Detection of Defects in Kenaf/Epoxy using Infrared Thermal Imaging Technique

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Abstract

Lignocellulosic fibrous polymeric composite materials have become an attractive replacement for heavier metals due to their superior fatigue and corrosion properties. In this study, Infrared (IR) thermal imaging technique has been used to detect the defect in unidirectional Kenaf bast fibre reinforced composite materials. IR thermal imaging technique or IR thermography is a surface thermal radiation measurement technique that is used to detect spatial variations in the measured surface temperature pattern. Thermography reveals flaws by searching anomalous hot-spots after thermal excitation. Thermography can be either categorized as active or passive. An active Infrared thermography has been proven to be a viable non-destructive testing for composite structures. In active thermography the surface of a sample is heated using an external heat source and then the surface temperature is monitored. The thermography analyses were verified by optical microscope and scanning electron microscope (SEM) investigations. The defect detection accuracy of this technique is 95%.

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Keywords: Non-destructive technique; thermal imaging; defects.

1. Introduction

Mechanical devices tend to become hot before they fail; so infrared is a very powerful tool for predictive maintenance. Infrared (IR) imaging is simpler than visible-light machine vision in that there is no illumination needed to target. It detects the hot spots and highlights the things that are about to fail, giving an immediate visual map of the emerging problems. Everything emits infrared radiation, and the hotter it is, the greater the intensity of the radiation. IR cameras focus on the incoming radiation at each

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point into an electronic signal and display in a thermal image picture containing temperature data with the brightest points present as the hottest point [1]. IR thermal imaging transforms the thermal energy, radiated from objects in the infrared band on the electromagnetic spectrum, into a visible image and each energy level is represented by a color [2]. Nowadays the application of this non-destructive technique was successfully exploited not limited to engineering but also in food industry [3], agriculture [4], architecture [5], environment [6], medical [7] and meteorology [8]. However, research on non-destructive method in lignocellulosic fibrous polymeric composite materials is limited.

2. Experiment

2.1. Materials

A treated Kenaf bast fiber provided by the Institute of Tropical and Forest Product (INTROP), UPM, Serdang, Selangor, Malaysia was used in this study. The raw Kenaf bast fibers were combed to disrupt and untangle the strong bonds between individual fibers. Bernard et al. [9] reported that combed fiber exhibits stronger mechanical properties than uncombed fiber. The Kenaf bast fibers were cut to a length of 23 cm using scissors. Epoxy with a density of 1.15 g/cm³ was used as a binding material.

2.2. Fabrication of Kenaf/epoxy specimens

The composite samples were prepared by combining the Kenaf bast long fibers and the epoxy resin through a hand lay-up process followed by compressing the composite using hot-press compression molding, with a mold similar to the one used to fabricate the epoxy samples. One of the main issues with Kenaf fiber reinforced composites that needs to be addressed is an uneven fiber distribution [10]. Kenaf fibers are difficult to be separated manually and to visually disperse evenly during manufacturing [11]. For a total volume ratio of 60:40 per cent Kenaf bast fiber to epoxy with a thickness of 0.1 cm, 17.25 g of Kenaf bast fibers and 7.95 g of epoxy were prepared. For a total volume ratio of 60:40 per cent Kenaf bast fiber to epoxy with a thickness of 0.3 cm, 51.8 g of Kenaf bast fibers and 23.8 were prepared. For a total volume ratio of 60:40 per cent Kenaf bast fiber to epoxy with a thickness of 0.5 cm, 84.0 g of Kenaf bast fibers and 45.4 g of Kenaf bast long fibers were prepared. The composites were compressed using a hot-press compressing machine at a temperature of 70 °C and a pressure of 50 Bars. The mould was preheated for 3 min followed by pressing for 20 min and venting for 7 times to maintain uniform thickness and prevent air from entering the mould.

2.1. Thermal imaging

IR thermal imager or IR camera is basically a camera with an IR detector. In this study the IR camera used is from IR Fluke Flexcam and an active thermal imaging approach was applied to detect the defects of Kenaf/epoxy composites. Kenaf/epoxy specimens were heated in an oven at 100 °C for 60 min. As claimed by Maldague (2001) [12], in active thermography, the surface of a sample is heated using an external heat source and the surface is monitored. The Kenaf/epoxy specimens were placed on a non-metal stand so as to avoid heat dissipation through conduction from the stand. Then thermal images were recorded. These experiments were conducted for an emissivity of 0.92, with a room temperature of 29.9 °C and a relative humidity of 70%.
2.2. Optical microscopy

An optical microscope was used to verify the detection of defects on the Kenaf/epoxy surface by thermography.

