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Deformation and fracture of polymer/metal composites subjected to cold rolling

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ABSTRACT

Cold rolling of a sandwich composite with a metallic strip inclusion in a polymeric matrix can produce a range of outcomes, including deformation and fracture of the inclusion. Using different material combinations under the same processing parameters, the results ranged from minor deformation, to folding and/or loss of adhesion, and fracture of the inclusion, with fracture particles varying in size and shape. Comparisons are made between the resulting structures after cold rolling of the polymer/metal composite to geological formations. In particular, the fracture particles obtained resemble rock structures known as boudins. The phenomena of boudinage and folding encountered in the cold rolling of polymer/metal composites is similar to that seen in geology formations although the time and size scale of these events are several orders of magnitude apart. The experimental results reported show that cold rolling applied to a polymer/metal sandwiched composite induces deformation and fracture behaviors that depend on the mechanical properties of the constituents, deformation behavior of the polymeric matrices, interfacial adhesion, and process parameters such as rollers speed and nip-gap.

1. Introduction

Metal inclusions in polymeric composite materials under a process of cold rolling and folding can exhibit fracture under certain conditions. The deformation and fracture patterns observed are similar to those found in some rock structures [1,2]. Similarities are also found with the microstructure of laminate ceramic composites subjected to rolling and folding [3], multilayer ceramic tubes that have undergone co-extrusion [4], as well as some metal/metal laminate subjected to rolling processes [5,6]. The common factor among these processes is the deformation of two contiguous phases with different mechanical properties, which could produce necking and/or fracture of one of the composite constituents.

Our interest in this phenomena began with the use of cold rolling (also called calendering) for the purposes of grain refinement in shape memory alloys [5,7], later it was expanded to cold rolling of multilayer materials for the purposes of particle production [8]. This research, as well as that of others [9,10], has shown that a particle disperse composite can be produced through plastic deformation using cold rolling of a sandwich composite made of layers of dissimilar materials. The work presented here is focused on two layers of polymer and metal or alloy strips between them as the initial condition.

In the experimental work reported below, sandwich composites were made using polypropylene (PP), polycarbonate (PC), or high-density polyethylene (HDPE) as the matrix phase, and strips of pseudoelastic nickel titanium alloy or titanium as the inclusion phase. A sampling of the various fracture and folding patterns obtained for the different composites is shown in Fig. 1. The fracture particles varied in size, shape, and in some cases, the inclusion did not break but rather folding and/or loss of adhesion was observed. The range of materials investigated provides an interesting window into the phenomenon of cold rolling.

2. Background

Under certain conditions the fracture patterns observed after cold rolling a metal inclusion in a polymeric matrix sandwich resemble fragments of rock layers called boudins. There is substantial literature on these formations. These geological structures occur when a competent rock layer surrounded by a less competent rock matrix is subjected to layer-parallel extension or layer-normal compression. The term competent is used by geologists to identify the stronger or stiffer layer, while the less competent or incompetent layer is the weaker or ductile layer [11–19]. Pollard and Fletcher [20] point out that these terms "do not refer to an explicit type of material behavior." In those studies where the layers of rocks have been considered as viscous fluids, competency has been

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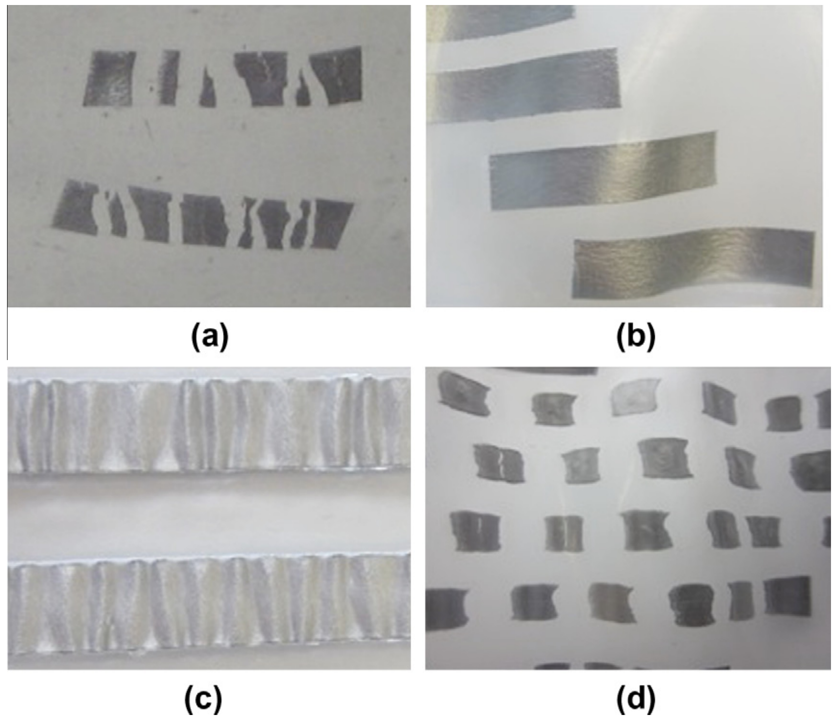

