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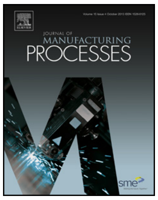

Technical Paper

Numerical and experimental investigations of hydro-mechanical deep drawing process of laminated aluminum/steel sheets

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ABSTRACT

The application of hydro-mechanical deep drawing (HMDD) process on laminated sheets combines advantages of both process and material to improve the forming condition of poor formable light-weight metals such as aluminum alloys. In this research, the HMDD process of anisotropic laminated bimetallic sheets has been analyzed using a 3D finite element simulation with implementing Fortran based code for accurate modeling of non-uniform oil pressure distribution. To verify FE results, experimental works were conducted on the widely used laminated aluminum/steel sheets. Based on the developed FE model, parametric studies were performed to investigate the effect of material parameters such as layers thickness and lay-up arrangement on the forming condition, process window and formability of aluminum sheet as key process parameters. Results demonstrated that suitable process condition to attain a successful forming of bimetallic aluminum/steel sheets can be predicted by developed FE model reasonably. Also, It shown that wider working zone was achievable with decrease in drawing ratio, reduction in thickness of sheet with lower strength layer and also when aluminum sheet is in contact with punch (A/S lay-up). In addition, the higher limiting drawing ratio (LDR) and lower thinning in low formable aluminum sheet would be achievable in A/S lay-up than S/A lay-up.

1. Introduction

Application of laminated structures and components made of sheet metals with mismatch materials has been developed primarily because of making various combined mechanical, physical, and chemical properties by the base materials. Laminated metal sheets can be fabricated using different joining methods such as explosive welding, roll bonding and adhesive bonding. Among, two-layer composite sheets manufactured by roll bonding composed of one layer with appropriate strength and a good corrosion resistance, wear resistance, or electrical conductivity of the other layer, have found wide applications in chemical, electrical, ship, food and building industries [1].

In recent years, much attention has been paid on forming processes of applicable two-layer metal sheets by several researchers. Due to different mechanical properties of base materials and key role of failure analysis of these laminated sheets, formability of two-layer sheets is of great interest by researchers. Parsa et al. [2] investigated the effect of thickness ratio and layers arrangement on the achievable drawing ratio in the deep drawing of aluminum/stainless steel two-layer sheets numerically and experimentally. Results showed that the aluminum to steel thickness ratio of 1/3 can result in a maximum drawing ratio. Formability of aluminum/copper two-layer sheets fabricated using the roll bonding process at different thickness ratios was studied by Tseng et al. [3] through finite element (FE) simulation and experiment. Because of residual stresses induced in the laminated sheet by the rolling process, it was reported that the formability of monolithic sheets is higher than that of two-layer sheets. Morovvati et al. [4] showed that the necessary blank holder force to avoid wrinkling in the conventional deep drawing of the aluminum/steel two-layer sheet prepared by adhesive bonding is lower and higher than that for a monolithic sheet of the base material with higher and lower strength, respectively. Jalali et al. [5] studied the effect of mechanical properties of base materials on formability of A1100/St13 two-layer sheets. The proposed theoretical model demonstrated that the forming limit diagram of the two-layer sheet is between the one of the constituent materials. Using experimental and numerical

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investigations on the deep drawing of aluminum/copper two-layer sheets, Atrian and Saniee [6] demonstrated that the layers arrangement can significantly affect the final part characteristics. Maleki et al. [7] studied the bonding strength and the critical thickness reduction in the rolling process of aluminum/steel two-layer sheets by using the analytical, numerical, and experimental approaches. They reported that the bonding strength and the critical reduction can be considerably affected by the yield strength and initial thickness of layers. The significance of adhesive bonding properties for the formability of steel two-layer sheets was researched by Satheeshkumar and Narayanan [8]. Based on experimental tensile tests, they concluded that by increasing the ratio of hardener to resin, the formability increases. Also, implementing an adhesive layer with a specified thickness between the two base layers can result in an improved longitudinal elongation when compared to a monolithic sheet or a two-layer sheet without any adhesive layer.

In previous researches, investigation on formability of sheets by making them as laminated sheets in the traditional forming processes like conventional deep drawing have been considered. Besides the conventional techniques, the sheet hydroforming process itself lead to an improvement in the formability of the sheet metal. Also, application of hydroforming process with high fluid pressure makes sure that sheet and punch contacts together during forming process tightly. Therefore, sheet hydroforming processes can be utilized to form multi-layer sheets with limited formability sheets more effective. In recent years, different sheet hydroforming methods have been extensively developed on forming of monolithic sheets and have been studied by using experimental and analytical approaches. Among them, hydro-mechanical deep drawing (HMDD) is one of the most widely used processes. In the HMDD process, as the punch moves against the pressurized fluid beneath the sheet, the blank is deformed to conform to the punch geometry. Fig. 1 schematically illustrates the HMDD process with its hydraulic circuit.

