Direct injection molding and mechanical properties of high strength steel/composite hybrids

Yiben Zhang\textsuperscript{a,b}, Lingyu Sun\textsuperscript{a,b}, Lijun Li\textsuperscript{a,b,*}, Bincheng Huang\textsuperscript{a,b}, Taikun Wang\textsuperscript{c}, Yantao Wang\textsuperscript{c}

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

**ABSTRACT**

Metal polymer hybrid technology is a promising way of automotive weight reduction and safety improvement. In this study, high strength steel and glass-fiber reinforced PA66 composite were integrated by direct injection molding process. The mechanical properties and failure behavior of steel/composite hybrids under tension, bending, mode I and II fracture loads were investigated experimentally, theoretically and numerically. The properties of the interface between steel and composite were measured using double cantilever beam and end-notched flexure tests for the first time. The analytical model and finite element simulation considering the interface mechanical behavior were proposed and validated. They can be utilized to predict the mechanical properties and progressive failure process of hybrid material cost-effectively and accurately. It is found that the cracks initiate at the interface, and then propagate through composite until the hybrid material loses load-carrying capacity completely. The steel dominates the load-bearing capacity, and the interface dominates the failure process. The results obtained in this study offer a scientific guidance and theoretical basis for the engineering application of metal polymer hybrid materials.

1. Introduction

Due to excellent lightweight performance and high degree of integration, metal polymer hybrids (MPHs) are being used with increasing frequency to replace traditional all-steel components such as automotive bumper beams, instrument-panel cross beams and front-end modules [1–3]. Especially in the automotive industry, high strength steel (HSS)/glass-fiber reinforced polymer (GFRP) hybrids have attracted a significant amount of attention for their low material cost and good load-bearing capacity. However, fabricating MPHs is a challenging subject since metal and polymer have very different chemical and physical properties. These differences cause problems such as poor bonding between metal and polymer.

Therefore, different methods have been developed to obtain MPH materials and parts. For example, metal and polymer are formed separately and then connected through adhesive bonding [4–6], plastic-rivets [7], or melting a pre-laid specific membrane on a metal surface in the over molding [8,9] processes. However, adhesive bonding needs more positioning and curing time. Plastic-rivets decreases the strength of steel due to the holes required and melting a pre-laid specific membrane increases the tooling cost and cycle time.

Direct injection molding (DIM) [10] is a new technology proposed for almost one step manufacturing MPHs, which does not need punching dozens of holes, processing over-molded edges or interlocking rivets. Nonetheless, there are still some problems that hinder its wide application. For example, a surface pretreatment prior to injection molding is often needed for improving adhesion between metal and polymer. Nowadays, the pretreatment methods include primer coating [11], grit blasting [12], laser ablation [13], plasma treatment [14], chemical etching [15], chemical solution modification [16]. Combinations of these methods are also available and often utilized, e.g. ammonia aqueous etching and plasma treatment [17]. However, these methods have poor joining efficiency and compatibility with existing production lines because they need additional pre-process tools besides stamping and injection molding. Therefore, it is imperative to develop a new DIM technology possessing low cost, high efficiency and good compatibility.

The limited knowledge on the mechanical properties of hybrids restricts the further promotion of DIM technology. Hence, comprehensive understanding the mechanical properties, damage propagation and final failure modes of MPHs is the premise of industry application. Moreover, most of published studies only focused on the overall...
performance of MPHs with specific geometry [18–21]. The interface between metal and polymer is generally assumed perfect bonding in their simulation. To eliminate the geometric or architectural effects, it is essential to obtain the fundamental properties at material coupon level. Dlugosch et al. [4] fabricated the HSS/GFRP hybrid coupons by glue and then tested their mechanical properties. They found the hybrids possessed different energy dissipative mechanisms and failure modes from individual steel or composites. However, the interface in DIM hybrids is very different from the glue layer. Currently, the large errors in simulation of DIM hybrid structures [22] come from the perfect bonding assumption due to the lack of experimental data and interface constitutive model. This new type of interface may possibly lead to different failure mechanisms, which needs another analytical model to describe its fundamental mechanical behavior, and also requires accurate numerical simulation method based on the experimental data.

This paper aims to establish a comprehensive knowledge system for DIM MPH materials through a series of work. Firstly, a new DIM technology with the surface pretreatment method well compatible with stamping process was proposed, and four kinds of high strength steel/ composite hybrid coupons were fabricated by this technology and tested (Section 2.1–2.3). Then, an analytical method was proposed to predict the mechanical properties of hybrids (Section 2.4). Next, the numerical modelling and simulation procedures were introduced (Section 2.5). The progressive damage behavior of the interface between metal and polymer was considered. Finally, the experimental, analytical and numerical results were compared and discussed (Section 3).

