Advanced Composite Materials

ISSN: 0924-3046 (Print) 1568-5519 (Online) Journal homepage: http://www.tandfonline.com/loi/tacm20

Repair of aircraft structures using composite patches bonded through induction heating

Minho Kim, Hansang Kim & Wooil Lee

To cite this article: Minho Kim, Hansang Kim & Wooil Lee (2015) Repair of aircraft structures using composite patches bonded through induction heating, Advanced Composite Materials, 24:4, 307-323, DOI: 10.1080/09243046.2014.899553

To link to this article: http://dx.doi.org/10.1080/09243046.2014.899553

Advanced Composite Materials, 2015
Vol. 24, No. 4, 307–323, http://dx.doi.org/10.1080/09243046.2014.899553

Taylor & Francis
Taylor & Francis Group

Repair of aircraft structures using composite patches bonded through induction heating

Minho Kim[a], Hansang Kim[b]* and Wooil Lee[a]*

[a]*Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Republic of Korea;* [b]*Department of Mechanical Engineering, Gachon University, Seongnam, Republic of Korea*

(*Received 9 January 2014; accepted 26 February 2014*)

In this study, we investigated the use of composite patches to repair aluminum alloy double-lap joints. The carbon composite patches were cured using induction curing or oven curing. Joints were repaired using precured or cocured composite patches. The bond strengths of the different joints were compared. We also investigated whether the incorporation of carbon nanotubes (CNTs) in the adhesive bondline affected bond strength. We found that the induction-cured samples exhibited bond strengths similar to those of the corresponding oven-cured samples; this was true for both the baseline and the CNT-reinforced samples. Further, the samples processed using cocured patches exhibited higher bond strengths than did the corresponding samples processed using precured patches. In the case of both the precured and the cocured patch samples, the dispersion of 0.5 wt% CNTs in the adhesive bondline increased the bond strength slightly. The effect of the two different types of patches placed on top of the aluminum substrate on the rate of temperature increase by induction curing was shown experimentally, and, numerical simulations were performed to verify the experimental results. The results from this study show that the induction curing and co-curing method may be regarded as a sound and efficient method for composite patch bonding repair.

Keywords: composite patch repair; adhesive; induction heating; bonded joints; carbon nanotubes

Introduction

The development of composite materials has led to the creation of a new method for the repair of metallic structures, namely, a method based on the adhesive bonding of composite patches. Bonded patch repair is mechanically efficient and is a cost-effective method for maintaining both military and civil aircraft.[1] Bonded composite patches have been used widely for repairing cracks and defects in aircraft structures in recent years.[2] This technology offers many advantages over mechanical fastening or riveting, including improved fatigue behavior, restored stiffness and strength, reduced corrosion, and ready moldability into complex shapes.

Bonded patch repair is performed by adhesively bonding a patch to the damaged area. Proper curing of the adhesive is critical for ensuring the strength and integrity of the repaired part. Traditionally, the hardening of the adhesive has been performed by placing the joint, and hence the structure to be bonded, in an oven or autoclave until

*Corresponding authors. Email: hskim70@gachon.ac.kr (Hansang Kim), wilee@snu.ac.kr (Wooil Lee)

the adhesive is fully cured. Inherent drawbacks of this technique are the extremely long periods required for complete curing,[3] and the unavoidable simultaneous heating of the metallic substrate with the composite patch. This can have negative effects on the durability of the repair work, because of the stresses induced by the difference in the coefficients of thermal expansion of the metal substrate and the composite patch. Ideally, when bonding a composite to a metal, one should avoid heating the substrate when the composite is being cured. This means that the metal base in contact with the adhesive should be heated to a depth of a few millimeters only.[4] Baker et al. [5] performed repairs on Mirage aircraft using the boron fiber-reinforced plastic crack-patching technique. Schubbe and Mall [6] investigated whether a cracked thick aluminum panel could be repaired with a bonded composite patch. They examined the effects of various patch parameters (i.e. the patch length and patch-to-panel stiffness ratio) related to asymmetric bonded repair on the fatigue behavior of a cracked thick aluminum plate in the unrestricted condition by characterizing the effects of these parameters on the crack growth rate, debonding behavior, and fatigue life.