Lang et al. [9] conducted some experiments to investigate the process window in the one-layer HMDD process assisted by radial pressure at the flange edge. They found that by increasing the drawing ratio, the process windows for the pre-bulging pressure, the gap between the blank holder and the die, and the pre-bulging height become narrower. Fazli and Dariani [10] employed FE simulations based on the shell formulation to establish safe working zones for the fluid pressure vs. the drawing ratio in the HMDD of axisymmetric aluminum cups under the assumption of a uniform chamber pressure. They showed that it will be possible to reach higher drawing ratios in the HMDD process than in the conventional deep drawing if proper die radius, initial chamber pressure, and friction condition are adopted. In a similar work by Azodi et al. [11], using a tensile instability criterion under the plane strain assumption it was analytically shown that as the drawing ratio and the punch corner radius increase the critical fluid pressure decreases. Choi et al. [12] presented an analytical model capable of predicting wrinkling, fracture, and floating condition of the one-layer sheet metal in the warm HMDD process of axisymmetric parts and obtained the process window for the three effective parameters including the fluid pressure, the blank holder force, and the punch speed at a specified working temperature. The safe working zone in the HMDD of square cups was studied by Rahmani et al. [13] through FE modeling. They concluded that increasing the friction between the blank and the punch results in a wider working zone while decreasing the friction between the sheet and the blank holder has a reverse effect. Also, a higher drawing ratio can be achieved by using a larger radius of the punch corner.

Unlike the above mentioned work mainly focused on the hydroforming of monolithic sheets, Lang et al. [14] conducted numerical and experimental investigations on the hydroforming of multi-layer metal sheets consisting of a very thin aluminum layer in the middle and two steel sheets on both sides of that layer. Effects of layers arrangement and anisotropic properties of the two outer layers on the formability of the thin aluminum layer were studied. It was shown that the formability of the thin aluminum layer can be improved further as higher friction coefficients are considered between layers. To enhance the limited formability of the titanium alloy sheet, Tseng et al. [15] implemented the sheet hydroforming process for manufacturing a battery housing made of a titanium/aluminum two-layer sheet. Recently, instability of two-layer metal sheets in the HMDD process has been analyzed by Bagherzadeh et al. [16]. They predicted forming force and maximum fluid pressure as both experimentally and theoretically. The effect friction, layers arrangement and layers thickness ratio on the maximum critical pressure was assessed. Results showed that the analytical model is capable for calculating the maximum fluid pressure but cannot predict the entire safe working zone for the fluid pressure as well as formability, strain and thickness distribution of layers accurately.

In this research, a 3D finite element model was developed for accurate simulating the HMDD process of AL/St bimetallic sheet using commercial code Abaqus with dynamic explicit method. Unlike the previous researches considering a constant pressure on blank surface in the HMDD of monolithic sheets, a non-uniform fluid pressure model varying with time is incorporated into the Abaqus software as user-defined subroutine. The key parameters in sheet hydroforming such as entire process window (fluid pressure working zone), forming force, strain and thickness distribution of layers and forming limit diagram (LDR) predicted for HMDD process of laminated AL/St sheet. The experimentally validated FE model is used for studying the effect of layers arrangement on process parameters.

2. Experiments

2.1. Laminated sheets

Regarding wide industrial applications of aluminum/steel laminated sheets, in this research, two-layer sheets of low carbon steel st13 and aluminum alloy AA1050-O are considered. The selected sheet metals profit from the strength and formability of the steel sheet as well as the corrosion resistance, low density, and electrical conductivity of the aluminum sheet. Aluminum/steel two-layer sheets of 1.1 mm thickness with different combinations of the base sheet metals thickness were laminated by a two-component polyurethane base adhesive using binding method as described in [16]. The mechanical properties of the base sheet metals were determined according to ASTM E8-M standard along the rolling directions of 0°, 45°, and 90°, as depicted in Table 1.

Table 1
Mechanical properties of the base materials.

Properties	Low carbon steel (St13)	Aluminum (AA1050-O)
Thickness, t (mm)	0.4	0.7
Young modulus, E (MPa)	210,000	70,000
Yield strength, Y_0 (MPa)	152	35
Tensile strength, Y_S (MPa)	282	75
Strain hardening exponent, n	0.29	0.275
Hardening coeff., K (MPa)	496	112
Lankford anisotropy coefficients		
r_0	0.97	0.42
r_{45}	1.05	0.60
r_{90}	1.42	1.33