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Original Research Article

Prediction of formability of adhesive bonded steel sheets and experimental validation

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ABSTRACT

The main aim of the present work is to predict the formability of adhesive bonded sheets and validate the same with experimental results at different adhesive properties. The tensile and in-plane plane-strain formability tests are carried out to predict the formability of adhesive bonded sheets. The forming limit strains are predicted using thickness gradient necking criterion (TGNC) and effective strain rate criterion (ESRC), and validated with the experimental limit strains. A simulation methodology has been analyzed thoroughly in the present work, and the prediction accuracies are compared and discussed.

The results show that the adhesive bonded blanks show improved elongation and forming limit strains as compared to un-bonded base materials with increase in hardener/resin ratio of adhesive. The true stress–strain predictions are accurate as compared to experimental data. There is a moderate difference in adhesive bonded sheets limit strains between predictions and experiments. This may be due to the absence of interface bonding between adhesive and base materials during predictions. The necking criterion, TGNC, shows better prediction as compared to ESRC.

1. Introduction

Adhesive bonding is one of the efficient structural component joining techniques in which an intermediate adhesive layer is used to bond substrates of different materials. Adhesive bonded sheets fabricated by this technique are utilized in the structural applications. Basic studies on the adhesive systems have been carried out to investigate the influence of different hardener/resin ratios and filler materials in the epoxy adhesive system. d'Almeida and Monteiro [1] investigated the influence of different resin/hardener ratios of the epoxy monomer, diglycidyl ether of bisphenol-A (DGEBA), with an aliphatic amine, triethylene tetramine (TETA) on mechanical properties by compression test. The results showed that the epoxy rich systems showed brittle behaviour which is associated with the development of a rigid macromolecular structure and the hardener rich systems showed fracture behaviour with a large deformation.

In the modelling of adhesive bonded blanks, Crocombo [2] stated that the term global yielding, which applies when a path of adhesive along the overlap region reaches the state in which it can sustain no further significant increase in applied load. It was found that global yielding gives accurate joint strengths

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during prediction. Kim et al. [3] introduced the superimposed finite element method for adhesive bonded joints to overcome difficulties in manual meshing technique. A cohesive zone model was used to model the interface between substrates and adhesive layer. It was found that the simulation of adhesive joints with the superimposed finite element method is efficient in view of the finite element discretization and shows accurate results.

The formability study on a two layer metallic sheet (Al1100/St12) bonded by polyurethane adhesive were performed by Aghchai et al. [4]. The two-layer sheet was assumed as an equivalent to a one-layer sheet by deriving equivalent mechanical parameters. In the other method, the mechanical properties of each layer were separately utilized to the two-layer sheet. It was observed that the two layer sheet improves the formability of a sheet which has low formability, but the influence of adhesive layer was not addressed. Morovvati et al. [5] investigated the influence of BHF on wrinkling of two-layer (aluminium-stainless steel) sheets bonded using polyurethane adhesive in the deep drawing process through an analytical method, FE simulations, and experiments. The results showed that the optimum BHF is dependent on the blank geometry, material properties and lay-up. It was observed that increase in blank holding force (BHF) decreases wrinkling in the deep drawing. Parsa et al. [6] carried out spring back evaluation of AA3105/polypropylene/AA3105 sandwich sheet materials after being subjected to double-curvature forming. Numerical simulation of double-curvature forming process was carried out using finite element programmes. It was found that the increase of tool radius in one direction not only decreased the spring back in that particular direction but also reduced the spring back in right angular direction.

Satheeshkumar and Ganesh Narayanan [7] investigated the influence of adhesive properties on the formability of adhesive-bonded dissimilar steel sheets. It was postulated and demonstrated that the improvement in formability of adhesive bonded blanks is due to the increase in elongation or improved plastic deformation of adhesives with increase in hardener/resin ratio. Further, increase in aspect ratio of artificially generated adhesive defects defect reduces the ductility of adhesive layer and thereby decreases the formability of adhesive bonded blanks. It was highlighted that the aspect ratio of the finite adhesive defect influences significantly on the formability of adhesive bonded blanks [8].

Takiguchi and Yoshida [9] analyzed the plastic bending of adhesive-bonded sheet metals through V-bending experiments. The specific increase of shear strain, as well as of the punch load which related directly to the change of the die-sheet contact boundary conditions was analyzed. The condition of deforming sheet at the initial stage supported by two edges of die was so called 'air-bending condition'. It was recommended that the air-bending operation for adhesive-bonded sheet metals for suppressing the shear deformation of the adhesive layer to within an acceptable limit. Further, the same authors proposed a new technique of plastic bending of adhesive-bonded sheet metals. The effect of forming speed on the deformation characteristics of adhesively bonded aluminium sheets was analyzed through V-bending experiments and numerical simulations using a rate-dependent constitutive model of plasticity for the adhesive. It was found that the large shear deformation and the geometrical imperfection caused by large transverse shear deformation occurring in the adhesive layer are suppressed by high-speed forming since the deformation resistance becomes higher at high strain rate [10].

From the above discussion, it is understood that the adhesive properties influence significantly the mechanical properties of the adhesive bonded blanks. The studies on the formability of bonded sheets have been addressed to a lesser extent. Most of the present studies are based on the delamination behaviour, strength requirement and rheological analysis. The main objective of the present work is to predict the forming behaviour of adhesive bonded sheets, namely tensile behaviour and in-plane plane strain (IPPS) formability, at different adhesive properties. Since adhesive bonded blanks are being used in almost all manufacturing sectors, this study will be helpful to sort out quickly the decisions by conducting similar virtual experiments. The mechanical properties of adhesives obtained from tensile tests are utilized for predicting the forming behaviour of adhesive bonded blanks without considering interfacial bonding between adhesive and base materials. The limit strains of adhesive bonded blanks are evaluated by using thickness gradient based necking criterion (TGNC) and effective strain based necking criterion (ESRC) which are used for predicting limit strains of unbonded sheet metals. These two necking criteria are used to check the applicability of predicting the limit strains in adhesive bonded blanks. Finally, the predicted results are validated with experimental data.

2. Methodology

In this section, the materials used in the experiments and the method of determining mechanical properties of epoxy adhesive, DDQ steel and SS 316L sheet metals are discussed. The method of evaluating the forming behaviour of adhesive bonded blanks through experiment is described. The representation of adhesive bonded blanks to predict their formability is illustrated. The formulation for predicting the true stress–strain behaviour of adhesive bonded sheets, and the necking criteria used for predicting the limit strains in base materials constituting adhesive bonded blanks are also presented.

2.1. *Experimental materials and mechanical properties*

Two dissimilar materials namely deep drawing quality (DDQ) cold rolled steel ($C\% = 0.100$, $Si\% = 0.12$ and $Mn\% = 0.600$) and stainless steel (SS316L) ($C\% = 0.016$, $Si\% = 0.335$, $Mn\% = 1.209$, $Cr\% = 16.413$, $Ni\% = 10.222$) sheets were used as base materials in the fabrication of adhesive bonded blanks. The thickness of base materials is 0.6 mm each. The base materials were tested as per ASTM E646-98 standard and the mechanical properties are tabulated in Table 1. The plastic strain ratio (*R*) was evaluated as per ASTM-E517 standard. The adhesive system used in this study was commercially available Bisphenol-A-Epicholorhydrin type epoxy resin (Part A) and Polyamidoamine type hardener (Part B). The adhesive properties are varied by changing the hardener/resin ratio. The stoichiometric ratio of hardener/resin ratio of epoxy adhesive system is 0.8:1.