2. Materials and methods

2.1. Materials

The metal used was dual-phase steel DP 590+Z (Benxi Iron and Steel Group Corporation, China) with 1 mm thickness. The injection molding polymer used was Ultramid® A3HG7, a kind of 35 wt% short glass-fiber reinforced PA66 (PA66-GF35) with 3 mm length fibers, manufactured by BASF Application Chemical Company of China. Its melting temperature is 260 °C.

2.2. Fabrication process

In this study, a new direct injection molding process was developed, as shown in Fig. 1. Before injection molding, the steel surface was pre-processed by pressing with embossing die in order to obtain micro-mechanical interlocking structures. In the actual production, the microstructures of steel stamping surface facing the injection part can be manufactured by a punch with micro convexes. Simultaneously, the steel surface pretreatment and stamping are completed. Hence, this process is well compatible with the existing stamping line.

The direct injection molding process is comprised of three steps:

Step 1. The steel plate was cut into specific shape and dimension. Then, the steel surface facing the injection part was purified with ethanol and embossed by a hydraulic indenter to form a diamond-shaped microstructure pattern.

Step 2. The embossed steel insert was heated to 370 °C in a heater table, and then it was moved into the mould by hand rapidly. The steel insert was positioned by the cylindrical magnets in the mould. The mold temperature was 80 °C. Before injection, the temperature of the steel insert can be maintained at 200 °C based on multiple measurements, which was helpful to reduce the mismatched thermal expansion stresses between steel and polymer [23].

Step 3. The injection molding was carried out at the injection rate of 20 cm/s under melt temperature of 270 °C. The maximum machine clamp force was 3800 kN. The injection pressure was 13.5 MPa, and hold pressure was 45 MPa. The cycle time was approximately 60 s, wherein the hold time was 15 s and the cooling time was 30 s.

In order to improve the versatility and efficiency of the mould in the lab research, inspired by “Chinese movable type printing”, the mould was designed as a combination components that could replace the cavity core, as shown in Fig. 2. Four kinds of specimens were manufactured and tested, i.e., tensile, bending, double cantilever beam (DCB) and end-notched flexure (ENF) specimens. For the DCB and ENF specimens, pre-crack was prepared by spraying release agent in the specified zone of HSS surface before injection molding, rather than presetting polytetrafluoroethylene (PTFE) film due to the high temperature of injection molding would cause severe deformation of the PTFE film.

Fig. 3 shows the multi-scale images of pre-processed steel surface by hydraulic embossing technique. It is found that the periodical microstructures (Fig. 3(a)–(c)) have appeared on the steel surface, which improve the surface roughness and contribute to form micro-mechanical interlocking (Fig. 3(d)). The length of the upper open rectangle is 400–450 μm, and the depth is 150–200 μm. In injection molding process, the melt polymer flowed across concave objects and cooled down, and hence a series of micro-mechanical interlocking structures formed between steel and polymer.

2.3. Experimental procedures

In order to characterize the mechanical properties of MPH material including modulus, strength and interface fracture toughness, the tensile, three-point bending, DCB and ENF tests were carried out. All experiments were conducted at room temperature environment on a MTS E45 machine with a load cell (range up to 50 kN). Loading velocity was 2 mm/min to assure a quasi-static condition. At least five valid
experiments per variant were conducted to assure statistic robustness.

2.3.1. Tensile test

The dimension of tensile specimens (Table 1) was determined according to ASTM standard D638. The MPH sample was made of 1-mm-thick steel sheet and 1-mm-thick polymer using the direct injection molding process. The GFRP sample was 2-mm thick fabricated by the injection molding process. The steel sample was machined from a 1-mm-thick steel plate.

The tensile tests were conducted until total failure and full separation of both clamped ends. The clamping bar was held constant for the entire duration of the experiments. Additional cap strips were not required since no slipping occurred and failure was rarely initiated within the clamps. In the stress-strain curve, the slope in the linear elastic regime was interpreted as the modulus, and the maximum stress was defined as the tensile strength of hybrids.

