Materials and Design 132 (2017) 215–224

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Evaluation of the physical mechanisms of adhesively bonded metal-based hybrid material systems under tensile loading

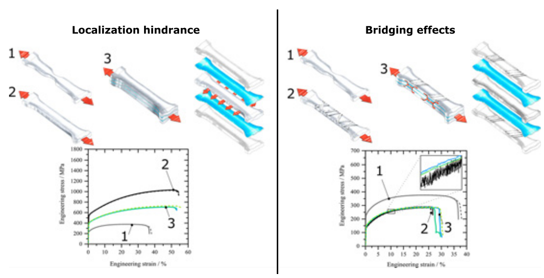
D. Hummelberger [a,c,*], L. Kärger [a], K.A. Weidenmann [b], J. Staeves [c], F. Henning [a]

[a] Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology (FAST), Lightweight Technology (LBT), Karlsruhe, Germany
[b] Karlsruhe Institute of Technology (KIT), Institute of Applied Materials (IAM), Karlsruhe, Germany
[c] BMW Group, Research and Innovation Centre (FIZ), Munich, Germany

HIGHLIGHTS

- The physical mechanisms supporting effect, multiple necking and lateral contraction hindrance lead to changes of the manifestation of PLC bands.
- A 5% improvement in elongation at break in comparison to the monolithic aluminum can be demonstrated.
- The physical mechanisms localization hindrance and bridging effect lead to a change in strain path of the intermediate HC220Y layer.
- The change in strain behavior enables stabilization of plastic instabilities of the HC220Y layer, thus enlarged uniform elongation.
- An up to 25% improvement in uniform elongation compared to monolithic HC220Y can be achieved by this type of hybridization.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 March 2017
Received in revised form 17 May 2017
Accepted 1 July 2017
Available online xxxx

Keywords:
Hybrid material systems
Experimental characterization
Strain field
Temperature field
Finite element analysis
Strain path

ABSTRACT

Hybrid material systems result from the specific combination of different materials. For optimized design of hybrid materials for lightweight structures, a profound knowledge regarding the interaction of its constituents is essential. This paper systematically analyzes and assesses adhesively bonded hybrid material systems consisting of different sheet metals in terms of their underlying physical mechanisms under uniaxial tensile loading. Hybrid solutions constructed of Interstitial-Free steel and twinning-induced plasticity steel as well as combinations of Interstitial-Free steel with an aluminum alloy are investigated in the course of this work. It is shown that the hybridization-induced mechanisms, bridging effect, multiple neck formation and localization hindrance, contribute to changes in the strain paths of the individual layers of the hybrid material system. These changes of the strain behavior enable stabilization of plastic instabilities of specific layers and, based on that, an up to 25% improvement in uniform elongation of these layers in comparison to the monolithic material. By consistent implementation of a design strategy based on the presented mechanisms for the stabilization of plastic instability, material combinations with improved ductility and tensile strength can be obtained.

* Corresponding author.
E-mail address: david.hummelberger@kit.edu (D. Hummelberger).

http://dx.doi.org/10.1016/j.matdes.2017.07.001
0264-1275/© 2017 Published by Elsevier Ltd.

1. Introduction

Hybrid material systems are created by the specific combination of materials from different classes, levels and/or sub-levels [1,2]. As a result, complex property profiles can be achieved which cannot be attained by monolithic material solutions. Despite the fact that hybrid materials are already partly in series in different industries, a comprehensive understanding for the specific selection and combination of materials of the composite is still lacking in many areas. As a consequence, the potential of hybrid composite materials cannot be fully utilized. For a more efficient design of future lightweight structures, a profound knowledge of the interaction of the individual components of the hybrid material system is essential.

One of the first studies on the quasi-static tensile behavior of laminated metal composites (LMCs) combining ultrahigh carbon steel (UHCS) with 304 stainless steel, Hadfield manganese steel or Fe-3%Si alloy is presented by Lee et al. [3]. They performed tensile tests on roll bonded laminates after different conditions of selective heat treatment. The combination of UHCS and 304 stainless steel results in about doubled elongation at break in comparison to the single UHCS. However, the ductility of monolithic 304 stainless steel is far from being achieved [3].

In addition, the improvement of ductility of roll bonded laminates containing steel sheets is presented inter alia by Bouaziz et al. [4], Syn et al. [5], Koseki et al. [6], Inoue et al. [7] and Lesuer et al. [8]. Two-layered LMCs containing martensitic steel and high manganese twinning-induced plasticity (TWIP) steel result in high yield strength and especially high uniform elongation [4]. An improvement of tensile ductility and strength can also be attained by composites constructed of UHCS and brass [5], of high strength (martensitic) steel and high ductility (austenitic or low carbon) steel [6,7] as well as magnesium alloy and austenitic steel [6]. An enhancement of elongation at break with decreased layer thickness is presented by Syn et al. [5] and Inoue et al. [7]. According to Ref. [5], this effect of the layer thickness is attributed to residual stress whose influence on delamination is reduced with decreasing layer thickness.