Adhesives with low curing temperatures have been developed for repair applications; however, they require the use of portable heating systems, such as heat lamps or heat blankets, when used for field repairs. In addition, such adhesives are ineffective for repairing thick structures and result in substantial heat loss due to the surrounding materials.

Electromagnetic induction, on the other hand, can be used to locally and rapidly heat the area close to the adhesive bondline.[3–7] This allows for the efficient repair of the metallic substrates in aircraft, and hence, may be regarded as a more efficient process than the methods that require heating systems. Induction heating-based techniques allow for greater control over the distribution of heat, which is applied only to the composite patch; further, the metallic base is heated to a very small depth.[4] Recently, significant research has been carried out to adapt induction heating to composites to ensure low cost and reduced processing times. A remotely located induction coil transfers electromagnetic energy to the repair structure, which, in turn, radiates thermal energy in the plane of the bondline. This technique allows for the rapid heating of the adherends and, through thermal conduction, the rapid heating of the adhesive. In addition, owing to the noncontact nature of induction heating, it may be possible to bond several layers at the same time, resulting in reduced repair times. Conventional heating techniques, such as those involving the use of heat blankets, can only bond one layer at a time. Mathur et al. [8] reported a genetic algorithm that can be used as a computationally efficient tool for cut mesh-design for the induction-bonding process. Yarlagadda and Kim et al. [7] focused on the through-thickness heating behavior during the induction processing of carbon fiber-based prepreg lay-ups.

A number of researchers have reported the benefits of incorporating carbon nanotubes (CNTs) in polymeric composites. For example, it was found that an epoxy-based polymer matrix composite exhibited an increase in modulus and strength during both tension and compression after the incorporation of CNTs.[9,10] However, a common problem encountered when using CNTs is ensuring that they are uniformly dispersed. CNTs have a tendency to attract each other and form agglomerates. In order to overcome this issue, mechanical means of dispersion, such as high-power shear mixing and sonication, have been studied.[11] Further, a recent study investigated the increase in the strength of joints when CNTs are dispersed along the interface. CNTs can be categorized as being single-, double-, or multi-walled, on the basis of the number of concentric graphene sheets that constitute the individual nanotubes. CNTs have shown promise in improving the mechanical, electrical, and thermal properties of composites in numerous applications.[12] It has also been demonstrated that CNTs, when dispersed along a fully bonded scarf joint interface, could improve the Modes I and II fracture toughnesses of the joint. Burkholder et al. [11] investigated how the addition of various types of CNTs to the adhesive affected the fracture strength during Mode II loading. Srivastava [13] studied the use of C/C and C/C–SiC composites as substrates bonded with thin layers of multi-walled CNTs (MWCNTs) that either contained or did not contain an epoxy resin.

This study focused on the use of adhesive joints (double-lap joints) to bond aluminum-composite sections of interest of aircraft structures; however, the results should be applicable to other types of structures as well. The objectives were to investigate the effects of various bonding parameters on the fracture strength of the formed bond. It should be noted that the data presented in this study allow for both a comparison of different curing methods (oven and induction curing) as well as different fabrication techniques (the use of precured patches or the use of cocured patches). A true comparison of the curing and fabrication methods would have involved a comparison of the strengths of double-lap adhesive joints. Another aim of the study was to investigate how the addition of CNTs in the adhesive bondline affects the shear strength during tensile loading. This was also determined on the basis of the strengths of the double-lap adhesive joints. The study involved the preparation of five joints for each condition, and testing their shear strengths by increasing the load until failure.