For a better understanding of the failure mechanisms of hybrids under tensile loading, tensile experimental processes are recorded by the high-speed photography. SEM images and optical micrographs are used to analyze the observed mechanical response to the microstructure. The digital image correlation (DIC) method is used to measure the full-field deformation and obtain the failure strain of MPH.
2.3.2. Bending test

Bending specimens were determined according to ASTM D790, as listed in Table 2. MPH sample consists of 1-mm-thick steel and 1-mm-thick GFRP. GFRP sample is 2-mm thick, and steel sample is 1-mm thick. The 3-point bending tests were conducted using a setup with two supports and one crosshead with a radius of 5 mm. The supports had a span distance of 32 mm.

For bending tests, the modulus $E_b$ is assessed according to the respective standard for FRPs DIN EN ISO 14125 with Eq. (1) as

$$E_b = \frac{\Delta F}{4\Delta s b t^3}$$

where $l_0$ is the free length between the supports. $\Delta F$ and $\Delta s$ are the change of force and the change of displacement, respectively.

Bending strength $\sigma_{\text{max}}$ is defined as

$$\sigma_{\text{max}} = \frac{3}{2} \frac{F_{\text{max}} l_0}{b t^2}$$

where $F_{\text{max}}$ is the maximum force.
2.3.3. Interface fracture tests

Mode I and II cracks are the most common interface failure in structures. DCB test is the representative method for characterization of the mode I fracture toughness. Specimens for DCB tests were designed according to China aerospace standard HB 7402, consisting of 2-mm-thick GFRP phase and 1-mm-thick metal phase (Fig. 4). ENF test was used to characterize mode II fracture toughness. Specimens for ENF tests were designed according to China aerospace standard HB 7403, consisting of 2-mm-thick GFRP phase and 1-mm-thick metal phase (Fig. 5).

In DCB and ENF tests, the matt white paints were sprayed on the specimens to assist the observation of crack tip propagation. Additionally, a paper ruler was glued at 5 mm intervals under the bond line to facilitate the crack length measurement. A digital camera was used to record the crack lengths per 5 mm intervals during testing so that the crack length parameters could be generated. Interface characterization tests were conducted until the crack propagated by 40 mm.

Mode I fracture toughness ($G_{IC}$) was calculated via Eq. (3):

$$G_{IC} = \frac{F \delta}{2ba} \times 10^3$$

Fig. 6. FE models of (a) tensile specimen; (b) bending specimen; (c) DCB specimen; (d) ENF specimen.

**Fig. 7.** Bi-linear constitutive relationship in cohesive zone model.

**Fig. 8.** The tensile (a) force-displacement and (b) stress-strain curves of the hybrid and constitute materials.

where $a$ is the delamination length counting from the load/displacement application points; $b$ is the specimen width; $F$ is the critical load at
the point of deviation from the linearity of the load-displacement curve and $\delta$ is the corresponding displacement.

Mode II fracture toughness ($G_{IIc}$) is calculated using Eq. (4):

$$G_{IIc} = \frac{9EIa^2}{2b(3L^3 + 3a^3)} \times 10^3$$

where $2L$ is the span length.

2.4. Analytical prediction method

2.4.1. Tensile performance of hybrid material

The metal polymer hybrid coupons can be regarded as a sandwich structure composed of metal-interface-polymer three phases, therefore its effective modulus can be derived based on the rule of mixture. Moreover, as reported in Ref. [24], the tensile curves of metal polymer hybrid materials show a three-stage feature: elastic deformation stage before steel yielding (Stage I), the stage from the yielding of the steel to the fracture of composite (Stage II) and the stage from the fracture of composite to the fracture of steel (Stage III). Based on these characteristics, an analytical model is proposed.

Based on rule of mixture, effective tensile modulus of MPH is calculated by Eq. (5):

$$E_{RMH} = \frac{(E_{r,HS} \cdot A_{HS} + E_{r, Interface} \cdot A_{Interface} + E_{r,GFRP} \cdot A_{GFRP})}{A_{RMPH}}$$  (5)
where $E_t$ is the effective tensile modulus. $A$ is the corresponding cross section ratio, whose subscript indicates the type of material or phase. The composite with short fibers is assumed to be isotropic.

