AN IMPROVEMENT OF THE LOW-COST VACUUM-BAG-ONLY PROCESS FOR CARBON/EPOXY LAMINATED COMPOSITES

P. Sratong-on[1*] and S. Suwannawong[1]

[1] Faculty of Engineering, Thai-Nichi Institute of Technology, Bangkok, 10250, Thailand.
*Corresponding author: pimpet@tni.ac.th

Keywords: Vacuum-Bag-Only, Commercial electric oven, Void content, Carbon fiber-reinforced plastics, Image Analysis

ABSTRACT

The curing process under pressure in autoclave ovens results in high-quality carbon fiber-reinforced plastic (CFRP) parts; however, the cost of an autoclave is typically unaffordable for small-scale enterprises. The Vacuum-Bag-Only (VBO) technique can produce CFRP parts with comparable mechanical properties to those made in autoclaves using a commercial electric oven. However, curing of thermosetting plastic is recommended with more than two ramps and isothermal holds, leading to the need for a complex controller system. Hence, composite curing ovens are rarely available as commercial products. This study proposes a single-hold curing cycle for carbon fiber prepreg with specimens cured in a simple electric oven. Plain-weave carbon fiber prepreg with a size of 120 x 240 mm was fabricated in a stacking sequence of [0°/90°/0°/90°]. The specimens were divided into two groups: specimens with and without pressing at room temperature to reduce entrapped air in the prepreg before curing. All of the specimens were cured from room temperature to 120 °C and held at this temperature for 50 mins followed by air cooling. A tensile test (ASTM D3039/3039M) was performed, and the specimens' surface porosity and internal porosity were determined using optical microscopy and X-ray micro-CT, respectively. The specimen that was pressed before curing exhibited lower surface quality due to surface porosity changes at the fiber cross-junctions. Accordingly, this specimen displayed lower ultimate tensile strength than the specimen without pressing before curing.

1 INTRODUCTION

The demand for carbon fiber-reinforced plastic (CFRP) is increasing due to high strength-to-weight ratio and high corrosion resistance relative to metal; therefore, CRFP is widely used in applications such as aircraft structures and sports equipment. CRFP also has important applications as an environmentally friendly material in the automotive sector. In recent decades, reducing CO_2 emissions has become a key issue worldwide, with combustion engines making a major contribution to current CO_2 emissions. Thus, some countries, e.g., European nations, China, America, and Japan, have announced regulations to control CO_2 emissions from vehicles. T. Ishikawa et al. reported that the CO_2 emissions from driving decreased by 20g/km per 100 kg decrease in vehicle weight [1,2]. Accordingly, metal parts in vehicles can be replaced by CFRP to reduce the total vehicle weight. While several automobile companies have utilized CFRP as a substitute for metallic parts, this practice tends to be limited to motorsports and luxury cars due to the difficulties involved in CFRP mass production, to which several factors contribute. One is the delicate fabrication process for CFRP compared to metal; as the mechanical properties of CFRP are dependent on the fiber orientation, specialist techniques for the layup of CFRP into the mold are required. Additionally, most resin matrixes are thermosetting plastics, which can be cured by applying one or more temperatures followed by an isothermal hold, resulting in long curing cycles required for each part. Good quality CFRP can be cured using an autoclave oven with applied pressure during heating; however, the capital investment cost required for this material is high.

Recently, cost-effective methods that do not require the use of an autoclave (i.e., out-of-autoclave (OOA) processes) have been developed. A fast and cost-effective OOA process is the resin infusion process, in which the resin is impregnated into dry fabrics. However, the vacuum required during the resin impregnation step causes the formation of air bubbles, which degrades the mechanical properties of the resulting CFRP [3]. Vacuum-assisted resin transfer molding (VARTM) has low capital investment costs and a moderate production rate. In this process, entrapped air can evacuate through a permeable membrane; however, low-viscosity resin and an additional permeable membrane are required [4]. The Vacuum-Bag-Only (VBO) process has also been proposed, which can produce comparable mechanical properties of CFRP to that manufactured in an autoclave oven. Dry fabrics with impregnated resin or prepreg can be used in this process with low-cost manufacturing tools, and the specimen can be cured in an electric oven. However, the drawbacks of the VBO process are the higher amount of void content (0.5–3%) compared to the number of voids produced from autoclave fabrication (0–1%) [5].

