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An experimental study on mechanical properties of a novel hybrid metal–polymer joining technology based on a reaction between isocyanate and hydroxyl groups



Omid Izadi^a, Peiman Mosaddegh^{a,*}, Mohammad Silani^{a,b}, Mohammad Dinari^c

^a Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, 84156-83111, Iran

^b Institute of Structural Mechanics, Bauhaus-Universität Weimar, Marienstr. 15, D-99423 Weimar, Germany

^c Department of Chemistry, Isfahan University of Technology, Isfahan, 84156-83111, Iran

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ABSTRACT

This study developed a novel joining technology to produce a hybrid polymer–metal material. The technology is based on a reaction between isocyanate groups (NCO) in a solution and hydroxyl groups (OH) on a metal surface. This technology has some advantages compared with other joining methods, such as lack of stress concentration and mechanical and thermal residual stress in the metal structure and very low cost. The effects of different process parameters including the NCO/OH ratio, mould temperature, and polymer melt temperature on the strength of adhesion were investigated employing single lap shear tests. Also, the mechanical behaviour of the hybrid under tensile load was investigated using uniaxial tensile tests. The results showed that increasing mould temperature or melt temperature reduces adhesion strength. Moreover, adhesion strength reaches a peak and then decreases by increasing the NCO/OH ratio. Most importantly, tensile test results showed that the new material postpones the necking phenomena of the stainless steel, and increases the deformation of stainless steel before fracturing by 16%. It is an important result in metal forming that stainless steel can withstand more deformation in its plastic regime.

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1. Introduction

Today, various industries including automotive industry intend to reduce structural weight without altering desirable mechanical properties. Lacking one material with all the properties, automotive industry should combine different materials together to achieve multiple properties in one sample. One of the best choices for achieving this goal is composites and metal–polymer hybrid materials, which provide the possibility of having the benefit of the combined mechanical properties of these two materials. In fact, hybrids can provide some benefits that cannot be obtained with individual components such as weight saving, better dimensional stability, and part reduction. Part reduction contributes to reducing assembly steps for manufacturing multi-functional components [1,2]. Polymer–metal hybrids are now replacing metal structures in front-end modules of automotive [1]. Furthermore, polymer–metal

hybrids can be used in other fields such as computer and electronics industries [2–4].

Joining polymers and metals is a challenging technology since the two materials have very different chemical and physical properties. These differences cause problems such as poor adhesion between polymer and metal insert [4]. Consequently, different methods for joining a metal to a polymer to produce an industrial hybrid material have been developed to overcome this problem. These methods can be grouped into three major categories: (a) mechanical joining; (b) chemical modification of a polymer to enhance adhesion; and (c) using a third component.

1.1. Mechanical joining

In the first method, joining a metal and a polymer is carried out by the mechanical interlock technology. The simplest method in this technology involves going all round the edges and holes created on the metal insert by means of an over-moulded polymer [5]. Despite the wide use of this method in industry, it displays significant shortcomings. In some cases, geometry or the function of the specimen does not allow making edges [1]. In some other

* Corresponding author.

E-mail address: mosaddegh@cc.iut.ac.ir (P. Mosaddegh).

cases, grit blasting [6], sandpaper [7,8], or shot peening [9] is used to roughen the metal surface to increase the mechanical interlocking. A costly method employed for mechanical interlocking is using laser to create some micro-structures on the metal surface, which is costly [10–12]. Moreover, some researchers [13] used a novel hybrid metal-composite joining technology. In their work, cylinder-pins and ball-head-pins were welded on the metal surface to improve mechanical interlocking. In addition, in some cases, clinching technology [14,15] for joining aluminium to polymer or rivet [16,17] for joining metal to carbon fiber reinforced polymer is using. Lambiase and Ko [18] used two-steps clinching for joining aluminium to carbon fiber reinforced polymer. Despite the applicability of the mechanical joining method to most polymers, it has some drawbacks such as formation of stress concentration near the created roughness [7,19], creation of mechanical and thermal residual stress in the surface layer of the metal, and the need for preheating of the metal layer [9].

1.2. Chemical modification of a polymer to enhance adhesion

In this method, the chemical structure of a polymer is modified to increase the adhesion of polymer to metal. Ochoa-Putman and Vaidya [20] investigated the effect of the functionalization of a polymer on its strength of adhesion to metal. They modified polypropylene by maleic anhydride, adding polar functional groups, to increase the adhesion of the polymer to the metal. Also, in the study by Salladay and Stevens [21], polyamide was modified by self-ordering polyester-amid as a co-polymer which improved adhesion to the metal. The advantage of this method is that it does not require any significant pre-treatments on the metal surface to attain the desired amount of polymer-to-metal adhesion strength [1]. However, this method displays significant shortcomings. For example, the necessity of maintaining the structural integrity of the polymer does not allow modifying the chemical structure of the polymer in some cases. In addition, Salladay and Stevens [21] indicated the adhesion of the thermoplastic melt to the mould body by chemical modification of the polymer.