Experimental

Adhesively bonded double-lap joint shear (DLS) samples were manufactured using two different curing methods: conventional oven curing and induction curing. The bonding shear strengths of the oven-cured samples were compared with those of the induction-cured ones. In addition, two different types of patches were used in the DLS samples: precured carbon-composite patches and uncured preimpregnated laminate patches that were co-cured with the adhesive. The bonding shear strengths of the precured patch samples and the co-cured patch samples were also compared. CNTs were incorporated in each sample type at the bondline to improve the bonding strength. The materials, sample preparation procedures, and test methods used in the study are described in this section.

Materials

The adhesively bonded DLS samples were fabricated using a film-type adhesive, as illustrated in Figure 1. The samples consisted of a composite patch bonded to flat Al-6061-T6 aluminum substrates using a single ply of AF-163-2 K adhesive film (3 M, US). The height, width, and thickness of the Al-6061-T6 aluminum alloy plates were 110, 25.4, and 3 mm, respectively. Two aluminum alloy plates were bonded together through a butt joint with the adhesive film and composite patches. The patches consisted of eight layers of the carbon-epoxy preimpregnated laminate ($[0]_8$) UN200NS (Hankook Carbon Inc., Korea). The planar dimensions of the patch and the adhesive film were 25.4 mm × 25.4 mm, and their thicknesses were 1.6 and 0.24 mm, respectively. Two types of patches were prepared. The first type were precured patches, which consisted of eight layers of a carbon-epoxy preimpregnated laminate cured using a hot press for 90 min at 120 °C. The 25.4 mm × 25.4 mm precured patches were machined

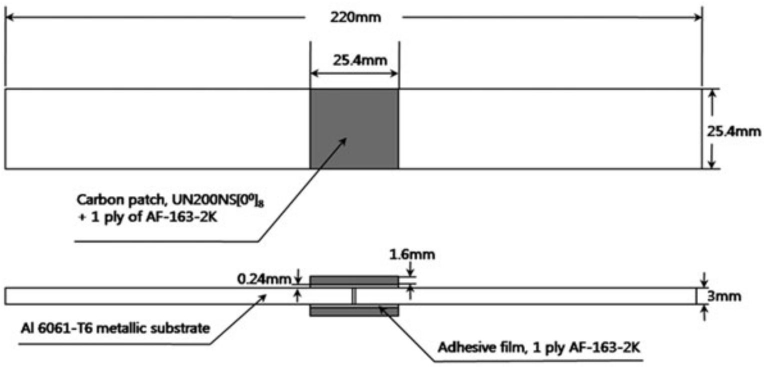

Figure 1. Schematic of patch sample configuration.

from a 270 mm × 270 mm-cured plate. The second type of patches were cocured patches, which consisted of the uncured prepreg material used for the precured patch, and were to be cocured along with the adhesive. The fiber orientation of the patches coincided with the loading direction.

Sample fabrication

Surface preparation

The surfaces of the aluminum substrates were subjected to a complex preparation procedure, in order to ensure strong adhesion. The procedure was performed in several stages and included mechanical preparation and chemical activation. The surfaces were initially cleaned with reagent-grade acetone to remove grease and organic build up. The next step consisted of removing the aluminum oxide layer from the surfaces by abrasion with 220-grit sandpaper. The surfaces were wiped with a lint-free rag to remove any remaining debris. The exposed surfaces were rinsed in acetone, air dried, and cleaned with methyl ethyl ketone. Then, silane, used as a coupling agent, was applied immediately to minimize surface oxidation. Finally, the silane-treated surfaces were dried with hot air for 10 min. The precured patch surfaces were treated in the same manner as the aluminum substrates.

Lay-up procedure

The baseline samples were processed as per the following series of steps. First, a single layer of the AF-163-2 K adhesive film was placed on both sides of the aluminum substrate after its surfaces had been treated. Then, either a precured composite patch or an uncured prepreg patch, which was to be cocured with the adhesive, was placed on top of the adhesive film.