Since voids can degrade the mechanical properties of CFRP, e.g., tensile strength, interlaminar shear strength (ILSS), several techniques have been suggested to decrease the void content of the VBO process [6–8]. D. Zhang et al. studied the mechanism of void growth kinetics during consolidation in the VBO process under different dwell times in consolidation cycles [9]; they examined the void content using X-ray micro-CT and identified that the air entrapped within plies can be eliminated during the consolidation process. S. Park et al. presented a method to improve the quality of composite laminate from the VBO process based on a study of the viscosity–temperature dependency of resin [5]. They found that low-viscosity resin is necessary since it can provide sufficient flow into dry fiber tows, leading to lower porosity. S. Hwang et al. proposed curing kinetics and viscosity modeling to optimize the curing parameters of the VBO process [10]. Their study suggested that the rheology characteristics of resin play a crucial role in void formation during the curing stage of the VBO process. Y. Mujahid et al. developed a double VBO technique with a modified cure cycle in which the lowest void content can be accomplished [11]. Their study reported reductions of 48.33% in surface porosity and 23.7% in internal void content; as a result, the tensile and flexural strength values of the material were increased by 1% and 3%, respectively, compared to the conventional VBO process. However, the double VBO technique is complex, has higher consumable equipment requirements for the vacuum process, and the modified cure cycle takes more than eight hours due to requiring a more than two-step curing cycle. The VBO process in general requires the installation of complex controller systems in an electric oven. Thus, specialized composite curing ovens are less common in commercial settings; in addition, these ovens are usually made to order. Thus, the cost of this approach is potentially prohibitive for SMEs. In contrast, commercial electric ovens, e.g., toaster ovens, are cheap and readily available. Theoretically, although the cross-linking of resin can occur within the operating temperature range of commercial ovens, there are no reports to date regarding its use in the curing of CFRP.

This study investigated the tensile strength and defects in CFRP that was cured using a commercial electric oven. Due to the limitations of the functionality of commercial ovens, a single-hold curing cycle was adopted to simplify the curing process. The surface defects and internal voids of the CFRP were observed using digital microscopy and X-ray micro-CT, respectively. In addition, the quality of the resulting CFRP sample is discussed.

2 MATERIALS AND METHODS

2.1 Sample Preparation and Experimental Procedures

The 200 gsm plain-weave carbon fiber-reinforced epoxy plastic (DeltaPreg, Italy) was purchased as a prepreg form and cut into 120 mm x 240 mm sheets. The laminate of the carbon fiber-reinforced epoxy plastic consisted of four plies, constructed using a [0°/90°/0°/90°] stacking sequence. Two laminates were prepared: one was pressed using a glass plate and the other was prepared without pressing before the start of the curing process. The VBO process was performed to fabricate the laminates. A release film was applied at the top and bottom of both laminates. One side of the laminates was placed on a 350 mm x 350 mm aluminum mold. In the with-press laminate, a glass plate of 35.5 cm x 100 cm size with a weight of 7.5 kg was applied to the entirety of one side of the surface area as a preliminary step to eliminate the entrapped air in the laminate before curing. The glass plate was then removed. In contrast, the glass plate was not applied to the without-press laminate. A breather cloth was applied to the top surface. Figure 1 shows the setup of the VBO process. The vacuum bag covered all the aluminum mold. After the installation of the vacuum system, the air inside the vacuum bag was suctioned until the pressure reached -1 bar. In this study, a commercial electric oven (OTTO model TO-765 toaster oven) was selected, because this model is cheap, can be found easily in supermarkets, and is made in Thailand. All of the laminates were cured from room temperature, held at 120 °C for 50 minutes, and then aircooled. After the curing process was completed, the thickness values of the laminates were examined, with each laminate found to have a 1 mm thickness. The surface porosities of the laminates were observed using a digital microscope with 2,000x magnification before the tensile tests were conducted.

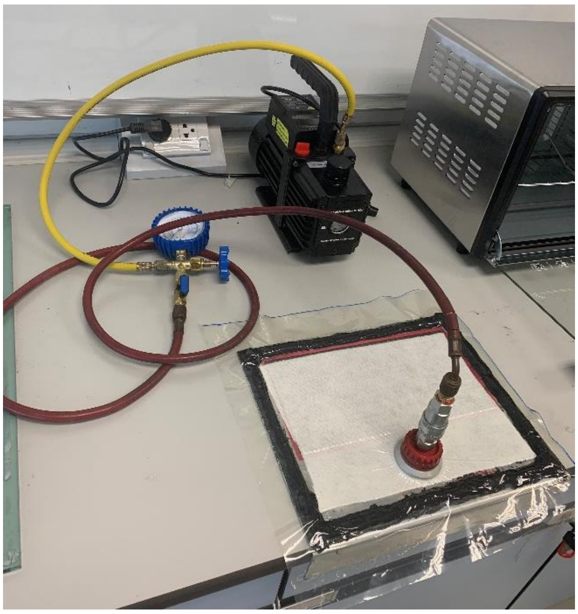
Figure 1: Image illustrating the Vacuum-Bag-Only process setup before oven curing.