Assume that all materials have identical tensile strain. The equations for tensile stress $\sigma_{MPH}$ are different according to the deformation stage:

Before the steel yields ($\varepsilon_y$), average stress $\sigma_{MPH}$ can be calculated by Eq. (6):

$$\sigma_{MPH} = \varepsilon(E_{HSS}A_{HSS} + E_{Interface}A_{Interface} + E_{GFRP}A_{GFRP})/A_{MPH}, \quad \varepsilon < \varepsilon_y$$

For the strain from the yielding of the steel to the fracture of GFRP ($\varepsilon_f^1$), $\sigma_{MPH}$ can be calculated as Eq. (7):

$$\sigma_{MPH} = (\sigma_yA_{HSS} + \varepsilon(E_{GFRP}A_{GFRP}K))/A_{MPH}, \quad \varepsilon < \varepsilon_f^1$$

where $\sigma_y$ is the yield stress of steel, and $K$ is the strain hardening coefficient of composite.

For the strain from the fracture of composite ($\varepsilon_f^1$) to the fracture of the steel ($\varepsilon_f^2$), $\sigma_{MPH}$ can be calculated as Eq. (8)

$$\sigma_{MPH} = (\sigma_yA_{HSS})/A_{MPH}, \quad \varepsilon < \varepsilon_f^2$$

Therefore, the equations for tensile force $F_{t,MPH}$ are as follows:

---

**Fig. 11.** Fracture morphology of the composite: (a) longitudinal section, (b) transverse section and its local views at magnifications of (c) 300 and (d) 800.

**Fig. 12.** The bending curves of hybrid and the constitute materials.

**Fig. 13.** The force-displacement curves of (a) DCB and (b) ENF specimens of hybrids.
where $l_0$ is the gauge length; $S$ is the displacement, the subscript $y, f_1$ and $f_2$ indicate the deformation stage as described in Eqs. (6)--(8).

2.4.2. Bending performance of hybrid material

The effective bending modulus is expressed by Eq. (10):

$$E_{b,MPH} = \left( \frac{A_{HSS} + A_{Interface} + A_{GFRP}}{A_{MPH}} \right)$$

where $E_b$ is the effective bending modulus. $A$ is the corresponding cross section ratio, and the subscript indicates the type of material or phase.

Combined with Eq. (1), the equations for bending force $F_{b,MPH}$ are calculated as Eq. (11):

$$F_{b,MPH} = \begin{cases} 
\frac{4b^2h^3S}{3EI_{MPH}} & S < S_f \\
\frac{4b^2h^3S}{3EI_{HSS}} + \frac{4b^2h^3S}{3EI_{GFRP}} & S_f \leq S \leq S_{f_2} \\
\frac{4b^2h^3S}{3EI_{HSS}} & S_{f_2} \leq S \leq S_{f_2}
\end{cases}$$

where $S$ is the displacement, and the subscript indicates the deformation stage as described in Eqs. (6)--(8).

2.5. Numerical simulation

2.5.1. Finite element modelling

In order to evaluate the mechanical behavior of steel/composite hybrids numerically, four kinds of FE models were established according to the experimental conditions in Abaqus/Explicit software, as shown in Fig. 6. The metal phase and composite phase were modelled using C3D8R elements with 8-node linear brick, reduced integration.
and enhanced hourglass control. The interface between steel and composite was modelled using 8-node three-dimensional cohesive COH3D8 elements. Wherein, the supports and crosshead in the three-point bending and ENF models were simplified as rigid bodies. The mesh in the deformed zone was refined, and the minimum size of elements was 1 mm.

In the tensile and DCB models, the fixed surfaces were applied a full constraint at all degrees of freedom (DoFs). The moving surfaces were realized by displacement boundary conditions. In the bending model, the rigid impactor was assigned a mass and an initial z-velocity while constrained at the remaining DoFs. Based on literature data [25], a general friction coefficient of 0.3 was applied to all surface pairings in the contact domain.

### 2.5.2. Constitutive models

For steel and PA66-GF35, the segment of true stress-strain curves after necking onset has to be modified for a better insight into the material local response of the specimen which is important in validation simulation. Two essential steps similar as Ref. [26] are used in this paper.

Step 1. Conduct tension test and process the strain hardening curve up to the necking point.

Step 2. Extrapolate the curve according to a hardening law. In this study, Ludwik Law [27] is used:

$$\sigma = \sigma_0 + A \cdot (\varepsilon^p)^n$$  \hspace{1cm} (12)

where, $A$ and $n$ are the parameters. With two constraints keeping continuity of the curve and the identical slope, only one of the two parameters is independent.

Cohesive zone model is introduced to simulate the interface behavior, in which stress is expressed as a bi-linear function of the displacement [28,29], shown in Fig. 7. Fracture toughness is considered as the most important factor in the damage condition analysis [30]. Hence, in this paper, fracture toughnesses ($G_{IC}, G_{IIc}$) are identified from DCB and ENF experiments. The initial stiffnesses ($E_I, E_{II}$) and maximum stresses ($T_{I, max}, T_{II, max}$) are identified from simulation-based inverse identification methods.