1.3. Using a third component

Within this approach, a third component such as an adhesive or a promoter is used for priming the metal surface prior to the injection moulding process to enhance adhesion between the metal insert and the over-moulded polymer. Silane with amino and vinyl functional groups is the most commonly used primer [22]. It enhances the adhesion between organic and inorganic materials [1]. Boerio and Shah [23] carried out a comprehensive study of using a primer. They investigated interactions occurring at the interface between injection-moulded polyvinyl chloride (PVC) and steel substrates pre-coated with thin layers of aminosilanes [23]. Honkanen et al. [3] also conducted a comprehensive study on using silane. They used amino silane as a coupling agent between injection-moulded thermoplastic urethane and stainless steel. They investigated the effect of silane treatment parameters such as silane concentration and different controlled oxidizing steel surfaces on the formation of a silane layer and related it to the adhesion [3,24,25]. Valenza et al. [26] also used silane with an epoxy group to improve adhesion between aluminium and a glass fiber reinforced polymer. This method also has some shortcomings. For example, silanes are costly chemical materials, and the chemical and thermal environments encountered can affect the adhesive strength.

In this work, a novel polymer-to-metal joining technology based on bond formation with metal surface was developed. In other words, the technology is based on the reaction between isocyanate groups (NCO) in a solution and hydroxyl groups (OH) on a metal surface. The process of producing the polymer-metal hybrids is

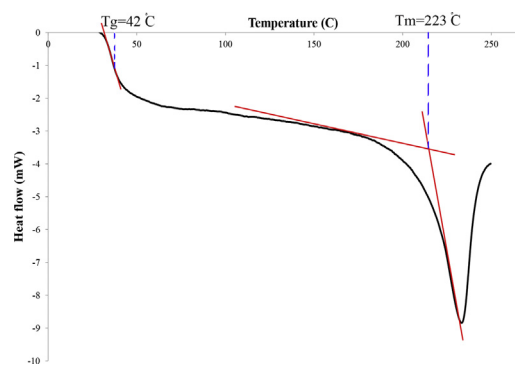


Fig. 1. The DSC plot for PA6.

comprised of three steps: 1) preparing the surface of the metal insert, 2) dipping the treated metal insert into a solution consisting of isocyanate and hydroxyl groups, and 3) injecting the polymer on the primed metal insert. This method has some advantages, compared with the above-mentioned methods: lack of stress concentration in the metal surface, lack of mechanical and thermal residual stress in the metal structure, and low cost. To quantify the achieved results, the single lap shear joint tests were performed to assess the effect of the NCO/OH ratio, mould temperature, and polymer melt temperature on the bond strength. After obtaining parameters causing maximum bond strength, a tensile specimen based on optimum parameters was manufactured to study the mechanical behaviour of the polymer-metal hybrid material under a tensile test. All plastic-metal hybrids in this work were prepared by injection moulding, as this method can be used to manufacture integrated structures in one step.

2. Experimental procedures

2.1. Materials

The insert metal used was stainless steel (SS) AISI 304 (Outokumpu Inc., Finland) 1 mm thick. The injection-moulded polymer was polyamide 6 (Akulon F223-D, DSM, Netherland) with glass transition temperature of 42 °C and melt temperature of 223 °C. The Differential Scanning Calorimetry (DSC) test was performed on the samples with the heat rate of 30 °C/min (Fig. 1). The final specimen was 4 mm thick, including a metal substrate and an over-moulded polymer of 1 mm and 3 mm thick, respectively. Two types of specimens were produced: one for the single lap shear test and the other for the tensile test. The single lap shear test specimen was manufactured based on ASTM D5868-01 [27] to investigate the effect of different parameters on the bond strength. The tensile specimen was manufactured based on ASTM D638 type I [28] to investigate the mechanical properties of the hybrid under tensile load.

Toluene diisocyanate (TDI, commercially available as 2, 4-TDI, Karoon Petrochemical Co., Iran) was used for supplying isocyanate groups. TDI is a common material used for producing polyurethanes. Polyol is also another common material utilized for producing polyurethanes that consists of hydroxyl groups. Commercially available polyol (grade Wanol F3147) was provided by Wanhua Co., China. Wanol F3147 is a glycerol-based polyether polyol. TDI and polyol are low cost materials. Fig. 2 shows the reaction between isocyanate and hydroxyl groups in the solution to form urethane linkage [29].

The reaction between NCO and OH groups also takes place between the isocyanate group in the solution and the hydroxyl group on the metal surface, as shown schematically in Fig. 3. Fig. 3 shows the single lap shear test specimen and all possible reaction occurring in it.

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