The specimens for tensile testing (ASTM D3039) were prepared by cutting each carbon fiber laminate into six pieces with dimensions of 12.5 mm x 240 mm using an EXTEC Labcut 5000. The tensile testing was conducted using a universal testing machine (Zwick/Roell, Model Z100SH) with a strain rate of 0.01/min. According to the ASTM D3039 standard, at least five specimens must be tested. Thus, the remaining sample of each laminate was used for internal porosity measurement using X-ray micro-CT (Skyscan 1173, Bruker). Since the size of voids is generally at a micrometer scale or below, high-resolution image is required to observe them. For the X-ray micro-CT analysis, the laminate was cut to dimensions of 12.5 mm x 30 mm x 1 mm. A full scan was operated with 40 kV and 40 μA, four frames per projection, and 2x2 binning mode. Consequently, an image pixel size of 12.1 μm was achieved.

2.2 An Image Analysis for Observation of Voids

Figure 2 shows the division of the 12 areas used for the digital microscope observation of the surface voids for a single laminate sample. The laminate was clamped using a holder. Due to the limitations of the forward and backward adjustment of the holder, only the height and left–right position could be adjusted. Therefore, only the areas numbered 1–4 and 9–12 could be observed. The lens focus and height of the holder were adjusted until the voids were visible in the display. These conditions were maintained and used throughout the observation of surface voids. The laminate was then removed and graph paper was inserted for void size measurement using ImageJ software.

Figure 2: Diagram illustrating the area numbers of the carbon fiber laminate samples divided for digital microscope observation of voids.

To observe voids inside the laminate, X-ray micro-CT was used, from which three-dimensional images can be reconstructed. The through-thickness voids can be investigated using the segmentation method in 3D Slicer software. Furthermore, orthographic projection planes can be created and moved within three-dimensional images in the software. Accordingly, two-dimensional images of the voids can then be exported for void content analysis.

3 RESULTS AND DISCUSSION

3.1 Tensile Properties of Carbon Fiber Laminate Cured by Commercial Oven

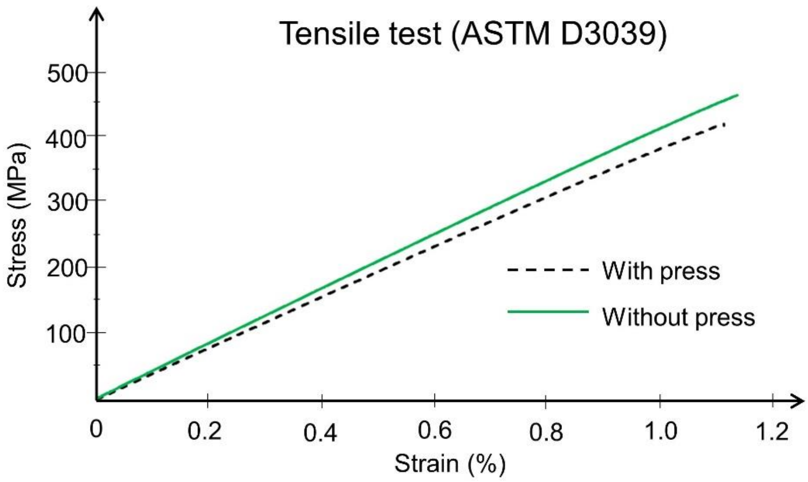

Figure 3: The stress–strain curves of two groups of carbon fiber laminates (with and without press) under tensile testing (ASTM D3039).

