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Modeling of bending characteristics of symmetric tri-layer laminated Sheet materials

Ganesh Govindasamy[a]*, Mukesh K. Jain[b]

[a]*Aleris Rolled Products Inc. 26677, West 12 Mile Road, Southfield 48034, Michigan, USA.*
[b]*Department of Mechanical Engineering, McMaster University, 1280 Main St West, Hamilton, L8S4L7, Ontario, Canada.*

Abstract

Bending of sheet materials is widely applied to shaping many automotive, aerospace and other industrial components. Tailored laminate sheet materials are desirable in bending applications where monolithic sheets do not meet the design requirements or manufacturing demands. An accurate analytical model can be effectively utilized for rapid design of components for laminated sheet materials for a given application. Many analytical models based on advanced theory of bending have been proposed in the literature to predict plane strain bending characteristics of monolithic sheet materials. However, there are very few such models for laminated sheet materials. In this study, an analytical model for tri-layer laminated sheet material is developed based on advanced theory of bending. The model considers Mises yielding and Ludwik non-linear plastic hardening with Bauschinger effect for various laminate thickness ratios. Also, a 3D FE model based on Marciniak-Kuczynski (MK) bend test design is developed to assess pure bending characteristics of a symmetric tri-layer aluminum sheet laminate with softer and thinner clad layers on both surfaces and a harder thicker core in the middle. The through-thickness tangential stresses from the analytical model are compared with those from FE model for different clad to matrix thickness ratios. The tangential stresses decrease in magnitude with increasing aluminum clad thickness ratios in the analytical model. This behavior is in good general agreement with the results from the mid-width section for the FE model. The analytical and FE models also yield similar order trend in relative thickness change with increasing clad thickness ratios and with increasing specimen radius of curvature. The 3D FE model exhibited anticlastic curvature at the edges as a result of strain inhomogeneity across the width. Unlike the tangential stress distribution, the tangential strain is maximum at the specimen edges than at the mid-width. The inhomogeneity in stress and strain across the bend line shows that plane strain condition is not consistent across the width of the sheet.

Keywords: Bending, laminate sheets, Analytical modeling, FE analysis

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1. Introduction

Extensive research efforts have been made towards developing engineering materials of superior mechanical properties and performance capabilities in recent years. Performance limitations of monolithic materials in corrosive environments and increasing demands of lightweight materials for automotive applications without compromising much on the strength and stiffness are some of the driving factors for developing multi-layered materials. The increased interest and fast multiplying usage of multi-layered materials is discussed in the recent review work of Gibson [1]. Different alloys are typically roll-bonded to have a multi-layered clad/core structure which provides a unique combination of formability and corrosion resistance, as well as mechanical properties such as strength, ductility, fatigue, impact resistance [2]. Some applications of laminate sheet materials include steel and aluminum bonded sheets for corrosion resistance and weight reduction designed for automotive body [3], roll bonded high strength aluminum alloy coated with soft corrosive resistant pure aluminum for aerospace applications [4] and brazed dissimilar sheets for heat exchangers with differential thermal conductivity and corrosion resistance [5]. Other than roll bonding, a recently developed method that has significantly facilitated large-scale production of multi-alloy, multi-layered Al laminates is the direct co-casting ingot solidification (or fusion) process [6]. With the advances in the manufacturing of laminated sheets, it is apparent that a comprehensive study of the mechanics of laminate sheets would be useful for optimizing the material and geometric composition of the laminate systems. Joining of dissimilar materials in a single component creates inhomogeneity which may result in discontinuity of stress distributions across the sheet thickness when such components are formed by plastic deformation processes, and thus place limitation on their design. Bending of laminated sheet metals is clearly an important area of study because of its wide spread application in sheet metal forming industry. Several approaches to predict bending characteristics of monolithic sheets materials exist in the literature but only a few for laminated sheets. The objective of this work is to develop a mathematical model for symmetric tri-layer laminate sheet material from an existing model for monolithic material. Comparison of model results with 3D finite element plane strain bending in terms of stresses and strains across the mid-section of the thickness area of bending is also carried out to assess its usefulness and limitations.

Nomenclature
σ_{01}, σ_{02} yield strength of matrix and clad
K_1, K_2 strength coefficient of matrix and clad
n_{L1}, n_{L2} strain hardening exponent of matrix and clad (Ludwik hardening law)
r general radius of curvature of a fiber
r_m radius of curvature of the mid surface.
r_i, r_y inside and outside radius of curvature of bent sheet, respectively
r_n current radius of curvature of neutral surface
r_u radius of curvature of unstretched fiber
r_a radius of curvature of inner laminate boundary fiber
r_b radius of curvature of outer laminate boundary fiber
t, t_o deformed and original laminate thickness, respectively
t_{c1}, t_{c2} thickness of inner and outer laminate layers
q_1, q_2 inner and outer laminate to matrix thickness ratios (t_{c1}/t, t_{c2}/t)
$\bar{\epsilon}$ effective strain
$\bar{\sigma}$ effective stress
ε_θ, ε_r tangential strain $\varepsilon_\theta = \ln (r/r_u)$; radial strain $\varepsilon_r, = -\varepsilon_\theta$
σ_θ, σ_r tangential and radial stress components, respectively
η relative thickness, t/to
ρ relative radius of curvature of neutral surface, r_n/r_u,
κ relative curvature, t/r_m