Processing Technology for WSF Sandwich Composite Plate

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The dominant processing technology for the woven spacer fabric (WSF) sandwich composite plate includes preparing a composite of resin and filling of foam. This process begins with composite preparation, followed by filling, or filling first and then preparing the composite. The main difference is that the core layer in the first method is impregnated with resin, which can effectively improve the bearing capacity in the loading process, but the internal connection structure combined with the interface with foam is poor, which worsens the integrity of the plate, resulting in shear failure. The second preparation process can produce excellent integrity and good synergy between the filling material and the internal connection structure, but the carrying capacity is worse compared with that of the first preparation method. In the actual preparation process, fiber stiffness depends on the choice of the preparation method. For fiber with greater stiffness (such as carbon fiber, glass fiber, and basalt fiber), the method of first preparing the composite and then filling is generally adopted. In contrast, for fibers with high flexibility (such as polyester fiber, aramid, and polypropylene), the method of filling first and then preparing the composite is adopted.

Keywords: core yarn structure ; cross-linking structure ; filling process ; molding process ; sandwich structure

1. Filling Process for WSF Sandwich Composite Plate

1.1. Core Material

Polyurethane (PU) foam, phenolic foam, concrete, and cementation materials are widely used as core materials, but their choice depends on the application field for the woven spacer fabric (WSF) sandwich composite plate. Because of its lightweight, high strength, and low thermal conductivity, PU foam composites have been reported to be useful energy-efficient materials in construction, traffic, and cold-chain transportation.

To enhance the mechanical properties of PU foam, Hamid et al. [1] added natural nanostructured zeolite particles to the polyurethane foam, and this greatly enhanced the PU. Concrete foam is ordinarily applied in infrastructure construction because, compared with conventional concrete, it is lightweight and more economical; however, this results in low infrastructural stability and strength [2]. Comparing PU foam with concrete foam, Wang et al. [3] found that the performance and energy absorption capacity of PU was generally better than those of concrete foam. However, the fire grade of PU foam is lower. In subsequent studies, Wang et al. [4] used a mixture of cemented foam and mortar to fabricate novel ductile cementitious composites with low thermal conductivity and high fire grade in building fire prevention. In addition, the phenolic foam is exceedingly flame retardant (refractory, low toxicity, and low smoke), exhibits heat resistance and heat preservation, and its bubble hole size reduces while its rigidity increases with increasing foam density. The brittleness, high powder rate, and poor impact resistance properties of phenolic foam is offset by the toughness provided by fiber or polyamide resin. If the polyamide resin toughens the phenolic foam, the compression strength is reduced, but the adopted fiber is different patterns [5] due to the agglomeration of fibers.

1.2. Filling Technology

The filling technology for the WSF sandwich composite plate is mostly hand lay-up technology. This technique is composed of two methods: filling-the-foaming-agent method and setting-the-temperature-for-the-foaming method. In the foaming-agent method, the fabric is placed in the mold first, and then the volume expansion of the liquid during the foaming process pushes the two surfaces apart [6][7]. Although this method allows for control of the foaming speed and uniformity of cell size and shape, the design flexibility of the plates is poor, and it is not easy to achieve a large-scale and optimal production level. In addition, few studies report the vacuum-assisted molding process. Vaidya et al. [8] used a 25.4 mm–diameter infusion tube to quickly inject the foam, and it properly controlled the amount of foam injected. However, like temperature foaming, such as epoxy foams, this process is rigorously controlled by using foaming temperature [9] to achieve the desired cell size and shape, uniformity, and improved foam density [10]. In addition, other process parameters such as pressure and concentration of components could also be applied.