The average tensile stress and strain values of five specimens were plotted, as shown in Fig. 3. The with- and without-press laminate specimens were broken at strains of 1.11% and 1.14%, respectively. The strain values at fracture in both laminates were similar; however, the with-press laminate exhibited lower ultimate tensile strength (417.5 MPa) than the without-press laminate (463.8 MPa); thus, the ultimate tensile strength difference between the two laminates was 11.08%. The tensile modulus values of the with- and without-press laminates can be determined from the slopes of the stress–strain curves in Fig. 3, corresponding to values of 37.61 GPa and 40.68 GPa, respectively. Thus, the difference in the tensile modulus values was 8.16%. The observed decrease in the ultimate tensile strength and tensile modulus values of the with-press laminate may be caused by the presence of voids in the specimens [6,12]. D. Purslow concluded that the void content should not exceed 2% for fair-quality laminate composite materials; in addition, specimens containing more than 5% void content were found to have very poor quality [13]. Therefore, the presence of surface voids and internal voids within the samples should be further investigated.

3.2 An Analysis of Surface Voids in Carbon Fiber Laminate

Figs. 4 (a) and (b) show the surface voids in area numbers 3 and 10 (Fig. 2) of the with-press laminate, respectively. A notable finding of this analysis was that the epoxy resin showed non-uniform hardening, particularly at the cross-joints of the weave fiber. This is because the epoxy resin was unable to flow through the cross-joints of the weave fiber during heating. As a result, the resin was hardened before it passed through consecutive plies. Some pinholes were detected at the surface of the with-press laminate as shown in Fig. 4 (b). Pinholes commonly occur when air bubbles in the resin are unable to escape during the curing process. Since both pinholes and imperfectly cured resin at the surface can be occasionally detected by the naked eye, they are usually eliminated in surface finishing steps, such as grinding. Thus, they can be considered as the minimum unacceptable defects in carbon fiber laminates. However, the existence of both surface defect types results in low surface quality. To date, few reports have been published regarding the effects of pinholes and imperfectly cured surface resin on the mechanical properties of carbon fiber laminates. In addition, internal voids, which are not visible to the naked eye and cannot be eliminated with surface treatments, have a more adverse effect than surface defects on the mechanical properties of carbon fiber laminates [8]. Hence, most makers generally eliminate surface defects by grinding because it is a low-cost process that can mitigate cosmetic issues.

