material modelling and accurate contact interaction in obtaining reliable simulation results. They also discussed industrial applications of finite element simulations in automotive manufacturing. Their work became an important reference for computational sheet metal forming analysis.

Makinouchi [6] Makinouchi proposed improved contact algorithms for industrial sheet metal bending simulations. His research demonstrated that accurate contact modelling between punch, sheet, and die is essential for realistic deformation prediction. The study also highlighted the influence of friction conditions on stress concentration and bending force. Makinouchi emphasized the importance of numerical stability and convergence in nonlinear finite element analysis. His work improved industrial simulation techniques for sheet metal forming.

Belytschko et al. [7] Belytschko and co-authors introduced nonlinear finite element methods for large deformation and contact analysis. Their work focused on explicit finite element techniques suitable for highly nonlinear bending operations. The study demonstrated the advantages of explicit methods in handling contact convergence issues. Their research also discussed numerical stability and mesh distortion during large deformation simulations. The contribution became highly influential in computational mechanics and industrial forming analysis.

Kim and Yang [8] Kim and Yang investigated springback prediction in high-strength steel sheet bending. Their analysis showed that mesh refinement strongly affects prediction accuracy of springback and stress distribution. The study compared different mesh densities and demonstrated that fine mesh near bending regions improves numerical accuracy. Their research also analyzed the influence of material hardening models on springback behaviour. The work provided practical recommendations for mesh optimization in bending simulations.

Li et al. [9] Li and co-authors proposed adaptive meshing techniques for sheet metal bending simulations. Their study demonstrated that adaptive remeshing improves prediction accuracy near highly deformed contact regions while reducing computational cost. The research also discussed mesh distortion problems during large deformation analysis. Their work highlighted the importance of balancing computational efficiency and numerical accuracy. Adaptive meshing approaches proposed in this study became widely used in advanced finite element simulations.

Yoon et al. [10] Yoon and co-authors analyzed anisotropic deformation behaviour of aluminium sheets during V-bending operations. Their research showed that material orientation significantly affects springback and stress distribution. The study compared rolling direction effects on deformation behaviour and strain concentration. Their work demonstrated the importance of anisotropic constitutive modelling for lightweight aluminium structures. The research improved finite element prediction accuracy for aluminium sheet forming applications.

Hill [11] introduced one of the earliest and most influential anisotropic yield criteria for metallic materials. His work explained that rolled sheet metals exhibit directional mechanical properties because of grain orientation developed during rolling operations. The study demonstrated that isotropic plasticity models fail to accurately predict deformation behaviour in sheet metal forming applications.

Hill proposed mathematical equations for representing anisotropic yielding under multi-axial loading conditions. The research significantly improved finite element prediction accuracy for bending, stretching, and deep drawing operations. The anisotropic yield criterion became widely adopted in commercial finite element software such as ABAQUS, ANSYS, and LS-DYNA.The paper also highlighted the influence of material orientation on stress distribution and springback behaviour during bending operations. Researchers later extended Hill’s theory for advanced lightweight materials such as aluminium alloys and high-strength steels.One major contribution of Hill’s work is its application in predicting deformation characteristics in automotive body panel manufacturing. The theory remains highly relevant in modern sheet metal forming analysis because most industrial sheets exhibit anisotropic mechanical behaviour.

Wagoner and Chenot [12] provided one of the most comprehensive analyses of finite element methods used in metal forming applications. Their work discussed both implicit and explicit numerical techniques for solving nonlinear deformation problems in sheet metal forming processes.

The study emphasized that accurate constitutive material modelling is essential for reliable stress and strain prediction. The authors analyzed several material hardening models and demonstrated how strain hardening behaviour affects spring back and deformation during bending operations. Their research also investigated contact interaction between punch, sheet, and die surfaces. The paper showed that friction coefficient and contact algorithm selection strongly influence forming force and stress concentration. Another important contribution was the comparison between shell elements and solid elements in bending simulations. The study concluded that shell elements provide computational efficiency, whereas solid elements improve thickness variation prediction.

Wang et al. [13] proposed a machine learning framework for predicting springback behaviour in sheet metal bending operations. The study integrated finite element simulation datasets with machine learning algorithms such as artificial neural networks and support vector regression. Their research aimed to reduce computational time associated with conventional nonlinear finite element simulations.

