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Enhancing the joining strength of injection-molded polymer-metal hybrids by rapid heating and cooling

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ABSTRACT

The design of a variotherm injection mold and the corresponding temperature control system for metal-polymer joining was reported. Due to the importance of understanding the heat transfer process and metal temperature variation during the molding cycle for developing the above method of polymer-metal hybrid (PMH) formation, the thermal response of the metal surface was evaluated. The existence of a correlation between metal surface temperature and tensile lap shear force was revealed, and the surface temperature resulting in the best mechanical performance was determined. Finite element simulation was used to investigate the effect of metal surface temperature on the behavior of the melt flow thereon, revealing that air retained in the metal surface microstructures significantly affected PMH bonding strength. The fracture surfaces of PMH samples molded at different metal surface temperatures were examined, and the underlying fracture mechanism was explained.

1. Introduction

Polymer-metal hybrids (PMHs) are considered to be efficient energy-saving materials, being lightweight and exhibiting high mechanical strength, as exemplified by their use in numerous industrial components, ranging from large automotive parts to small electronic devices. Different approaches have been developed to produce PMHs, e.g., Thoppul et al. (2009) reviewed the use of mechanical interlocking to form PMHs and discussed the influence of geometric effects on their mechanical strength. Rodríguez-Vidal et al. (2016) explored laser joining of a low-alloy steel (HC420LA) with a glass fiber–reinforced polyamide (PA6-GF30), achieving strong bonding between these different materials. Liu et al. (2014) demonstrated the efficiency of joining metal and plastic by friction lap welding, investigating the influences of welding parameters on bubble formation and shear strength in a case study of aluminum alloy AA6061 and MC Nylon-6. Arenas et al. (2013) employed a structural adhesive to form Al-composite material joints, optimizing the joining process. Quan and Ivankovic (2015) claimed that hybrid materials can be joined using epoxy resins and investigated the influence of nanosized core-shell rubber particles on the mechanical/thermal properties and fracture toughness of the prepared samples. Despite the proven potential of these methods and their wide use in aerospace, automotive, and communication industries, they exhibit some limitations. For example, the use of holes/rivets to maintain structural integrity by mechanical interlocking is not allowed in many engineering applications, as is the use of welding equipment to implement fusion bonding. In the case of adhesive bonding, the adhesive cost, long curing time, and unwholesome gases released from the adhesive may pose a problem, as demonstrated by Hoikkanen et al. (2012). Besides, these methods are of limited use for joining plastic parts with complex three-dimensional (3D) structures with metals. Therefore, the above issues necessitate the development of alternative bonding technologies with lower cost and fewer processing steps.

To mitigate these problems, injection molding–induced PMH formation was proposed, providing advantages such as high molding efficiency and convenient molding of plastic parts with complex structures. For instance, Zoellner and Evans (2002) produced a PMH by placing metal sheets with flared through-holes in an injection mold and injecting fiber-reinforced Polyamide 6. By injecting a polymer melt into the gap between polymer and metal parts, Ramani and Moriarty (1998) successfully manufactured an aluminum-polycarbonate PMH. Drummer et al. (2010) used an MK^2 process to combine functional metal surfaces with polymer structures by highly efficient assembly injection molding. The above works proved that the injection technology can facilitate metal-polymer bonding. However, in earlier studies, the injected polymer melt was only used to form plastic rivets or was utilized as an intermediate layer to combine polymer and metal parts, requiring the constituent metal parts with through-holes and polymer parts to be produced in advance. Consequently, the molding efficiency and part quality are still subject to limitations. Recently, a novel direct injection joining technology based on surface microstructures (Micro-IJT) has been developed, producing high-quality PMHs and allowing metals to

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be joined with thermoplastics via direct injection of the latter into the metal surface microstructures. Although Kang et al. (2014) and Grujicic et al. (2008) showed that changing the surface microstructure or chemical composition can enhance bonding between metals and thermoplastics, the presented Micro-IJT process did not utilize chemical agents for simplicity and molding efficiency reasons. Therefore, mold cavity filling by the melt and metal surface microstructures were considered to significantly influence part quality, with low-viscosity and high-flowability polymer melts favoring microstructure filling. As demonstrated by Xiao and Huang (2014) and Xiao et al. (2016), the flow behavior of melts is greatly influenced by heat transfer during filling. Sahli et al. (2013) showed that mold temperature can affect part quality, including polymer replication ability, and Wang et al. (2013) investigated the effect of mold temperature on the surface appearance and mechanical properties of the produced composites. However, only few works describe the relationship of metal temperature and part performance for PMHs. Lucchetta et al. (2011) found that polymer overmolding on a metal support can be accompanied by the infiltration of high-temperature micron-size roughness features of the metal substrate with thermoplastic melt. Paul et al. (2015) also pointed out that PMHs could be produced by compression molding when the metal and the mold are heated above 120 °C. Unfortunately, the detailed effect of metal temperature in the injection process on PMH bonding strength has not been discussed. Herein, rapid heating and cooling were utilized to improve the flow ability of the melt and enhance PMH bonding strength. The heat transfer during heating and cooling stages was also investigated. Moreover, the design and production of a Micro-IJT mold and a temperature control system for PMH production were described. The metal surface temperature was evaluated by experimental and simulation techniques, and its effect on the melt flow behavior was systematically analyzed. Finally, Micro-IJT experiments were conducted to investigate the effect of metal surface temperature on PMH bonding strength and determine the underlying reasons of the improved bonding strength observed at increased metal temperatures.