2.3. Scanning electron micrograph (SEM)

Scanning electron microscopy (SEM) via Hitachi S-3400N SEM was used to determine the defects in the Kenaf/epoxy composites and to verify the results obtained from IR camera and the optical microscope. The dimensions for SEM specimens were 0.5 cm height × 1.5 cm width, prepared at different thicknesses of 0.1 cm, 0.3 cm, and 0.5 cm. All specimens were cut using an electrical hand-saw. The surfaces of the specimens were coated with a mixture of 80% Gold and 20% Palladium.

3. Results and Discussion

3.1. Thermography analysis

Figure 1a-c shows thermography of Kenaf/epoxy at 60:40 fiber loading to epoxy at a 0.1 cm, 0.3 cm and 0.5 cm of thicknesses respectively. Thermography is an image containing thermal data presented in a contour of color. Infrared thermal imaging transforms the thermal energy, radiating from objects in the infrared band of the electromagnetic spectrum, into a visible image; each energy level is represented by a color, or grey level [13]. Defects that lie below the surface will affect heat transfer rate when thermal energy is propagating in or out of the structures [14]. These defects or manufacturing defects are voids, resin-rich zones, and pockets of undispersed crosslinker, misaligned fires and also regions where resin has poorly wetted the fibers. These will be discussed details below and these thermography analyses will be verified using SEM and optical microscope.

![Thermography images](image)

Fig. 1. Thermography analyses of Kenaf/epoxy specimen with (a) 0.1 cm, (b) 0.3 cm and (c) 0.5 cm thickness

The results accuracy of using thermography analyses to detect the defects in Kenaf/epoxy specimens are 95%. These mean that the results of thermography have 95% matched with the results of using optical microscope and SEM. As recorded in Figure 1a, the identified defects area, had also been analyzed using optical microscope and SEM as shown in Figure 2. Figure 2 shows the defects area is caused by the presence of a lot of voids. Figure 1b shows the most defects area in specimen of 60:40 Kenaf/epoxy with 0.3 cm and Figure 3 shows the results on the defects area of this specimen by using optical microscope and SEM respectively. Figure 3 shows that the defect is caused by resin rich zones. Figure 1c shows the defects area of 60:40 Kenaf/epoxy with 0.5 cm and the result of the defects area for this specimen while
Figure 4 shows the results on the defects area of this specimen by using optical microscope and SEM respectively. Figure 4 shows that the defect is caused by pockets of undispersed crosslinker.

In this study the healthy parts are declared as an area which has fewer defects while the faulty parts are declared as an area which contain the most defects. The most defect area is defined as the area which contains a lot of imperfect due to manufacturing process such as fiber misalignment, poor adhesion of fiber-matrix bonding, voids and etc. and normally recorded as the highest temperature and represent with the red color. Specimen of Kenaf with 0.5 cm (refer Figure 1c) shows the most defect area followed by specimen with 0.3 cm (refer Figure 1b) and 0.1 cm (refer Figure 1a) respectively.

3.2. Manufacturing defects

Defects typically occur during the commercial production of composites and can be caused by batch-to-batch variations in the prepreg and sometimes by the manual construction known as a ‘lay-up’. Variability could arise from differences in the prepreg tack level during lay-up as a result of variable resin content. Composites can contain a number of defects introduced during manufacturing, which can considerably increase the likelihood of composite failure. Such defects include:

a) Voids
b) Resin-rich zones
c) Pockets of undispersed crosslinker
d) Misaligned fibres
e) Regions where resin has poorly wetted the fibers [13].

Voids are usually defined as air bubbles trapped in the matrix during composite fabrication, but voids can be caused by many factors. Voids will affect mechanical properties indirectly by enhancing the moisture pick-up and degradation of the interfacial adhesion of the fibre matrix [14]. Voids can also occur owing to the presence of impurities in the commercial epoxy resins used for the fibre-reinforced composites, which can lead to a significant impact on the cure behaviour of the epoxy. These impurities can be oligomers or residues of the synthesis reactions. Chlorohydrins are a typical impurity in epoxy resin [13]. Bascom et al. [15] used SEM to identify the deformation between F-185 resin and glass fibre; the micrograph showed evidence of the development of porous structures in the resin. Figure 2 shows voids in specimen of 60:40 Kenaf/epoxy with thickness of 0.1cm.