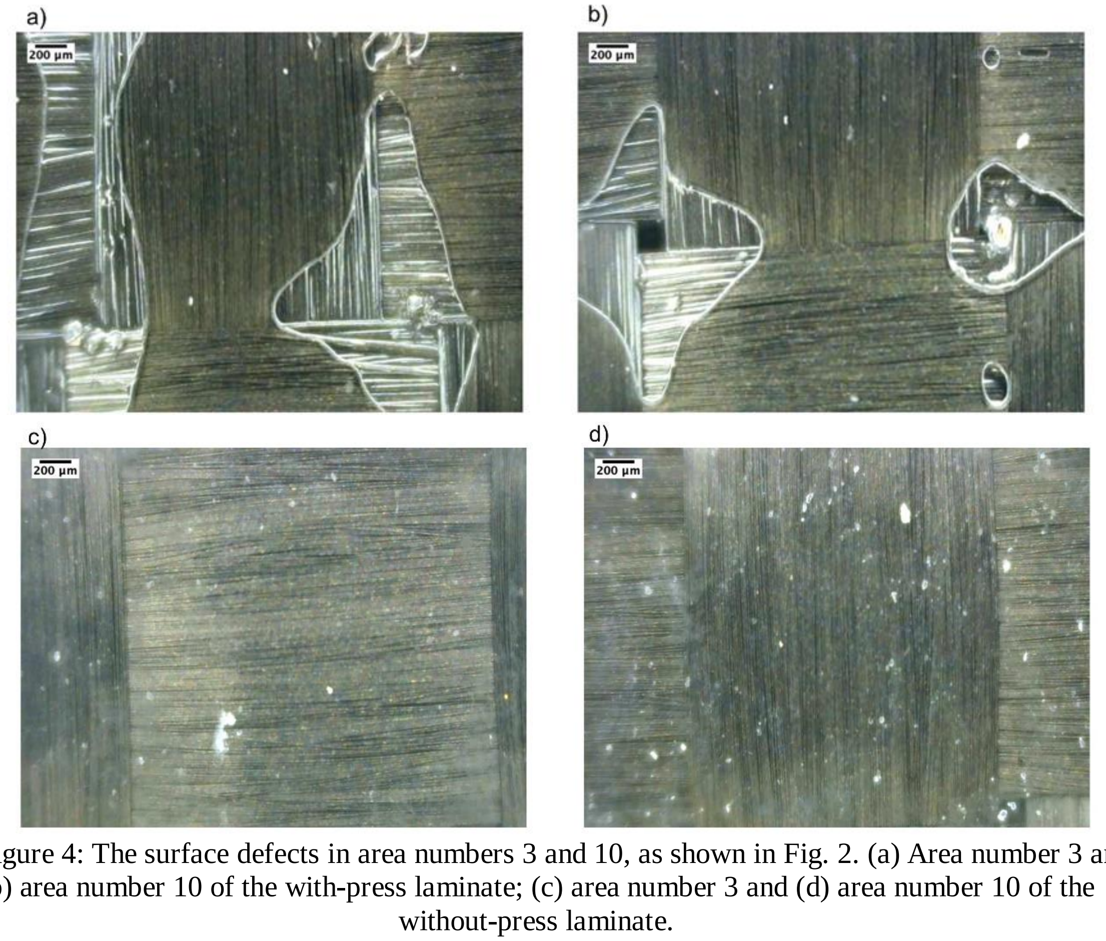

Figure 4: The surface defects in area numbers 3 and 10, as shown in Fig. 2. (a) Area number 3 and (b) area number 10 of the with-press laminate; (c) area number 3 and (d) area number 10 of the without-press laminate.

As shown in Figs. 4 (c-d), imperfectly cured resin and pinholes at the surface were not observed in the without-press laminate; however, tiny surface voids (white spherical shapes) were detected. As the difference in the fabrication process between the with- and without-press laminates was the compressive load imposed by the glass plate on one surface of the with-press laminate prior to curing, this compressive load may have affected the uncured resin in the prepreg, leading to the damaged surface appearance of the with-press laminate.

3.3 An Inspection of Internal Voids by X-ray micro-CT

The area containing the maximum area fraction of voids can be identified by sliding the orthographic projection planes in the 3D slicer software, as shown in Fig. 5(c). As shown, the maximum amount of voids occurred at the middle, as measured from the front surface view to the middle (Fig. 5(a)), and at half the thickness, as measured from the side view to the center of the specimen (Fig. 5(b)). Furthermore, non-uniform hardening of the resin at the cross-joints of the weave fiber observed on the surface of the with-press laminate in Figs. 4 (a-b) can be verified by the three-dimensional X-ray micro-CT images (Fig. 4(c)). However, the pinholes at the surface were not clearly observed in the X-ray micro-CT images.

Since it is difficult to measure the void content directly in 3D slicer software, the two-dimensional images shown in Figs. 5(a-b) were imported to ImageJ to determine the void content percentages. To estimate the percentage of the void content by area fraction, an appropriate threshold should be selected to cover only the area of voids. The circularity was also necessary as a criterion as the voids were near-spherical in shape. A circularity value of 0.0 value indicates an irregular shape whereas a value of 1.0 means a completely spherical shape. It was found that if the circularity criterion was not included, the needle-like gaps between the fibers were also included in the void area fraction and, hence, the void content percentage was incorrect. Therefore, a circularity value range of 0.3–1.0 value was selected since these values cover all of the void area. The maximum area fraction of voids estimated from Fig. 5(a) was 1.88%, corresponding to fair-quality mechanical performance.

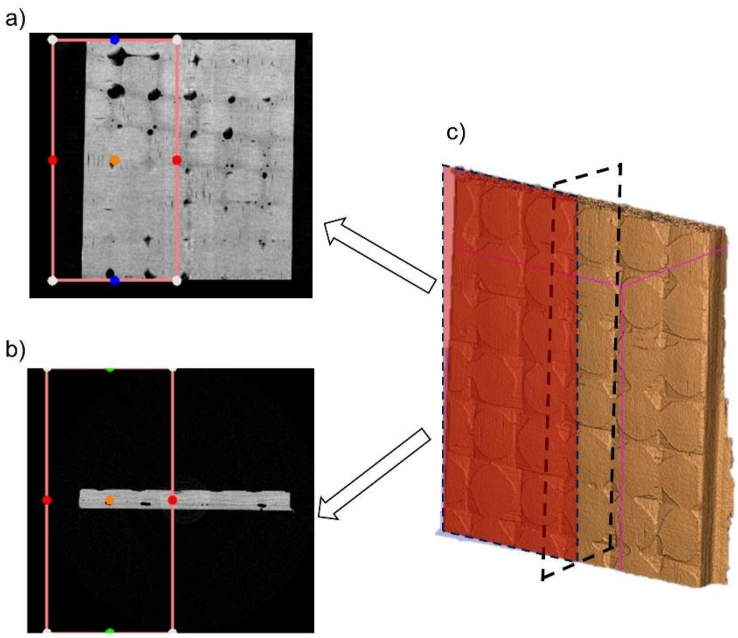

Figure 5: The segmentation of X-ray micro-CT images at the middle and half-thickness of the with-press carbon fiber laminate. (a) The projection image of the middle of the specimen from the front surface, (b) side view of the projection image shown in (a), and (c) red area indicating the orthographic projection plane used for segmentation in (a) and (b).