### 3. Results and discussion

#### 3.1. Experimental results

##### 3.1.1. Tensile properties

Fig. 8(a) shows the force-displacement curves of high strength steel/composite hybrid, pure steel and pure composite under tensile loading. Since the cross-section areas are different from individual specimen geometries, the force level of the composite has been scaled in order to provide comparability. The force of hybrid material is carried by steel

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$E_I$ (GPa)</th>
<th>$E_{II}$ (GPa)</th>
<th>$E_{II}$ (GPa)</th>
<th>$G_{IC}$ (kJ/m²)</th>
<th>$G_{IIc}$ (kJ/m²)</th>
<th>$T_{I, max}$ (MPa)</th>
<th>$T_{II, max}$ (MPa)</th>
<th>$T_{III, max}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>1.5</td>
<td>0.75</td>
<td>0.75</td>
<td>0.17</td>
<td>0.45</td>
<td>0.45</td>
<td>11.4</td>
<td>10.51</td>
</tr>
</tbody>
</table>

Fig. 17. Influence of the cohesive zone parameters on (a) DCB and (b) ENF numerical results.
and composite simultaneously. Fig. 8(b) shows the stress-strain curves of hybrid material and its constitute materials. PA66-GF35 composite specimen shows a typical brittle behavior, i.e., stress increasing nearly monotonously, and then, followed by a brittle fracture. Steel specimen has a power relationship between stress and strain after yielding. The hybrid material exhibits a complex piece-wise increase of stress with increasing strain. At the initial stage, the load was shared by steel and composite, and stress increases nearly proportionally with the increasing strain until the steel yield. At the second stage, stress increases stably with increasing strain until the fracture of composite. Subsequently, the load was carried solely by the steel, so the curve of hybrid material is consistent with that of steel.

Fig. 9 shows the failure process of hybrid material in the tensile experiment at lateral direction. It is found that the initial crack occurs in the interface (Fig. 9(b), rising to the loading direction in parallel, followed by composite phase failure (Fig. 9(c)) and steel phase failure (Fig. 9(d)), which are consistent with the force response in Fig. 8.

Fracture surfaces for steel and composite observed by SEM are shown in Figs. 10 and 11. Fracture surface of HSS is about 45° with respect to the loading direction (Fig. 10). Elongation at fracture is approximately 5.8 mm and proportion in reduction in area is approximately 47%. The higher magnifications in Fig. 10(c) and (d) reveal that some macroscopic voids are intermingled with fine microscopic voids on the fracture surface. Therefore, steel exhibits a typical ductile failure.

Fracture surface of PA66-GF35 composite is perpendicular to the loading direction (Fig. 11). Elongation at fracture is approximately 1.9 mm and proportion in reduction in area is approximately 8.5%, both of which are much lower than steel. Fibers stretched out unidirectional on the fracture surface in the higher magnification pictures as shown in Fig. 11(c) and (d). The composite exhibits brittle matrix fracture and fiber pull-out failure.

### 3.1.2. Bending properties

Fig. 12 depicts the force-displacement curves of hybrid material compared to pure steel and pure composite under bending loads. Since composite specimens and steel specimens have different cross sections, the force level of composite has been scaled in order to provide comparability. The force carried by hybrid material is contributed by steel and composite simultaneously. PA66-GF35 composite specimen shows a typical brittle behavior, and steel specimen exhibits ductile metal behavior. Hybrid material exhibits a complex piece-wise increase of stress with increasing strain.

### 3.1.3. Interface properties

The force-displacement curves of DCB and ENF specimens are shown in Fig. 13(a) and (b). The curves overlap each other well, indicating the test results are reliable. For DCB experiments, force-displacement curves show obvious bi-linear response. Force increases proportionally with the increasing displacement to the maximum load, after that force decreases linearly with some fluctuation. These fluctuations are caused by the fracture resistance [31,32]. According to Eq. (3) and the relationship in Fig. 7, Mode I fracture toughness ($G_{IC}$) is 0.17 kJ/m$^2$. For ENF experiments, the force-displacement curves also exhibit bi-linear response and mode II fracture toughness is 0.45 kJ/m$^2$.