![Fig. 2. Voids observed in Kenaf/epoxy specimens](image)

In their research, Dewimille and Bunsell [16] discussed preferential cracking in the neighbourhood of resin rich zones. It was also claimed that swelling of the resin due to the presence of water caused deformation in the resin rich zones, so that the weakened interfaces in the neighbourhood of these zones
were subjected to greater stresses and were therefore more likely to fail. Figure 3 shows resin rich zones in specimen of 60:40 Kenaf/epoxy with thickness of 0.3 cm.

![Fig. 3. Resin rich zones](image)

Pockets of undispersed crosslinker may be caused by incomplete curing, the distribution of curing agents or premature curing [13]. Before testing the properties of composite structures, it is important to understand the rheological and mechanical properties of the adhesive/epoxy. Changes in the adhesive due to incomplete curing can affect the results of the adhesion test [17]. Figure 4 shows pockets of undispersed crosslinker in specimen of 60:40 Kenaf/epoxy with thickness of 0.3 cm.

![Fig. 4. Pockets of undispersed crosslinker](image)

The undercuring of thermoset composites leads to lower performance properties in the final product. Numerous thermoset failures are associated with an incomplete cure. **Distribution of curing agents**: To achieve optimum curing and development of mechanical properties, the distribution of the hardener in a polymer composite needs to be uniformed. Because the incorporation of the hardener into an epoxy resin relies on the physical mixing of two viscous liquids, problems can sometimes arise due to poor distribution of the hardener. Apart from undercuring of the resin, globules of hardener-rich material can also act as failure sites. **Premature curing**: For proper conversion of a thermosetting resin, it is necessary to cure the polymer at a temperature below the gel point; otherwise the crosslinking molecules will not have sufficient mobility to migrate to the reactive sites of the polymer because of the increased viscosity of the system. Furthermore, if the resin cures prematurely, insufficient time is available for trapped gases to escape and for flow fronts to properly meld. As a result, cosmetic defects and weak weld lines can result, which may promote failure. Surface defects in thermosetting resins can be associated with premature gelation of the resin. For example, the use of a particular phenolic resin was producing
defective parts that were exhibiting hard surface imperfections. In this case, the surface defects were attributed to the resin reaching gelation before the cavity was completely filled.

The misalignment of fibres in natural fibre reinforced composites occurs as a result of weak interfacial adhesion of the fibre matrix and can also be caused by poor dispersion of the fibre-matrix. Khalina et al. [18] studied the mechanical and rheological properties of injection moulded short oil palm fibre reinforced polymer composites and reported that the roughing of the fibre possibly promoted mechanical properties such as interfacial bonding between the fibre and the matrix. Figure 5 shows misalignment of fibres specimen of 60:40 Kenaf/epoxy with thickness of 0.5 cm.

As reported by Sanadi et al. [19], the primary disadvantage of natural fibres is the poor interfacial adhesion due to the hydrophilic character of cellulose. Mohanty et al. [20] stated that all natural fibres are hydrophilic in nature. Hydrophilic cellulose is usually incompatible with a hydrophobic matrix material, as reported by Leman [21]. Therefore, this phenomenon leads to poor fibre dispersion and fibre-matrix interfacial adhesion. Figure 6 shows poor interfacial adhesion of specimen of 60:40 Kenaf/epoxy with thickness of 0.5 cm.

4. Conclusion

Infrared Thermal Imaging technique has been proved as a nondestructive testing (NDT) to detect defect in Kenaf/epoxy composite materials. Thermography analysis of Kenaf/epoxy as shown in Figure 1a-c has been verified using optical microscope and SEM. The defect detection accuracy of this technique is 95%. Typical occurring defects caused by manufacturing process such as voids, resin-rich zone, pocket
of undispersed crosslinker misaligned fibers and regions where resin has been poorly wetted fiber were
detected using this non-destructive method. Kenaf/epoxy 60:40 with 0.5 cm thickness contains the most
defect area.

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