Figures 6 (a-b) show the front and side views from the segmentation of the X-ray micro-CT images of the without-press laminate. A maximum internal void size of 0.2 mm was observed by measurement of the distance from the front surface in Fig. 6 (a) to the projection plane. Figure 6 (c) shows the three-dimensional images from the X-ray micro-CT image of the without-press laminate, in which the surface quality was consistent with the two-dimensional images obtained using a digital microscope in Figs 4(c-d). Notably, the surface quality of the without-press laminate is better than that of the with-press laminate. In addition, there were fewer surface defects and internal voids in the without-press laminate than in the with-press laminate. This observation may explain the degradation of the ultimate tensile strength and tensile modulus of the with-press laminate.

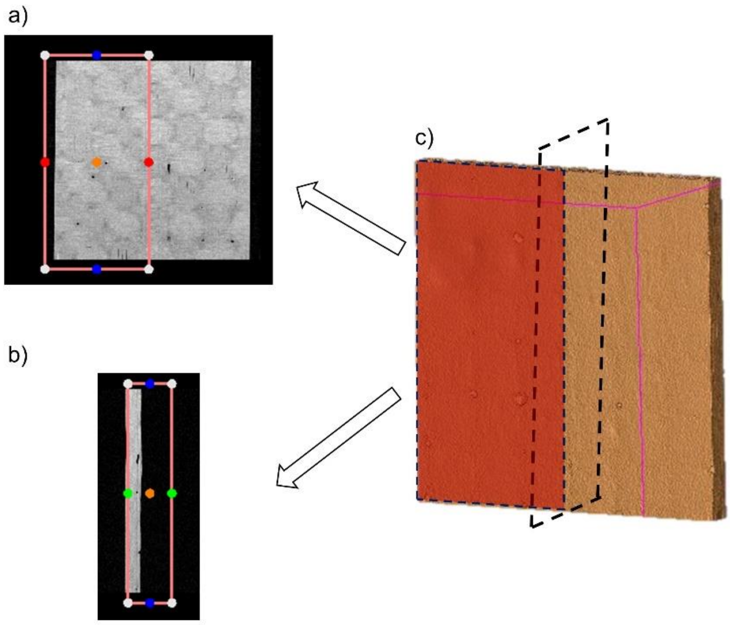

Figure 6: The segmentation of X-ray micro-CT images at the middle and half-thickness of the without-press carbon fiber laminate. (a) The projection image of the middle of the specimen from the front surface, (b) side view of the projection image shown in (a), and (c) red area indicating the orthographic projection plane used for segmentation in (a) and (b).

As described above, the area fraction of the maximum void content in Fig. 6(a) was evaluated using a similar measurement criteria setup in ImageJ. The results revealed a void content value of 0.88%; thus, according to Purslow's chart, the without-press laminate corresponds to a very good quality specimen. Consequently, our proposed single-hold curing cycle using a commercial electric oven represents an alternative low-cost method to create acceptable quality products from CFRP.

One possible reason that can explain the cause of low surface quality and abundant internal voids found in the with-press laminate is percolation flow in the composite. Hubert and Poursartip [14] explained that the percolation flow corresponds to the bleeding of uncured resin without in-plane fiber movement when pressure is applied in an autoclave oven. This flow mechanism is similar to squeezing a sponge, which causes bleeding out of the fluid. The resin can emerge from gaps between the fibers during compaction. The main cause of percolation flow is pressure gradients during heating, which can be programmed in an autoclave oven, and the viscosity of the resin. Percolation flow has previously been reported as typically occurring in low-viscosity thermoset resins [15]; therefore, during curing, as cross-linking occurs, low-viscosity thermoset resins can more readily bleed out from fiber gaps compared to high-viscosity resins. In this study, after each ply was stacked, one of the surfaces of the laminate was pasted on the aluminum mold. The release film was then applied to another surface, followed by the glass plate. As the glass plate was removed prior to the curing process, there was no pressure load applied to the laminate during curing. However, the DT806 series carbon fiber-reinforced epoxy plastic (DeltaPreg, Italy) [16] used in this study, was low-viscosity epoxy thermosetting. Hence, based on this information and evidence from the literature, it can be inferred that the compressive load from the glass plate applied to the laminate before curing could allow uncured resin to bleed out through the fiber gaps and cross-joints of the weave fiber, and the bled resin could not flow back due to the constraint of the release film. Accordingly, non-uniform resin hardening and internal voids were observed, particularly at the cross-joints of the weave fiber.

