Journal of Materials Processing Tech. 263 (2019) 385–395

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

Experimental investigation on mechanical properties and failure mechanisms of polymer composite-metal hybrid materials processed by direct injection-molding adhesion method

Lijun Li[a,b], Lingyu Sun[a,b,*], Zongmiao Dai[c], Zhenkai Xiong[c], Bincheng Huang[a,b], Yiben Zhang[a,b]

[a] School of Transportation Science and Engineering, Beihang University, 37 Xueyuan Road, Haidian District, Beijing, 100191, China
[b] Lightweight Vehicle Innovation Center, Beihang University, 37 Xueyuan Road, Haidian District, Beijing, 100191, China
[c] Zhengzhou Electromechanical Engineering Research Institute, Zhengzhou, 450015, Henan, China

ARTICLE INFO

Keywords:
Short fiber composite
High strength steel
Injection molding
Interface
Weight reduction
Microstructures

ABSTRACT

Multi-material hybrid application is an effective way of automotive weight reduction. This paper proposes and validates a direct injection-molding adhesion process for polymer composite–metal hybrid (PMH) materials to overcome several limitations of existing PMH technologies. The fundamental tension and bending properties of PMH materials are investigated by experiments. The force–displacement curves of PMH coupons present a multi-stage feature, which is the cumulative results of two constituent materials, and a typical stepwise progressive failure process was observed. Furthermore, scanning electron microscopy and digital image correlation observations reveal the failure mechanisms of PMH materials at micro-scale, including polymer composite–metal interface debonding, brittle fracture of thermoplastic matrix, glass fiber breakage or pull-out from matrix, and ductile failure of steel. The convex–concave interlocking mechanism plays an important role in PMH interface bonding. Under tension and bending loads, the rule of mixture prediction method for modulus and strength of PMH coupons have a high precise compared with the test results. These basic material characteristics may serve as a foundation for the future engineering applications of PMH load-bearing components.

1. Introduction

The selection of automotive structural materials is undergoing a transition phase from steel to fiber reinforced polymer (FRP), because of growing demand of weight reduction to save energy and decrease air pollution (Aghchai et al., 2017). Many steel components of automobiles are being substituted by polymer–metal hybrid (PMH) materials (Witik et al., 2011), such as bumper beams, floor beams, sub-frames and B-pillars (Grujicic, 2014). This technology integrates excellent mechanical properties of high strength steel (HSS) and complex geometry formability of thermoplastics into a single component/sub-assembly (Amancio-Filho and Dos Santos, 2009). When applied in automotive structures, bending is the typical in-service situation. Although a large number of tension tests have been conducted to characterize the basic properties of individual HSS or polymer composite, there are few experimental studies on tensile and bending properties of composite-HSS material systems (Dlugosch et al., 2016), which are the foundation of PMH structural applications.

To satisfy the requirements of short cycle time on mass-production and to be compatible with the existing stamping line, three typical PMH fabrication technologies, injection over-molding on metal with 5-mm diameter holes (Fig. 1(a)), over-molding metal by melting and welding the pre-coated polymer membrane (Fig. 1(b)), and adhesive bonding technology (Fig. 1(c)), have been developed.

In the first technology reported by Meurer (1999), the plastic rivets with short glass-fiber reinforced polyamide 6 formed by the holes (Fig. 1(a)) provide macroscopic mechanical interlocks of PMH structures, but also produce stress concentrators and possibly become the initial source of failure. Its another disadvantage is unsmooth appearance. In the second technology developed by Rhodia corporation in Bourguignon (2001), a separate injection molding component is welded by laser in Fortunato et al. (2010) or ultrasonic in Roesner et al. (2011) to the stamped steel through a thin layer of pre-coated polyamide on the metal surface, however it needs long cycle time, and also not compatible completely with the existing stamping line. The third technology, adhesive PMH bonding reported by Recktenwald (2005), in which adhesives with low surface energy are applied to assemble the stamped metal and glass-fiber reinforced polypropylene together.

* Corresponding author.
E-mail address: lysun@buaa.edu.cn (L. Sun).

https://doi.org/10.1016/j.jmatprotec.2018.08.039
Received 21 December 2017; Received in revised form 13 July 2018; Accepted 28 August 2018
Available online 29 August 2018

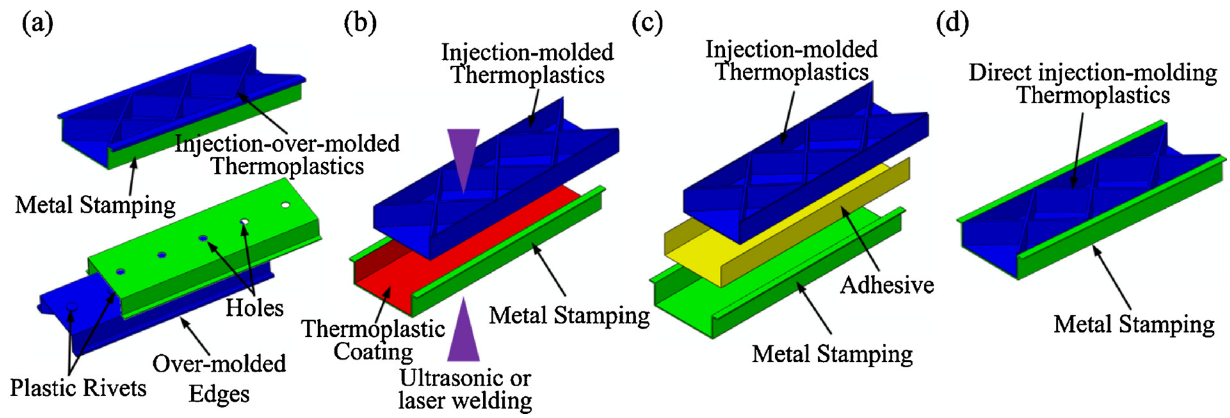

Fig. 1. Schematic drawing of PMH technologies: (a) injection over-molding, (b) over-molding metal, (c) adhesive-bonding, and (d) direct injection-molding adhesion.

