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Experimental investigation and numerical modeling of the bond shear strength of multi-layered 6000 series aluminum alloys

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Abstract

The use of high-strength aluminum alloys is one key factor for the realization of lightweight design in industrial applications. Besides alloying, it is possible to produce high-strength sheet materials using the Accumulative Roll Bonding (ARB) process. Based on a repetitive stacking and roll bonding process, multi-layered sheets with a nanocrystalline grain structure are produced. The bond formation is created by a cold welding process due to the high pressure in the rolling gap and cracks in the oxide film of the aluminum sheet material caused by the thickness reduction. The experimental investigation of the bond strength is crucial for the assessment of the formability of the multi-layered sheet material. High bonding quality is necessary in order to prevent failure mechanisms like delamination in subsequent forming operations. Furthermore, a numerical model, which contains discrete layers over the sheet thickness as well as their bonding mechanisms will be implemented in finite element analysis. This enables a process layout for forming operations by the prediction of delamination effects. Within this investigation, an experimental test method is presented to characterize the bond shear strength of multi-layered sheet material. The use of an optical strain measurement system enables the identification of the material behavior over the sheet thickness during the shear test. For this investigation a 16-layered aluminum alloy AA6014 is used. However, the bond shear strength of the last bonded respectively middle layer of the sheet material is investigated. The 16-layered material has 15 bonds over the thickness but the one in the middle has the lowest bond strength as it was only roll bonded once compared to the others, which were rolled at least twice. The bonding mechanisms are modelled using a tiebreak contact formulation in the finite element software LS-DYNA. Concluding, the numerical model is validated by comparison with the experimental results.

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Keywords: Sheet metal; Bonding; Modeling

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1. Introduction

Driven by the ongoing trend towards lightweight design in several industrial fields like the automotive industry, a demand for high-strength aluminum alloys exists. The Accumulative Roll Bonding (ARB) process, which was first presented by Saito et al. [1] in 1998 enables the production of high-strength sheet material by a repetitive stacking and roll bonding without changing the overall dimensions. A significant grain refinement is caused by high strains, which are characteristic for Severe Plastic Deformation (SPD) processes like ARB [2]. Besides the strengthening mechanism, a significant decrease of the formability is investigated for technological relevant aluminum alloys like the precipitation hardenable alloys of the 6000 series.

The forming behavior of multi-layered sheet material with 4 up to 256 layers was already investigated for the aluminum alloy AA6016 [3]. In bending experiments, the specimens failed by crack formation at the outer side of the bending edge as well as delamination of single layers. In this context, the characterization of the bonding behavior is crucial for the application of forming operations using roll bonded sheet material. Furthermore, a numerical model has to be established and validated for the prevention of delamination mechanisms within the scope of process design.

However, the assessment of the bond strength of multi-layered sheet material is challenging. There are several experimental methods, which can be carried out to characterize the bond strength. Buchner et al. [4] used the reverse bend test according to EN ISO 7799 in order to investigate the bonding behavior for 2-layered roll bonded composites of a 6000 series aluminum alloy and IF-steel. Within this test setup, the specimens are bent alternately to ± 90°. The bond strength is measured qualitatively by the number of bends before failure. Another method is the peel test according to ASTM-D1876-01 or DIN EN ISO 11339. Rectangular strips are peeled using a universal testing machine. The average peel strength can be calculated from the average peeling force over the measured distance divided by the width of the specimen. Jamaati and Toroghinejad [5] used this method to identify the effect of different rolling parameters on the bond strength for the aluminum alloy AA1100. The reverse bend test as well as the peel test are feasible to measure the influence of different process parameters like the rolling velocity on the bond strength. However, it is not possible to investigate a quantitative measure like the failure stress in normal as well as transverse direction of the bonded layers. Govindaraj et al. [6] presented the tensile bond strength test which enables the assessment of the failure stress in normal direction to the sheet plane. Circular specimens are glued together with aluminum rods on both sides in order to clamp it using a universal testing machine. Nevertheless, this method is limited by the tensile strength of the glue. The bond strength in transverse direction to the sheet plane was already investigated by Buchner et al. [4] for 2-layered aluminum-steel composites using shear tests. One groove is machined from each side of the specimen in normal direction to the sheets plane. The depth is equal to the thickness of one layer. The shear zone is defined by the distance between the slots, which has to be chosen with care in order to avoid plastic deformation outside the analysis area. Based on these prerequisites, the specimen preparation is challenging and the test method is limited to small shear stresses in comparison to the yield stress of the base material.

Within this contribution, an experimental procedure is presented to investigate the bond shear strength of multi-layered aluminum sheet material. Additional to the test setup presented by Buchner et al. [4] the method of Digital Image Correlation (DIC) is used in order to identify the local material behavior over the sheet thickness during the shear test. A finite element analysis is carried out with the commercial software LS-DYNA to model the shear test. The bonding behavior is mapped by a tiebreak contact formulation and is validated by the experimental results.

2. Material

The aluminum alloy AA6014 is used for the ARB process in this contribution. This material is a precipitation hardenable alloy, which is typically used in the automotive industry. In Table 1, the chemical composition according to the material suppliers' data sheet is presented. The initial sheet thickness is 1.0 mm and the sheet dimension used for the ARB process is 450 x 1000 mm^2. A solution heat treatment is carried out for the semi-finished product at a temperature of 520 °C for 1 hour prior to the roll bonding process.