4 CONCLUSIONS

This study proposed the use of a commercial electric oven to cure carbon fiber/epoxy plastic under VBO process due to the low investment costs and compared to the other composite curing ovens conventionally used for this process. Plain-weave carbon fiber laminate was prepared with a stacking sequence of [0°/90°/0°/90°]. Since the controller in the commercial electric oven could not be adjusted for multiple steps of the curing cycle, a single-hold curing cycle was proposed in which the samples were heated from room temperature and held at 120°C for 50 minutes. Two groups of laminates were fabricated (with- and without-press laminates). In the with-press laminate, a glass plate was applied at one of the surfaces of the laminate to eliminate entrapped air while another surface was pasted on the aluminum mold before the curing process. For the without-press laminate, the glass plate was not applied. The results from tensile testing (ASTM D3039) indicate decreases in the ultimate tensile strength and tensile modulus of the with-press laminate of 11.08% and 8.16%, respectively, compared to the without-press laminate. The surface and internal defects of the samples were further characterized by digital microscopy and X-ray micro-CT. The results can be summarized as follows:

(i) In the with-press laminate, the presence of imperfectly hardened resin and pinholes and the higher number of internal voids led to the observed degradation in the tensile strength and modulus of the carbon fiber laminate.

(ii) The compressive load from the glass plate applied at one surface of the laminate before curing could result in bleeding out of the uncured resin in prepreg form, particularly in the case of low-viscosity thermosetting resin, and the bled resin could not return due to the constraint of the release film. The uncured resin can flow out of fiber gaps and cross-joints in plain-weave textiles. As a consequence, pinholes, imperfectly hardened resin, and large internal voids can be clearly observed in the digital microscope and X-ray micro-CT images.

In both observations (i) and (ii), a compressive load applied to one side of the laminate before curing was unable to mitigate the entrapped air in the prepreg. In contrast, this load could introduce more potential defects due to bleeding flow of the uncured resin.

(iii) In the without-press laminate, the internal void content was measured as 0.88%, which corresponds to a very good quality CFRP according to Purlow’s chart [13]. This finding demonstrates the potential of commercial electric ovens to cure and produce high-quality CFRP-based products in the future. The use of commercial electric ovens can reduce investment costs and production cycle times; hence, this technology can be potentially transferred to small companies to help them fabricate fiber-reinforced plastics products by themselves.

5 FUTURE WORK

To ensure that commercial electric ovens can be used and yield products with high mechanical performance consistent with those from composite curing ovens, the curing time and temperature should be optimized to achieve the highest curing degree for single-hold curing cycles. Other mechanical properties such as the ILSS and flexural strength should also be further investigated. The mechanical properties of CFRP produced under perfect curing conditions are also required to allow effective comparisons to be made with laminates produced by commercial electric ovens. All of these factors should be initially investigated in laboratory-scale research.

ACKNOWLEDGMENTS

This project was supported by Thai-Nichi Institute of Technology (project 2102/A004) and Takahashi Industrial and Economics Research Foundation for the fiscal year 2021-2022. The authors are grateful to Dr.Sutep Joy-A-Ka, the specialist at Thailand Institute of Scientific and Technological Research, for the preparation of specimen for the mechanical tests and also Mr.Praprut Prommachat, research assistant, for technical supports. The authors are thankful for the support and advice about the preparation of specimens for X-ray micro-CT scanning from Mr.Manop Tirarattanasompot, a technician from Scientific and Technological Research Equipment Center, Chulalongkorn University.