The authors generated large datasets from finite element simulations under varying bending angles, material properties, friction coefficients, and mesh densities. These datasets were used to train predictive AI models capable of estimating springback with high accuracy. Their results demonstrated that machine learning models significantly reduced prediction time while maintaining acceptable accuracy levels. The study also highlighted that springback prediction strongly depends on material anisotropy, mesh quality, and contact conditions. The researchers concluded that AI-assisted simulation methods can improve process optimization in automotive manufacturing applications. This research represents an important advancement toward Industry 4.0-based intelligent manufacturing systems and demonstrates the integration of artificial intelligence with computational mechanics.

Park et al. [14] investigated the finite element analysis of multi-material sheet metal forming involving aluminium alloys and high-strength steels for automotive applications. The primary objective of the study was to evaluate deformation behaviour and stress distribution in hybrid lightweight structures.

The researchers used advanced constitutive material models and nonlinear contact algorithms in ABAQUS to simulate sheet metal bending operations. Their results demonstrated that material mismatch significantly affects stress concentration and springback behaviour near the joint interfaces. The study also analyzed the influence of contact pressure and friction conditions on deformation characteristics. Fine mesh refinement near contact regions improved prediction accuracy for localized strain concentration. The authors concluded that hybrid multi-material structures can reduce overall vehicle weight while maintaining structural integrity. However, accurate contact and mesh modelling are essential for realistic simulation results.

Chen et al. [15] proposed adaptive mesh refinement techniques for improving numerical accuracy in large deformation sheet metal bending simulations. The study focused on overcoming mesh distortion and convergence issues observed in conventional finite element analysis.

The researchers developed an adaptive remeshing framework capable of automatically refining highly deformed contact regions during bending operations. Their results demonstrated that adaptive meshing significantly improved stress and strain prediction accuracy while reducing computational cost.

The study also compared static mesh refinement and dynamic adaptive remeshing approaches. Adaptive remeshing showed better numerical stability and convergence performance for complex deformation problems. The authors emphasized that mesh quality strongly influences springback prediction and localized stress concentration near bending corners. Their work contributes significantly toward improving computational efficiency in industrial forming simulations.

Singh et al. [16] investigated thermo-mechanical finite element analysis of sheet metal bending for automotive applications using ABAQUS software. Their study focused on understanding the influence of temperature variation on deformation behaviour, residual stress distribution, and springback characteristics in stainless steel and aluminium alloy sheets. The authors observed that elevated temperature conditions significantly reduce springback because of thermal softening effects and improved ductility. Their analysis also showed that contact pressure and friction coefficient vary with temperature and strongly affect stress concentration near bending regions. García et al. [17] performed finite element investigation on hybrid aluminium-steel sheet bending for lightweight structural applications. Their results demonstrated that dissimilar material properties generate severe stress concentration near interface regions, while aluminium sheets exhibit higher deformation and springback compared to steel sheets. Zhou et al. [18] proposed an artificial intelligence-based mesh optimization framework for finite element sheet metal forming simulations. Their AI-assisted adaptive meshing method significantly reduced computational cost while improving stress prediction accuracy and numerical convergence stability in highly deformed regions. Ahmed et al. [19] investigated damage initiation and failure prediction in high-strength steel sheet bending using nonlinear finite element analysis. Their research revealed that smaller punch radius and improper contact conditions accelerate crack initiation because of severe localized strain concentration. Fine mesh refinement near bending corners improved damage prediction accuracy considerably.

Chen et al. [20] developed a digital twin-based intelligent monitoring framework for sheet metal forming processes by integrating finite element simulations, real-time sensor data, and machine learning algorithms. Their results demonstrated that digital twin systems improve manufacturing accuracy, reduce production defects, and enable real-time optimization of bending parameters such as punch displacement, contact pressure, and friction conditions. These studies collectively indicate that advanced finite element modelling, adaptive meshing, artificial intelligence, thermo-mechanical coupling, and digital twin technologies play a crucial role in improving prediction accuracy, computational efficiency, and manufacturing quality in modern sheet metal bending applications.

## III. COMPARATIVE ANALYSIS OF MULTI-MATERIAL BENDING

Comparative finite element analysis of multi-material sheet metal bending indicates that different materials exhibit unique deformation and springback characteristics under identical loading conditions. Stainless steel sheets generally demonstrate higher strength, improved rigidity, and lower deformation because of higher yield strength and modulus of elasticity.

However, larger punch forces are required to deform stainless steel sheets during bending operations.

Aluminium alloy sheets provide excellent lightweight characteristics and corrosion resistance, making them suitable for aerospace and automotive structures. Because of lower elastic modulus, aluminium sheets generally exhibit larger springback and deformation under bending conditions. Finite element simulations often show higher strain concentration and thickness variation in aluminium sheets compared to stainless steel sheets.