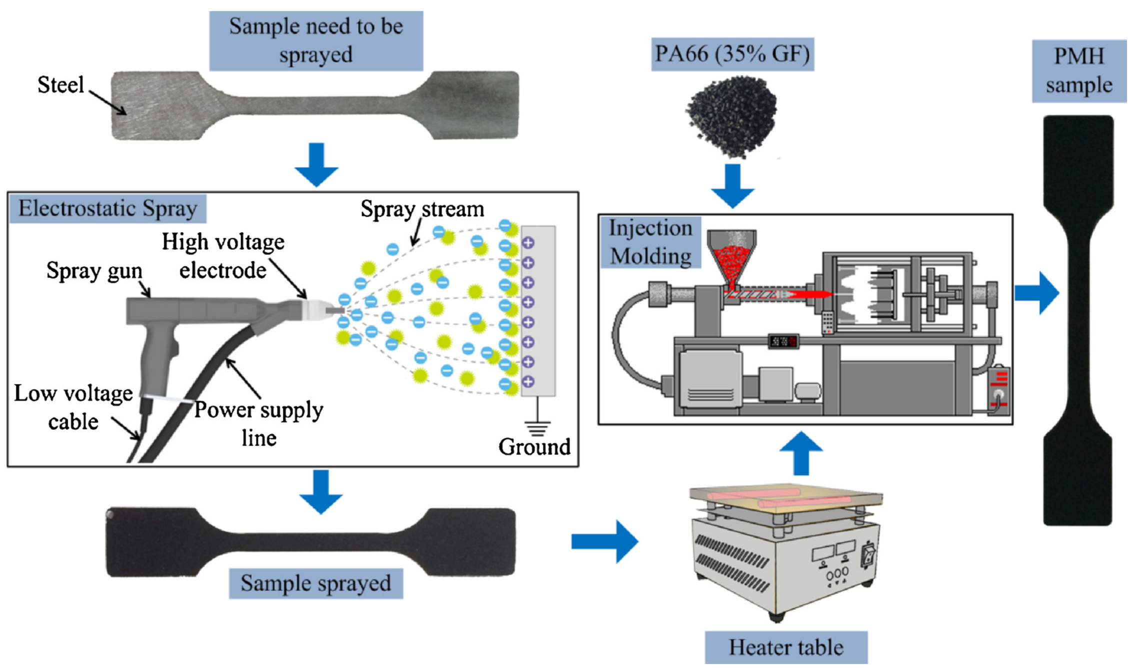

Fig. 2. Schematic illustration of direct-adhesion PMH process.

Nevertheless, it requires long curing time, and the dimensional accuracy of PMH structures is difficult to be controlled due to the presence of a glue layer.

Other novel PMH joining approaches focusing on surface preprocessing were also developed. For example, Ucsnik et al. (2010) prewelded small spikes onto the metal surface. Gude et al. (2015) utilized thermo-clinching to form mechanical locks of interface. Abibe et al. (2016) presented a friction-based injection clinching joining method. Additionally, some hybrid joining methods, such as weld bonding (Sadowski et al., 2014), rivet-adhesive (Pirondi and Moroni, 2009), bolt-adhesive (Bois et al., 2013), and adhesive embossing (Huang et al., 2013), are also potential choices for PMH. However, these methods usually need additional tools and they are time-consuming, weight-increasing, costly and not compatible to the existing stamping line. To fabricate lightweight and cost-effective PMH structures, Grujicic et al. (2008) proposed a new concept of direct injection-molding adhesion PMH (DA-PMH), as shown in Fig. 1(d), in which no plastic rivets, overmolded edges, and adhesives are required, but the metal surface needs to be preprocessed before injection molding. Although the feasibility of DA-PMH technology for load-bearing structural components has been validated theoretically and numerically by Grujicic et al. (2009), few experimental studies have been published because the requirement on perfect bonding and no warpage is too difficult to be satisfied, hence the interface pores, adsorption, inclusions, molecular diffusion, chemical reactions, and thermal-expansion coefficients mismatch between polymer and metal should be controlled optimally as reported by Huang et al. (2017). Otherwise, the interface possibly become the weakest layer in PMH structures. Therefore, it is essential to investigate the mechanical properties and the failure mechanisms of DA-PMH materials.

One objective of this paper is to provide an efficient and compatible DA-PMH process and validate the fabrication process by experiments, another objective is to evaluate the mechanical properties of PMH coupons at macro-scale and observe the failure mechanisms at micro-scale, and also provide a theoretical prediction model suitable for engineering application, based on the individual known properties of metal and polymer composite. The organization of this paper is as follows. Section 2 introduces the material types used, the process of specimen fabrication and properties measurement, and the method of theoretical prediction. Section 3 presents and discusses the experimental and theoretical results. The final section summarizes the academic contributions and suggests some future work.