MWCNTs (CM-150, Hanwha-Nanotech, Korea) were used in this study. The CNTs had a diameter of 10–15 nm and length of 25–35 μm. To disperse the CNTs in the epoxy resin (KFR 130, Kookdo Chemical Inc., Korea), the epoxy was dissolved in acetone, and the CNTs were mixed and dispersed in it using an ultrasonicator (CV 505 power supply and a CV 33 convertor, Sonics & Materials Inc., USA). The solvent was then evaporated in an ultrasonication bath (SD-D300H, SeongDong, Korea) to maintain the dispersed state. Finally, the suspension was placed in a convection oven for 1 h at 50 °C to evaporate the solvent completely. Figure 2 shows the CNT dispersion process.

The CNT-containing epoxy was mixed with the hardener (KFR140, Kookdo Chemical Inc., Korea) in a weight ratio of 10:3. The mixed solution was stirred by hand in a plastic cup to a consistent color and smooth texture; this took approximately 3 min. The mixed solution was applied to both sides of the adhesive surface layer using a plastic knife. Approximately, 0.13 g of the mixed solution was used for each sample. The CNT-reinforced samples were processed by the same method as that used for the baseline samples; the only difference was the insertion of the CNTs in the bondline in the case of the former. As was the case for the baseline samples, the CNT-reinforced samples were also fabricated using precured and cocured patches. The only difference, as mentioned previously, was that dispersed CNTs were applied along the joint interface to strengthen the bondline in the case of the reinforced samples.

Pieces of peel ply, breather cloth, and vacuum bagging material were placed on top of the stack, which was sealed on all the four edges with sealing tape. The air was suctioned to create a vacuum, and, depending on the sample type, either the adhesive or the cocured patch was hardened. The lay-up of the samples is shown schematically in Figure 3. Each sample was cured either in a conventional oven or by an induction curing method after being vacuum bagged.

Curing procedure

The oven and induction curing procedures used to harden the adhesive and the cocured patch are discussed in this section. In each case, the vacuum was consolidated to ensure

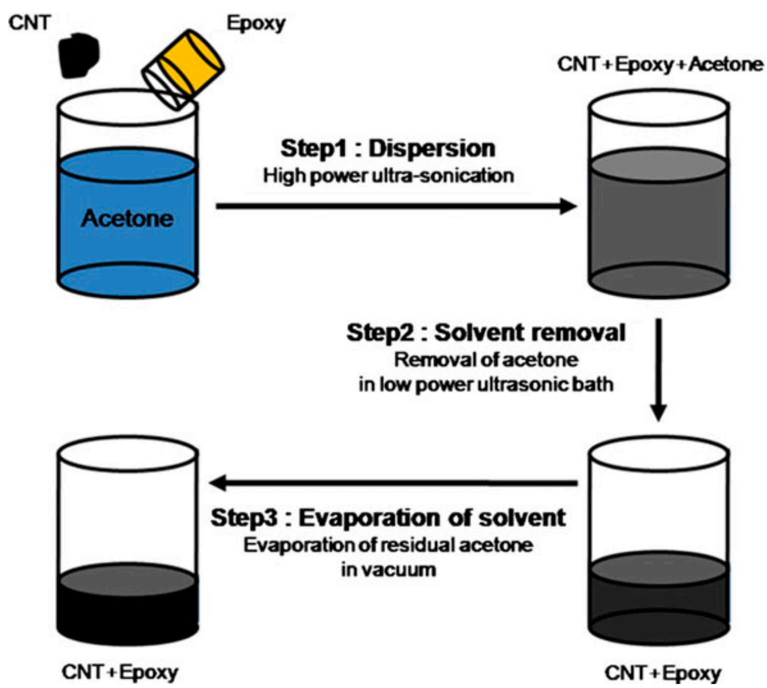

Figure 2. CNT dispersion process.