### 3.2. Analytical prediction

Fig. 14(a) compares the experimental tensile force-displacement curve with the analytically predicted result. Fig. 14(b) compares the experimental bending force-displacement curve with the analytically predicted result. Furthermore, Fig. 15 compares the results of the modulus and strength at GFRP rupture. It is found that the analytical results agree well with the experiments.

The tensile strength and bending strength are affected significantly by the properties of steel phase. The calculated values of bending modulus of hybrids are higher than the experimental results (Fig. 15(c)), and the error is approximately 22.22%. The errors may result from the cross section differences of pure steel specimen and pure composite specimen. Hence, a further improvement of analysis models are needed to characterize the variation of corresponding cross section ratio for steel, interface and composite.
3.3. Numerical simulation

3.3.1. Constitutive model validation

The constitutive relations of steel and composite in hybrid material are obtained by Eq. (12). The parameters $n$ and $A$ are identified and listed in Table 3.

Fig. 16 compares the experimental tensile stress-strain curves with the simulation results of PA66-GF35 composite and steel, respectively. The agreement is very good. Therefore, the constitutive models are validated.

Based on the experiments in Section 2.3.3, the cohesive zone properties of the interface are obtained, as listed in Table 4. The influence of each parameter on simulation results is assessed by DCB and ENF finite element models. For DCB case (Fig. 17(a)), either stiffness variation in the range of 0.5–2 times or maximum stress increased by 20% would have relatively small influence on the force-displacement curve response. Nevertheless, the fracture toughness increased by 20%, which affects the maximum force more significantly. Similar results are observed in ENF case (Fig. 17(b)) in the aforementioned variation range. Therefore, it is concluded that the numerical results are not sensitive to changes of stiffness and maximum stress. Similar results were reported by Zou et al. [29].

3.3.2. Tensile simulation

Fig. 18 shows the comparison of tensile mechanical response and failure modes between simulation, experiment and DIC results for steel/composite hybrid material. The tensile modulus and peak force values of simulation show good agreement with experimental results (Fig. 18(a)). Furthermore, the strain distributions in three representative stages of simulation (Fig. 18(b)) agree well with DIC results (Fig. 18(c)): When $t = t_1$, the steel yields, and the strain is approximately 0.002; When $t = t_2$, the PA66-GF35 composite fractures, and the strain is approximately 0.03; When $t = t_3$, the steel fractures, and the fracture strain is approximately 0.3. The hybrid material shows a typical progressive failure process. The simulation method developed in this paper can be used to predict the mechanical behavior of hybrid material cost-effectively and accurately.

3.3.3. Bending simulation

Fig. 19 shows the comparison of bending mechanical response and failure modes between the simulation and the experiment. The force-displacement curves agree well. Moreover, the FE model can predict the bending modulus, maximum force, delamination and fracture very accurately. As shown in Fig. 19(b), although the polymer is broken into two sections, the broken composite and the deformed steel are still integrated. It indicates that a strong bonding between the composite and the steel by injection molding process has been formed.

4. Conclusions

In this study, high strength steel and PA66-GF35 composite were integrated by direct injection molding process. The mechanical properties of steel/composite hybrid material were investigated using tensile tests and three-point bending experiments. The properties of the interface between steel and composite were measured for the first time using double cantilever beam (DCB) and end-notched flexure (ENF) tests. Analytical models based on the rule of mixture were developed to explain and support the experimental results. Moreover, a finite element simulation method to predict the mechanical behavior was proposed and validated. The following major conclusions can be drawn from the present study:

1. A new direct injection molding process combining the embossed technique and direct injection molding was validated by fabrication different kinds of steel/composite hybrid specimens. This process possesses the advantages of low cost, high efficiency and good compatibility with existing automotive production line.

2. The mechanical properties of hybrid material resembles a sum of the steel and composite. The steel dominates the load-bearing capacity, and the interface between steel and composite dominates the failure process. Moreover, the contribution of each constituent phase is affected by loading condition.

3. The rule of mixture can be used to predict the effective modulus and strength of hybrid materials composed of metal and polymer. The numerical simulation approach with cohesive zone model of the interface can predict the mechanical behavior of hybrid materials cost-effectively and accurately.

4. A comprehensive utilization of the analytical models and FE method proposed in this study can contribute to the performance evaluation and structural design of hybrid materials efficiently and accurately, which may serve as a foundation for the engineering application of metal-polymer load-bearing components.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51575023 and No. U1664250), the National Key Research and Development Program of China (No. 2016YFB0101606) and the Open Foundation of Henan Key Laboratory of Underwater Intelligent Equipment (No. KL03B1805).

References