The tensile behavior of laminates based on steel and aluminum sheets is examined by Semiatin et al. [9]. The stable and unstable plastic flow of three-layered stainless steel-clad aluminum and aluminum-clad stainless steel sandwich sheet materials is evaluated with uniaxial tensile tests. The tensile ductility is between the characteristic values of the two monolithic materials of the hybrid solution. In addition, unstable deformation occurs due to the necking of the layers and delamination arises through the plasticity-induced thinning of the individual layers [9].

First investigations on strain fields as well as the stress partitioning of roll bonded laminates containing steel sheets are presented inter alia by Lhuissier et al. [10], Nambu et al. [11] and Ojima et al. [12]. In Ref. [10], the strain fields are investigated for laminates constructed of 13 alternating layers of high-carbon steel (SUS420) and ductile steel (SUS301). The significantly improved tensile ductilities are attributed to the macroscopically homogenous strain field across the specimens. Thus, in the martensitic steel the onset of failure is delayed [10,11]. Stress partitioning in LMCs containing martensitic and austenitic layers was investigated during uniaxial tensile tests with in situ neutron diffraction measurements by Ojima et al. [12]. According to Ref. [12], the deformation mode is divided into three stages, a fully elastic, a partially plastic as well as a fully plastic stage. However, no detailed optical strain and thermography measurements as well as comprehensive numerical studies for the evaluation of the interaction between the constituents and the related mechanisms are performed.

Most of the mentioned investigations are performed on laminates processed by roll bonding or deposition. A study on the influence of bonding strength of the laminate interface on tensile ductilities of LMCs containing martensitic steel and austenitic steel is presented by Nambu et al. [13]. Comparative measurements of roll bonded and adhesively bonded sheet metal laminates are presented [13]. For this specific laminate, they found out, that with increasing bonding strength, improved increased tensile ductility can be achieved [13]. Nevertheless, the influence of the stiffness or the elongation at break of the intermediate adhesive layer on the interaction between the individual components of the laminate is not examined by Nambu et al. [13].

The present paper systematically analyzes and assesses selected hybrid material systems consisting of adhesively bonded sheet metals as well as their underlying physical mechanisms at uniaxial tensile loading. For the purposeful assessment of different underlying mechanisms, hybrid materials constructed of Interstitial-Free (IF) steel and twinning-induced plasticity (TWIP) steel as well as solutions consisting of IF steel with the aluminum alloy EN-AW 5182-O are selected. To investigate the interaction between their constituents systematically, structural adhesives with different stiffness and elongation at break levels are used for the adhesive bonding. In addition, hybridization-induced mechanisms for the targeted stabilization of plastic instabilities are evaluated in detail with complementary optical strain measurements, thermography and numerical simulation. By consistent implementation of a design strategy based on these underlying mechanisms, the ductility and also the tensile strength of such material combinations can be adjusted. Hence, locally tailored properties according to the local requirements can be obtained by hybridization of a cost-effective base structure with reinforcing patches.

2. Materials

2.1. Metals

In the course of this work, three different sheet metals are used to investigate the underlying physical mechanisms of different hybrid material systems systematically. An Interstitial-Free (IF) steel HC220Y, which is widely applied in the automotive industry, is used. The HC220Y has been produced by ThyssenKrupp Steel and is abbreviated as "HC" in the following. Furthermore, EN AW 5182-O (abbreviated as "AL"), a standard aluminum-magnesium alloy for body parts, is applied. This aluminum alloy has been provided by Constellium. In addition, an optimized twinning-induced plasticity (TWIP) steel (HSD®-steel X70MnAlSi15_2.5_2.5) from Salzgitter Mannesmann Forschung GmbH is used and is abbreviated as "HSD" (High Strength and Ductility) in the following. The investigated metals have a layer thickness of about 1.0 mm. The measured mechanical characteristics of the individual materials under quasi-static loading conditions are shown in Table 1.

2.2. Adhesives

Epoxy resin based cold-curing structural adhesives from Dow Automotive with a thickness of 0.15 mm are used for the adhesive bonding between the individual materials. The influence of adhesive stiffness and elongation at break on the interaction of the components of the hybrid material system is evaluated by using the structural adhesives which are listed in Table 2. The Betamate 2090 2:1 [14], which is abbreviated as "BM21" in the following, possesses high Young's modulus compared to Betamate 2090 1:1 (abbreviated "BM11") [15]. A complete parameter set, which is essential for numerical simulation, was not available for the experimentally tested BM11 and BM21. Therefore, BETAMATE 2098 (abbreviated as "BM98") [16] is applied for the numerical simulations.