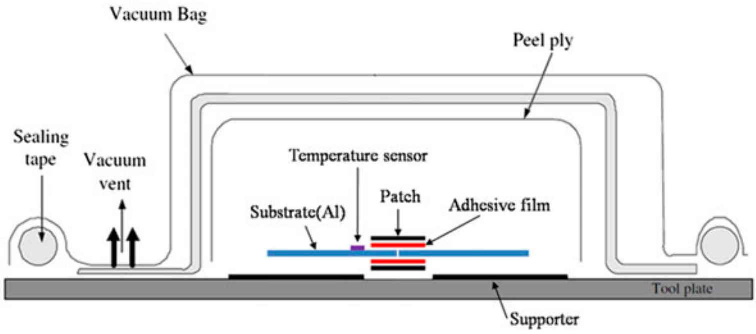

Figure 3. Sample preparation for oven and induction curing.

the uniformity of the applied pressure in order to achieve a constant adhesive bondline thickness.

Oven curing

In the conventional oven curing technique, the vacuum-bagged assemblies of the DLS samples were prepared as per the procedure mentioned above. On the basis of the manufacturers' recommendations for the adhesive and the prepreg laminate, the samples were cured at a temperature of 120 °C for 90 min. The cured panels were subsequently cut into five test samples using a water jet cutter.

Induction curing

A 3 kW induction heating unit (WI-340, DIK Co., Korea) was used in this study. It consisted of an alternating current (AC) power supply and an induction coil. The induction heating unit was capable of generating a peak-to-peak current of 0–70 A in the frequency range of 135–400 kHz. The power delivered to the coil was controlled with a 0–100 graded control. The power supply sent an alternating current through the coil, generating a magnetic field. The remotely located induction coil transferred electromagnetic energy to the aluminum substrate, which in turn, heated the aluminum substrate. The adhesive was heated by the conduction of heat energy from the rapidly heated aluminum substrate. A five-turn circular coil was used for curing the samples. A temperature sensor was connected to the induction heating system to maintain the substrate at a set temperature. Thermocouples, which measure temperature on the basis of an electromotive force, cannot be used with induction heating systems since the eddy currents generated in such systems can disturb the electrical sensing circuits of the thermocouples. Hence, we used a thermistor-based temperature sensor, as it is not affected by eddy currents.

The induction-cured samples were also prepared as per the procedure described above. After the preparation of the samples, the induction coil was placed above the vacuum-bagged assembly. It should be noted that the distance between the induction coil and the stack is of great importance, as it allows one to control the maximum temperature to which the assembly is subjected. The induction coil was placed 11 mm above the vacuum-bagged assembly. The temperature sensor placed on the substrate allowed the temperature in the vicinity of the bondline to be monitored. The temperature data were fed back to the power controller, which reduced or increased the power to maintain the temperature at 120 °C for 90 min. The detected bondline temperatures were always slightly higher than the substrate surface temperature, owing to conduction effects; however, the two temperatures were not significantly different, once the steady-state point was reached.

Bond strength measurement

DLS samples, shown in Figure 1, are well suited for testing adhesively bonded joints. The prepared samples were tested using a universal testing machine (Instron 810 with a 150 kN load cell) to determine the bond shear strengths of the various joints. Five samples were tested for each case. The samples were evaluated using the double-lap shear method in accordance with the ASTM D3528 standard for testing the strengths of adhesive DLS samples through tensile loading. All the measurements were performed at ambient temperature.

Results and discussion

Bond strength

Table 1 shows the results of the bonding shear strength tests; the standard deviations of the data are shown as well. The average failure strength for each group is shown in Figure 4. The error bars in this figure represent the standard deviation values of the experimental data. It can be seen from Table 1 that the standard deviation was relatively low for all the samples.