2. Micro-IJT process

2.1. Process principle and temperature control

The process of Micro-IJT molding is illustrated in Fig. 1. Initially, microstructures are formed on the surface of the fabricated metal substrate by an appropriate treatment, and the treated substrate is placed into a mold and heated to the desired temperature. Subsequently, the polymer melt is directly injected into the mold and surface microstructures of the metal. Finally, the metal and polymer melt are cooled, and the produced PMH is molded. This technology exhibits numerous advantages, avoiding the use of chemical agents or adhesives, not requiring holes/rivets for interlocking, ensuring structural integrity of the joined parts, and allowing polymer sections with complex structures to be molded. However, the high-temperature injection melt flow on the low-temperature metal substrate results in immediate thermal transfer between these two materials that can induce a relatively fast solidification of the melt skin layer and thus affect part quality, as shown by Li et al. (2011) and Santis and Pantani (2016). For the present process, this phenomenon can prevent the melt from infiltrating the microstructures of the metal surface, inevitably affecting the joining strength between the polymer and the melt. Besides, the low temperature of the metal can easily cause uneven cooling of the polymer melt, resulting in increased stress concentration at the joining interface and further influencing the joining strength. In contrast, if the metal substrate temperature is high enough, i.e., close to or above the glass transition temperature of the injected material, the solidified layer formed on the skin melt becomes thinner or disappears entirely. Moreover, high temperature decreases the viscosity of the polymer melt and increases its flow ability. All of these factors promote the filling of microstructures by the melt and improve bonding strength, implying that a proper temperature control system should be designed to satisfy the metal temperature requirements and allow it to be rapidly changed to enable high molding efficiency. A schematic diagram of the developed system is shown in Fig. 2.

In the above figure, solid lines represent pipe connections, and dashed lines represent signal connections. The designed system comprised cooling/heating equipment, temperature sensors, a core control and monitor unit, and associated switching valves and pipelines. In the heating stage, the mold and metal substrate were heated by system-controlled electric heating rods. When the temperature of the metal surface reached the required value, the polymer melt was injected into the mold cavity and the microstructures of the metal surface. After packing stages, inlet and one-way valves were opened to allow water to circulate in cooling channels to cool the mold and the molded part, with a pump used to enhance circulation. When the temperature decreased to the designated value, the mold was opened, and the PMH was ejected, followed by the next cycle. All above steps were unified by the core control unit, comprising a programmable logic controller (PLC), a touch screen, digital receiver modules, A/D converting modules, and input/output signal modules. Consequently, the metal temperature could be rapidly adjusted to satisfy the molding requirements.

2.2. Heat transfer process

In the Micro-IJT process, the metal and mold temperatures were adjusted using a temperature control system, as described above. In

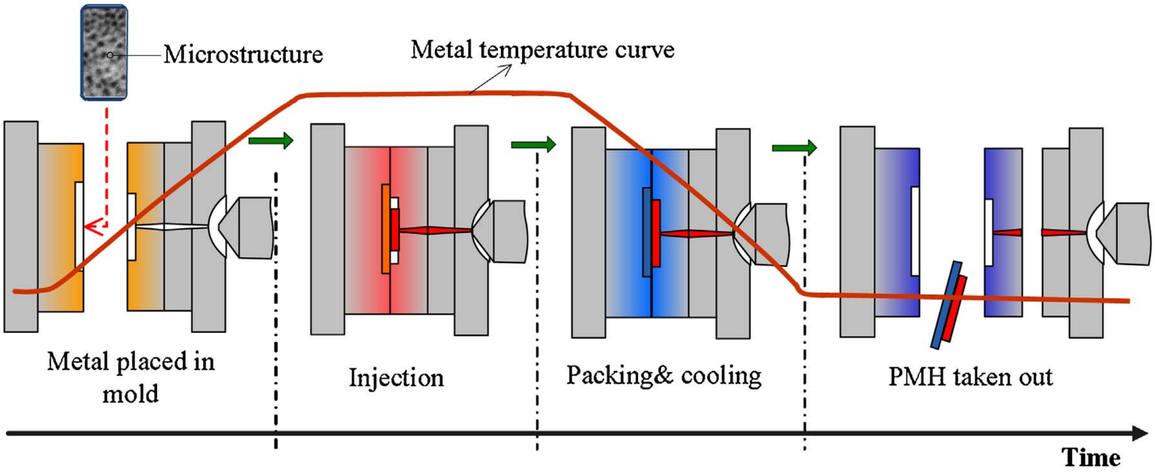

Fig. 1. Schematic representation of Micro-IJT molding.