Fig. 1. Inclusion fracture patterns obtained after metal/polymer composite fabrication process. (a) NiTi particles in PP matrix after 1 rolling cycle; particle size ranges from 0.1 to 0.5 cm. (b) NiTi strips in HDPE matrix; no break after 1 rolling cycle. (c) Ti strips in PC matrix; no break after 1 pass; the folds measured approximately 0.18 cm. (d) Ti particles in HDPE after 1 rolling cycle; particles average size was 0.4 cm. (One rolling cycle = several passes through the rollers reducing the nip-gap 0.05 cm each pass until a nip-gap of 0.076 cm was reached).

more rigorously defined as a function of the viscosity of the layer, where a more viscous layer is the competent layer and the layer with a lower viscosity or ability to flow represents the incompetent layer [21–24].

When layer-parallel extension or layer-normal compression are applied to the competent layer, flow in the less competent matrix parallel to the layer will occur, generating tensile stresses, extension, and finally fracture of the layer [11,25]. The shape of the boudin is determined by the properties of the layer, where strong brittle layers would produce rectangular boudins with sharp corners as those shown in Fig. 2a [26]. More ductile layers would allow plastic flowage and lateral elongation producing structures termed pinch-and-swell which result from necking. These structures may eventually fracture producing more oblong or lens-shape called lenticular boudins, or barrel-shape boudins [11,14]. Fig. 2b shows a barrel-shaped boudin with concave end that is believed to be the result of high plastic deformation imposed on the originally rectangular boudin. This kind of rock structure is also known as "fish-mouth boudins" [23]. Other rock structures known as folds occur when competent viscous layers in a less stiff matrix buckle when subjected to layer-parallel compression [15].

Structures such as the pinch-and-swell, and folding were explored by Smith's theory on formations of folds, boudinage, and mullions in Newtonian and non-Newtonian materials [21,22]. Using a general approach, Smith hypothesized that folding and boudinage are related structures that occur when a single layer is squeezed between two thick layers of different viscosity, establishing a state of motion with unstable small disturbances. Fig. 3 portrays a summary of the layer instabilities, where the stronger layer is depicted as the darker region, and the more ductile as the lighter region. The disturbances could grow into flow, fracture boudinage, folding, or mullions.

The parallels between the boudin and fold structures and the development of fracture and folding in a metal-alloy/polymer

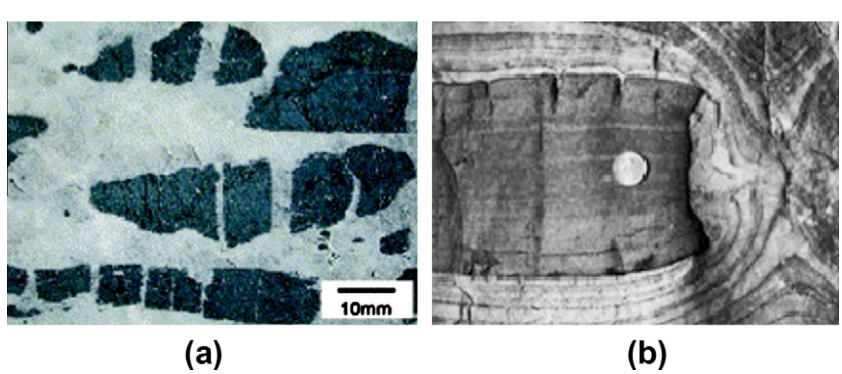

Fig. 2. Images of typical boudin fracture pattern in rock structures. (a) Rectangular boudin: Tourmaline grains in a quartz matrix from Western Australia [26]. (b) Shaped-barrel boudin with 'fish-mouth' shape ends: Boudin in calc-silica layer in marble, Khan Gorge, Namibia [23]. Coin shown for scale.