As can be seen from Figure 4, the data presented in this study allows for a comparison between the different curing methods as well as between the different patch fabrication methods. With respect to the curing methods, the bond strengths of the oven/precured patch samples and those of the induction/precured patch samples were almost similar, while the bond strengths of the oven/cocured patch samples were 8% higher than those of the induction/cocured patch samples. On the other hand, with respect to the patch fabrication methods, the cocured patch samples cured using oven and induction heating exhibited bond strengths 18 and 8% higher, respectively, than those of the corresponding precured patch samples.

Table 1. Bonding strength results of double lap joint samples.

Sample	Curing method	Patch	CNT reinforcement	Bonding strength (MPa) [Standard Deviation]
1	Oven cure	Precured	No CNT	14.8 [0.3]
2			CNT	16.4 [0.4]
3		Cocured	No CNT	17.5 [0.3]
4			CNT	18.1 [0.2]
5	Induction cure	Precured	No CNT	14.8 [0.3]
6			CNT	16.2 [0.6]
7		Cocured	No CNT	16.1 [0.8]
8			CNT	17.6 [0.8]

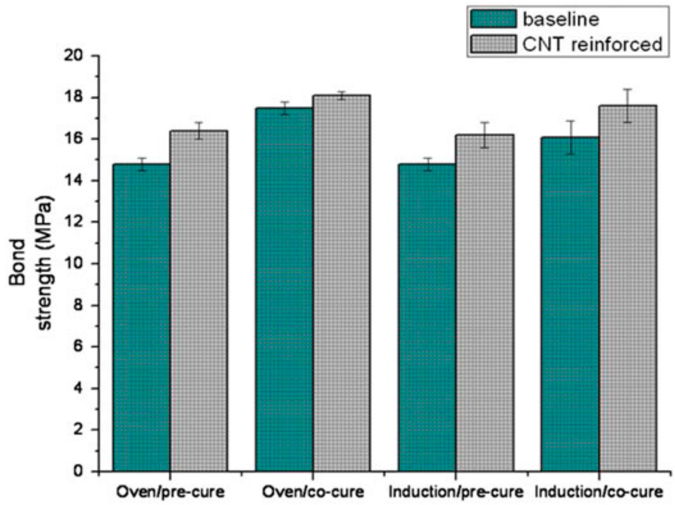

Figure 4. Bonding shear strengths of DLS specimens.

Therefore, according to the above-mentioned results, the curing method had a relatively small effect on the bond strength of the samples. Hence, it can be surmised that induction curing is as efficient as conventional oven curing in terms of bond strength. In addition, the test results also showed that the bond strengths were affected more by the patch fabrication method used (i.e. whether a precured or a cocured patch was used) than by the curing method used (i.e. whether oven curing or induction curing was used). These factors are discussed in detail later.

The effect of the incorporation of CNTs on the bond strength was also investigated. As shown in Figure 4, the bond strengths in the case of the samples with CNTs exhibited the same tendency as those of the samples without CNTs. The addition of 0.5 wt% CNTs to the oven/precure, oven/cocure, induction/precure, and induction/cocure patch samples increased the bond strengths by 10, 3, 9, and 8%, respectively, when compared to those of the corresponding baseline samples. The bond strengths of the CNT-reinforced samples were higher than those of the baseline samples for the following reasons. When CNTs are inserted on both sides of the adhesive layer, the strength of the adhesive interface layer between the substrates (or the patches) is enhanced because the CNTs in the interface layer probably form mechanically strong interlocks with the adhesive layer and the substrates (or the patches).

Figure 5 shows the fracture surfaces of the tested samples. The images in Figure 5(a) show the aluminum-side fracture surfaces, while those in Figure 5(b) show the patch-side fracture surfaces. The oven/cocured patch samples, which were stronger than the other samples, had a small, adhesive-free empty area on the aluminum side as well as on the patch side. On the other hand, the induction/precured patch samples, which were weaker than the other samples, had a large, adhesive-free area on both the aluminum side and the patch side. This means that the adhesion between the cocured patches and the aluminum substrates was stronger. This is likely because an even compressive load may have been applied during curing, owing to the lower stiffness of the uncured prepregs. Hence, the failure of the cocured samples was more likely to occur in the adhesive layer than at the interface failure.

