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Technical Paper

Characterization of weld attributes in ultrasonic welding of short carbon fiber reinforced thermoplastic composites

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ABSTRACT

Ultrasonic welding is a well-known technique for joining thermoplastics and has recently been introduced for joining carbon fiber reinforced thermoplastic composites. However, there is a lack of understanding on how weld quality attributes develop under different welding conditions, especially without using an energy director. In this paper, ultrasonic welding of an injection molded short carbon fiber reinforced composite is tested to investigate three important weld attributes, bonding efficiency, weld area, and horn indentation. From a two-level full factorial experiment, welding energy is found having the most important influence on joint quality, which is related to weld attributes. Thus, only welding energy is varied to simplify the analysis of weld attributes evolution during the welding process. After examining the microstructure of the cross sections and the fracture surface of the welded joints, several observations were obtained. First, the bonding formation for the carbon fiber reinforced composite is mainly through the polymer–polymer interface healing with involved carbon fibers as reinforcements. Second, the bonding efficiency and weld area increase with an increase in welding energy until they reach a threshold. As welding energy continues to increase, the bonding efficiency will decrease due to material degradation as pores develop, but weld area will remain unchanged. Finally, the difference of welding attributes leads to three failure modes of the joints, e.g. interfacial separation, nugget shear fracture, and nugget pull-out fracture, which are an indicator of the joint quality. These experimental observations provide insights toward the development of a robust ultrasonic welding process for fiber reinforced composites.

1. Introduction

Ultrasonic welding is a process in which high frequency ultrasonic vibration (typically between 20 and 40 kHz) is used to produce small amplitude displacements to generate interfacial heating [1]. Currently, there are two common ultrasonic welding techniques: ultrasonic metal welding and ultrasonic polymer welding. These techniques have different vibration directions. For metal welding, the vibration direction is parallel to the workpiece surface while for polymer welding it is perpendicular to the workpiece surface [2,3]. Because ultrasonic welding is fast, economic, and easy to be automated, its applications are quite extensive in a number of industries, including electronics, computer, and automotive industries.

Nowadays, more and more materials, including, thermoplastic composites are being ultrasonically welded. Among the thermoplastic composites, short fiber reinforced thermoplastic composites are considered a class of structural materials due to their excellent formability suitable for mass production, relatively low cost, and superior mechanical properties over the parent polymers. Taylor et al. [4] emphasized that ultrasonic welding is applicable to joint short fiber composite parts, especially those produced by injection molding.

A number of studies have been carried out recently to investigate the ultrasonic welding process for thermoplastic composites. Yousefpour et al. [1] reviewed the application of ultrasonic welding technology to thermoplastic polymers and described the advantages and the difficulties of using ultrasonic welding for thermoplastic composites. Benatar [3] discussed the weldability of thermoplastic composites. Benatar and Gutowski [5] analyzed

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the ultrasonic welding process and divided it into five steps: (1) mechanics and vibrations of the parts, (2) heat generation, (3) heat transfer, (4) flow and wetting, and (5) intermolecular diffusion. The bonding mechanism for ultrasonically welded thermoplastic composites is the polymer–polymer interface healing, same as the bonding mechanism for thermoplastics. Wool and O'Connor [6] and Wu et al. [7], divided interface healing process into five sequential stages: (1) surface rearrangement, (2) surface approach, (3) wetting, (4) diffusion, and (5) randomization. In stages (1) and (2) the two distinct interfaces still exist. Intimate contact between the two interfaces occurs in the wetting stage and the polymer chains are free to move across the interface via interdiffusion until the end of this stage. The latter stages of diffusion and randomization are the most important ones since the characteristic strength of the welded joints forms in these stages. According to these authors, two models are combined to describe these five stages of the interface healing process: the intimate contact model is used to describe the stages of surface approach and wetting [8] and the autohesion model for interdiffusion of polymer chains after intimate contact has been achieved. In the first model, a series of identical rectangles are proposed to represent the actual surface roughness and to define the initial contact between the two parts to be welded. In the second model, part of the polymer chains from one part will diffuse across the interface and entangle with the polymer chains on opposite side of the other part. In the "tube" model [9], each polymer chain is confined to a tube with a radius r, simulating the constrains caused by the other polymer chains. Thus, the movement of the polymer chain is restricted in transverse direction and is dominant along the tube. This movement, called reptation, allows the polymer chains to diffuse and overlap with other polymer chains (cross links for entangles). Hence, the critical healing process in ultrasonic welding starts when intimate contact is achieved and ends when the reptation time t_r has elapsed, which is defined as the time necessary for a polymer chain to exit totally the original tube in which it is confined.