REFERENCES

[1] T. Ishikawa, Overview of CFRP (carbon fiber reinforced plastics) application to future automobiles, *Journal of Society of Automotive Engineers of Japan*, **68**, 2014, pp.4-11 (In Japanese)

[2] T. Ishikawa, K. Amaoka, Y. Masubuchi, T. Yamamoto, A. Yamanaka, M. Arai and J. Takahashi, Overview of automotive structural composites technology developments in Japan, *Composites Science and Technology*, **155**, 2018, pp.221–246 (doi:10.1016/j.compscitech.2017.09.015).

[3] M. Afendi, W.M. Banks and D. Kirkwood, Bubble free resin for infusion process, *Composites Part A: Applied Science and Manufacturing*, **36**, 2005, pp.739–746 (doi:https://doi.org/10.1016/j.compositesa.2004.10.030).

[4] J. Vilà, F. Sket, F. Wilde, G. Requena, C. Gonzáleza and J. LLorca, An in situ investigation of microscopic infusion and void transport during vacuum-assisted infiltration by means of X-ray computed tomography, *Composites Science and Technology*, **119**, 2015, pp.12–19 (doi:https://doi.org/10.1016/j.compscitech.2015.09.016).

[5] S.Y. Park, C.H. Choi, W.J. Choi and S.S. Hwang, A Comparison of the Properties of Carbon Fiber Epoxy Composites Produced by Non-autoclave with Vacuum Bag Only Prepreg and Autoclave Process, *Applied Composite Materials*, **26**, 2019, pp.187–204 (doi:10.1007/s10443-018-9688-y).

[6] D. Saenz-Castillo, M.I. Martín, S. Calvo, F. Rodriguez-Lence and A. Güemes, Effect of processing parameters and void content on mechanical properties and NDI of thermoplastic composites, *Composites Part A: Applied Science and Manufacturing*, **121**, 2019, pp.308–320 (doi:10.1016/j.compositesa.2019.03.035).

[7] M. Mehdikhani, L. Gorbatikh, I. Verpoest and S. V. Lomov, Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance, *Journal of Composite Materials*, **53**, 2019, pp.1579–1669 (doi:10.1177/0021998318772152).

[8] I. Gagauz, L.F. Kawashita and S.R. Hallett, Effect of voids on interlaminar behaviour of carbon/epoxy composites, *Proceedings of the ECCM17 - 17th European Conference on Composite Materials, Munich, Germany, June 26-30, 2016.*

[9] D. Zhang, D. Heider, S.G. Advani and J.W. Gillespie, Out of autoclave consolidation of voids in continuous fiber reinforced thermoplastic composites, International SAMPE Technical Conference, *Long beach, California, United States, May 6-9, 2013*, pp.2327–2342 (doi:10.13140/2.1.2632.5289).

[10] S.S. Hwang, S.Y. Park, G.C. Kwon and W.J. Choi, Cure kinetics and viscosity modeling for the optimization of cure cycles in a vacuum-bag-only prepreg process, *International Journal of Advanced Manufacturing Technology*, **99**, 2018, pp.2743–2753 (doi:10.1007/s00170-018-2467-y).

[11] Y. Mujahid, N. Sallih, M.Z. Abdullah and M. Mustapha, Effects of processing parameters for vacuum-bag-only method on void content and mechanical properties of laminated composites, *Polymer Composites*, **42**, 2021, pp.567–582 (doi:10.1002/pc.25848).

[12] D. Zhang, D. Heider and J.W. Gillespie, Determination of void statistics and statistical representative volume elements in carbon fiber-reinforced thermoplastic prepregs, *Journal of Thermoplastic Composite Materials*, **30**, 2017, pp.1103–1119 (doi:10.1177/0892705715618002).

[13] D. Purslow, On the optical assessment of the void content in composite materials, *Composites*, **15**, 1984, pp.207–210 (doi:10.1016/0010-4361(84)90276-3).

[14] P. Hubert and A. Poursartip, A review of flow and compaction modelling relevant to thermoset matrix laminate processing, *Journal of Reinforced Plastics and Composites*, **17,** 1998, pp.286–318 (doi:10.1177/073168449801700402).

[15] O.J. Nixon-Pearson, J.P.H. Belnoue, D.S. Ivanov, K.D. Potter and S.R. Hallett, An experimental investigation of the consolidation behaviour of uncured prepregs under processing conditions, *Journal of Composite Materials*, **51**, 2017, pp.1911–1924 (doi:10.1177/0021998316665681).

[16] V. Low and V.E. Matrices, DT806 Resins – Technical Data Sheet, DeltaPreg, Italy, 2014, pp.1-9