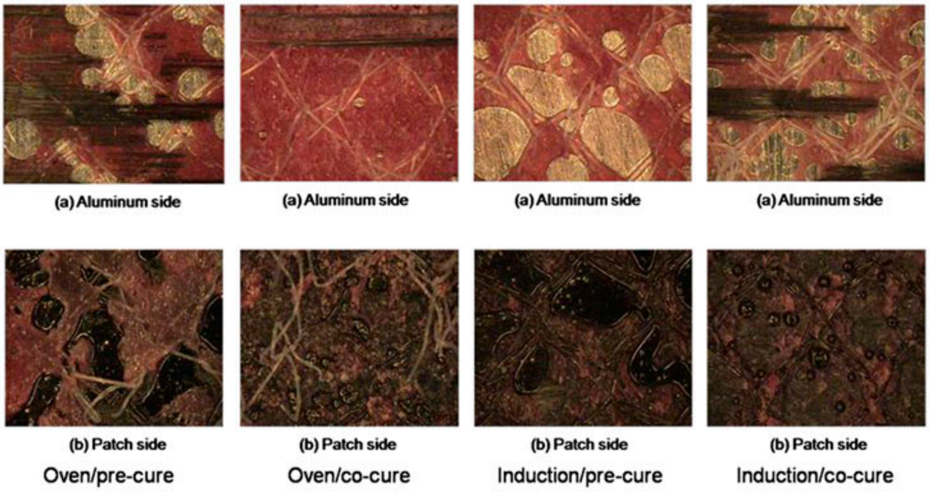

Figure 5. Fracture surfaces of tested samples.

Effects of cocuring

Surface roughness has a significant effect on the bond strength of adhesive bonds.[2] Mechanical interlocking between the adhesive and the substrate contributes significantly to the durability of joints. These facts suggested that the bondline profile may introduce an interfacial shear component at the adhesive-to-substrate interface and that this shear component might improve the fracture toughness of the joints. The bondline profile is critical to achieving durable adhesive bonds. An undulated profile leads to higher bond strength.[2] Therefore, we determined the bondline profiles of the samples along the interface between the adhesive and the patch.

Optical microscopy-based analyses of the samples were performed to obtain information regarding the bondline profiles. The bondline profiles of the oven/precure, oven/cocure, induction/precure, and induction/cocure baseline samples are shown in Figure 6. It should be noted that the bondline profiles of the precured and cocured samples were significantly different. The precured patch samples (oven/precure as well as induction/precure) had a relatively straight bondline profile, in contrast to those of cocured patch samples (oven/cocure as well as induction/cocure). The bondline profiles of the CNT-reinforced samples were similar to those of the corresponding baseline samples.

We quantitatively measured the bondline profiles of the samples using optical microscopy. The standard deviation values of the bondline profiles of samples are

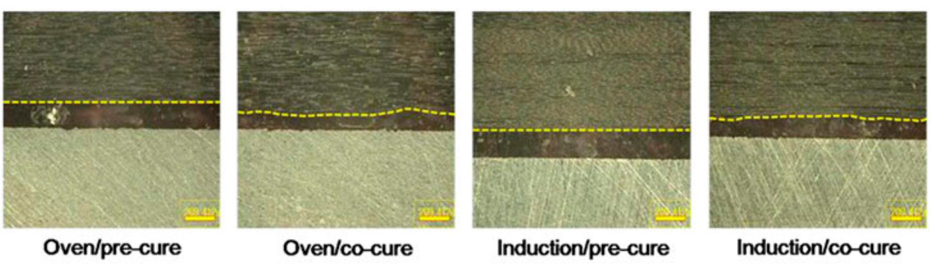

Figure 6. Bondline profile of baseline sample (200×).