Besides understanding of the ultrasonic composite welding process, the optimization of joint strength has been investigated in detail. Ramarathnam et al. [10] reported the influence of melt flow index on the lap-shear strength with different tie-layers as the energy directors. Villegas and Bersee [11] investigated the influence of energy directing surfaces on weld quality. Liu and Chang [12] studied the effects of welding parameters on the joint strength of ultrasonically welded Nylon composites based on a L18 orthogonal array of the Taguchi approach, and pointed out that amplitude, holding time, and the geometry of energy director have a significant influence on the joint property. Also, the increment of fiber content in the composite was found to improve the joint strength. Harras et al. [13] found that the optimum joint strength is correlated to the total energy input at the weld region and recommended the welding energy as the reliable control parameter during the welding process. Villegas [14] presented the joint strength development in ultrasonic composite wielding with flat energy directors, and related the joint strength to the welding process data, i.e. dissipated power and displacement of the sonotrode.

It is known that weld attributes (e.g. weld area and bonding efficiency) have an intrinsic relation with the weld quality and the accurate determination of the weld attributes evolution during the welding process is helpful to select the suitable welding parameters. Also, the weld attributes are necessary inputs for building a performance model to predict the joint quality [15]. Hence, it is important to characterize the weld attributes evolution during the welding process. During the ultrasonic composite welding, to concentrate the welding energy to rapidly initiate the melting of the joining surface, an energy director is normally used. However, the introduction of energy director will significantly increase the manufacturing cost. At present, no reference has been reported for the case without an energy director. In this paper, the weld attributes without an energy director are investigated. Generally, the weld attributes for thermoplastic composites are quite different from that for metal welding since the heating mechanism for thermoplastic composites mainly depends on intermolecular friction (i.e. viscoelastic heating), not interfacial friction. Thus far, few researches exists in the characterization of weld attributes in ultrasonic welding of polymers or composites even though there have been several studies in characterizing the weld attributes in ultrasonic metal welding. Lee et al. [16] characterized the critical weld attributes of the ultrasonically welded joints of Cu and Ni-plated Cu using microstructure images and hardness distribution. Lee et al. [17] established the correlation between some online features and the weld attributes in predicting the joint quality with the same materials. Additionally, the weld attributes of dissimilar materials, like aluminium to steel, are also investigated [18–22]. However, the characteristics of the weld attributes for thermoplastic composites have not yet been investigated in details.

In this paper, the weld attributes of an injection molded short carbon fiber reinforced nylon 6 composite are investigated as a result of changing welding energy. The remainder of the paper is organized as follows: Section 2 describes the material and experimental set-up; Section 3 defines three important weld attributes: bonding efficiency, weld area, and horn indentation; Section 4 presents the evolutions of the three weld attributes based on welding energy; and Section 5 concludes the paper.

2. Material and experimental set-up

In this paper, an injection molded short carbon fiber reinforced Nylon 6 composite with a weight fraction of fibers of 30% (30% CF Nylon 6) is tested to characterize the weld attributes. The mean diameter and length of the short carbon-fibers are ~8 μm and ~250 μm, respectively. Nylon 6 is a semi-crystalline material with a glass transition temperature of 47 °C and a melting temperature of 220 °C. It should be noted that the fibers were premixed with the thermoplastic matrix prior to injection molding. Due to the process of injection molding, the resulting orientation of the molded short fibers is multidirectional, but mainly oriented in three directions, as described below using the skin-core-skin structure [23]. In this structure, it is assumed that most fibers in the two surface layers, ~1/3 of the thickness, called skin, are oriented in the main injection flow direction (i.e. the longitudinal direction, or LD), as shown in the T/LD surface of Fig. 1(a), while the central layer, ~1/3 in middle of the thickness, called core, contains fibers transversally aligned to the main flow direction, or TD, as shown in the T/TD surface of Fig. 1(a). All coupons were injection molded with dimensions of 127 mm × 38 mm × 3 mm. Since humidity will affect the joint quality and cause the variation of measured results, all the samples were sealed in a plastic bag once they are injection molded and dry samples were used for ultrasonic welding.

A schematic of the experimental set-up is presented in Fig. 1(b). The coupons are welded with a lap-shear configuration along the longitudinal direction, where the overlapped area is 38 mm × 38 mm. A Dukane advanced iQ servo welder with the horn diameter of 9.5 mm is applied to generate 20 kHz vibrations (maximum amplitude 35 μm, which is applied from the welder supplier) and transfer them into a mechanical energy to the coupons, where the vibration direction is vertical. Different from other researches on ultrasonic welding of polymers or composites, the energy director is not used in the current process. For the closed-loop ultrasonic welding system, only five welding parameters can be selected to vary the welding conditions, i.e. trigger force, welding energy, plunging speed, holding time, and amplitude. To investigate the influence of the welding parameters on the joint performance, a