Copper and copper alloy sheets demonstrate excellent ductility and thermal conductivity. These materials are easier to bend and show lower cracking tendency during forming operations. However, their lower strength limits their use in heavy structural applications. High-strength steels provide superior crash resistance and structural integrity but exhibit significant springback because of high yield strength.

## IV. FINITE ELEMENT MODELLING

Finite element modelling of sheet metal bending involves geometry creation, material assignment, meshing, contact definition, and nonlinear analysis. Sheet metals are generally modelled using shell or solid elements depending on required accuracy. Punch and die components are usually treated as rigid bodies to reduce computational cost. Elastic-plastic constitutive models are used to represent yielding and strain hardening behaviour. Contact interaction between punch, sheet, and die significantly affects deformation and stress concentration. Penalty-based and augmented Lagrangian contact algorithms are widely used in commercial finite element software. Mesh quality strongly influences prediction accuracy and computational efficiency. Adaptive meshing techniques improve stress and strain prediction in highly deformed regions.

## V. EFFECT OF CONTACT AND MESH CONDITIONS

Contact conditions significantly influence punch force, stress concentration, frictional behaviour, and deformation characteristics during sheet metal bending. Higher friction coefficients increase stress concentration and forming force requirements. Mesh refinement improves prediction accuracy near bending and contact regions but increases computational cost. Adaptive remeshing techniques help balance numerical accuracy and simulation efficiency. Explicit finite element methods are commonly used for large deformation contact problems because of better numerical stability. Optimized contact and mesh control strategies are essential for accurate springback prediction and dimensional accuracy.

Finite element simulations generally model contact interaction between punch, sheet, and die using penalty-based or augmented Lagrangian algorithms. Higher friction coefficients increase bending force requirements and stress concentration near contact interfaces.

Mesh refinement is another critical factor influencing numerical accuracy in finite element simulations. Coarse mesh reduces computational cost but may fail to capture localized stress concentration accurately near bending regions. Fine mesh improves stress and strain prediction but increases computational time and memory usage.

Adaptive remeshing techniques automatically refine mesh near highly deformed regions while maintaining coarser mesh elsewhere. Researchers have demonstrated that adaptive meshing improves numerical stability and prediction accuracy during large deformation analysis. Several studies also reported that shell elements are computationally efficient for thin sheet analysis, whereas solid elements provide more accurate thickness variation prediction.

Explicit finite element methods are widely used for contact-intensive bending simulations because they handle nonlinear contact convergence more effectively than implicit methods. Contact stiffness, penetration tolerance, and friction coefficient strongly influence convergence behaviour and numerical stability. Optimized contact and mesh control strategies are therefore essential for obtaining realistic bending simulation results.

## VI. RESEARCH GAPS AND FUTURE SCOPE

Although considerable progress has been made in finite element modelling of sheet metal bending, several research gaps remain. Most existing studies neglect thermo-mechanical coupling and strain rate effects during bending operations. Future research should focus on AI-based mesh optimization and machine learning techniques for springback prediction. Advanced anisotropic material models and adaptive meshing strategies can improve numerical accuracy. Integration of sensor-based monitoring and computer vision techniques may enable intelligent manufacturing systems for real-time process control.

## VII. CONCLUSION

This review paper presented a detailed comparative finite element analysis of multi-material sheet metal bending under varying contact and mesh conditions. The literature review highlighted the importance of accurate material modelling, contact interaction, and mesh refinement in improving finite element prediction accuracy. Stainless steel provides high strength and rigidity, whereas aluminium alloys offer lightweight advantages. Copper alloys demonstrate excellent ductility and thermal conductivity, while high-strength steels provide superior crash resistance. Future advancements in adaptive meshing, AI-based optimization, and thermo-mechanical simulation are expected to improve manufacturing accuracy and process efficiency.

## VIII. CONCLUSION

This review paper presented a detailed comparative analysis of welded joints fabricated using stainless steel, aluminium alloy, and bronze weld materials under static loading conditions.

The literature review demonstrated that stainless steel welds generally provide superior structural performance under static loading. Aluminium alloy welds offer lightweight advantages, whereas bronze welds are suitable for brazing applications requiring moderate strength and thermal conductivity.

The study also highlighted important limitations in conventional static structural analysis methods. " Future research should focus on advanced thermo-mechanical modelling, microstructural analysis, and AI-based weld quality prediction systems for improving the reliability of welded structures.

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