2. Molding Process of WSF Sandwich Composite Plate

2.1. Resin Matrix

In the preparation of the WSF sandwich composite plate, epoxy resin, polyester resin, and phenolic resin are generally used, but polyester resin is preferred because of its low price and ease of handling [11][12][13]. Compared with polyester resin, epoxy resin is a widely used polymer, accounting for about 70% of the entire thermosetting resins market, because of its excellent thermal stability, fairly low thermal conductivity, outstanding electrical insulation, and chemical resistance [14][15][16]. The results demonstrated that epoxy-based composites had a stronger bending modulus, core shear stress, and bending stress, but appeared more brittle [17][18]. In comparison, polyester resin was prone to deformation and fiber/matrix-interface-layer separation. The brittle and weak shear resistance of the core layer has a significant effect on the properties of the WSF sandwich composite plate. Therefore, in the molding process, epoxy resin is customarily used as a composite material. Phenolic resins are a less-used resin system, except in the high-temperature field and anti-corrosion engineering because of their characteristics of high acid resistance, high-temperature resistance, dimensional stability and so on [19][20]. However, it is hard to prepare, resulting in WSF sandwich composite plates with poor mechanical strength and toughness. To improve phenolic resin toughness, Ferhat et al. [21] used multi-walled carbon nanotubes and nano-SiO_2 nanofillers within a resin, which improved toughness by 30%.

2.2. Molding Technology

The molding technology of WSF includes the hand lay-up process, vacuum infusion process (VIP), RTM process, and slot-coating technology. The hand lay-up process uses two methods to complete the processing: spraying and impregnation. Low-viscosity epoxy resin was sprayed on fabric, and then it was placed in a vacuum chamber and degassed and gassed three times to enhance the infiltration of the resin and remove any bubbles in the wet assemblies [22]. In the process of impregnation, the resin was applied to the ground fabric by using a spray gun, which was convenient for full permeation of both the piles and ground fabric [23]. It is a method widely applied in the molding process of WSF and WSF reinforcement core (it is a filling, but not complete molding, process). However, hand lay-up process has some limitations, including poor adhesion with fabric, easy penetration in the internal structure of the fabric, and uneven coating thickness. Consequently, the slot-coating technology was proposed by Doyen et al. [24] for use as a positive pump to control the thickness of the coating layer on upper and lower ground fabric through simultaneous coating [24] during the WSF molding process.

The VIP is divided into vacuum conditions and semi-vacuum conditions. In vacuum conditions, VIP is currently only applied in the molding process of hollow WSF sandwich composite plate, and not in the process for the WSF reinforcement core, which is difficult because incomplete impregnation easily emerges. Then, in the molding process of WSF, the core bar inserted into the hollow of the fabric is wrapped with non-porous Teflon sheets after the impregnating and curing of WSF [25]. This process requires a core bar to maintain its 3D shape and prevent damage to the internal structure. Although this method has more advantages, including lower fiber stiffness, it is limited by the characteristics of poor design flexibility and high specification and size of the core bar. For semi-vacuum conditions, WSF was impregnated with resin before the vacuum bag was removed to relax the piles to obtain a 3D hollow WSF sandwich composite plate, which potentially has uneven resin thickness and instability on the upper and lower ground plates. Thus, in the curing process, Ghanshyam et al. [26] used a metal frame to hold the 3D structure and avoid instability. Wang et al. [27] combined the hand lay-up process and the VIP. The method is a novelty, which involved coating of the WSF with resin, using the hand lay-up process for the pre-curing step, and then uniformly infusing resin to the fabrication plate by using VIP.

The RTM process involves infusing low-viscosity resin to a vacuum mold to a produce a composite [28]. Compared with the hand lay-up process and the VIP, the RTM is a less studied method, because it requires very high precision for the mold. Low precision will affect the uniformity of the resin distribution for preform when the vacuum is not enough or bubbles exist in the resin fluid, which produces heavy and hard-to-operate plates with limited design flexibility [29]. However, composite plates produced through the RTM process have excellent performance compared to those produced by using the hand lay-up process [28]. The RTM process is inclined to form an interphase between the resin matrix and reinforcement in the vacuum-pressure-improving property [30], but this interphase is not obvious in atmospheric pressure for the hand lay-up process.

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