shown in Table 2. The standard deviation values of the bondline profiles for all the precured patch samples were 1.2–3.5 µm, while the standard deviation values of the cocured patch samples were approximately 6.3–11.9 µm. In other words, the cocured patch samples had a more crooked bondline profile than did the precured patch samples; this was true for both the baseline and the CNT-reinforced samples. As was noticed previously, the cocured patch samples exhibited higher bond strengths than those of the corresponding precured patch samples; again, this was true for both the baseline as well as the CNT-reinforced samples.

Effects of induction curing

We performed experiments to determine whether induction curing is an efficient technique (and whether induction heating a suitable heating method) for metallic substrates associated with the repair with aircraft. The experiments were performed to check whether the patches on aluminum substrates affected the temperature increase rate of the substrates during curing by induction heating. Three different experiments were performed under the same induction output conditions (i.e. current of 70 A and frequency of 150 kHz). The first experiment involved heating only an aluminum substrate by induction. The second involved heating the cured composite patch on an aluminum substrate. Finally, the third involved heating the uncured composite patch (uncured prepreg) on an aluminum substrate. Each sample was heated by induction until the temperature reached 120 °C. The experiment setup is shown in Figure 7. The distance between the aluminum substrate and the induction coil was 11 mm. We determined the rate of temperature increase of the aluminum substrate using a thermistor-based temperature sensor placed between the aluminum substrate and the patches.

Experimental results

The efficiency of inducting heating is dependent on the electrical and thermal conductivities of the materials placed between the aluminum substrate and the induction heating coil. As shown in Figure 8(a), the temperature of the aluminum substrate increased at a greater rate when only the substrate was heated than when the aluminum substrate was heated while having an uncured patch placed on top of it. It took 30 min to heat the aluminum substrate to 120 °C in the former case, while the temperature reached only 116 °C after 80 min in the latter case. This is presumably because the heat generated by induction heating is transferred to the uncured patch, resulting in the curing of the prepreg. Meanwhile, the assembly consisting of a cured patch placed on top of the aluminum substrate heated more quickly than did the aluminum substrate alone. In this case, it took only 22 min for the temperature of the assembly to reach 120 °C. This result may be attributed to the fact that the cured patch kept the aluminum substrate warm, while the aluminum substrate, when heated without a cured patch, was exposed to the environment and radiated heat. However, in real-life applications, the uncured

Table 2. Standard deviation values of bondline profile (unit: micron).

	Oven/precured	Oven/cocured	Induction/precured	Induction/cocured
Baseline	3.5	11.9	1.2	6.3
CNT	1.8	6.9	1.3	6.6

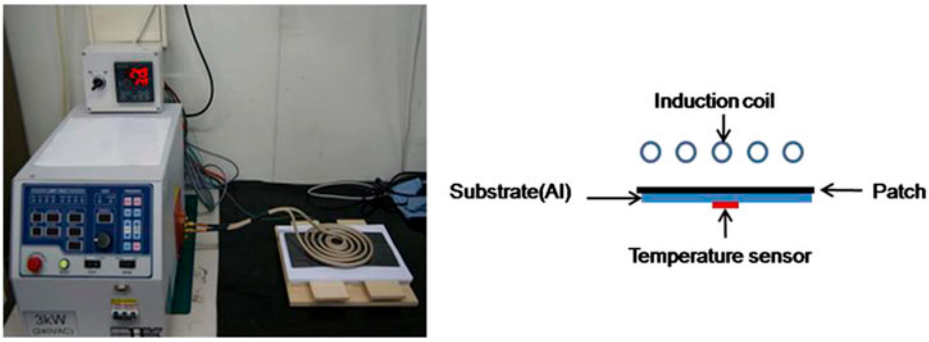

Figure 7. Induction heater and experimental schematic.

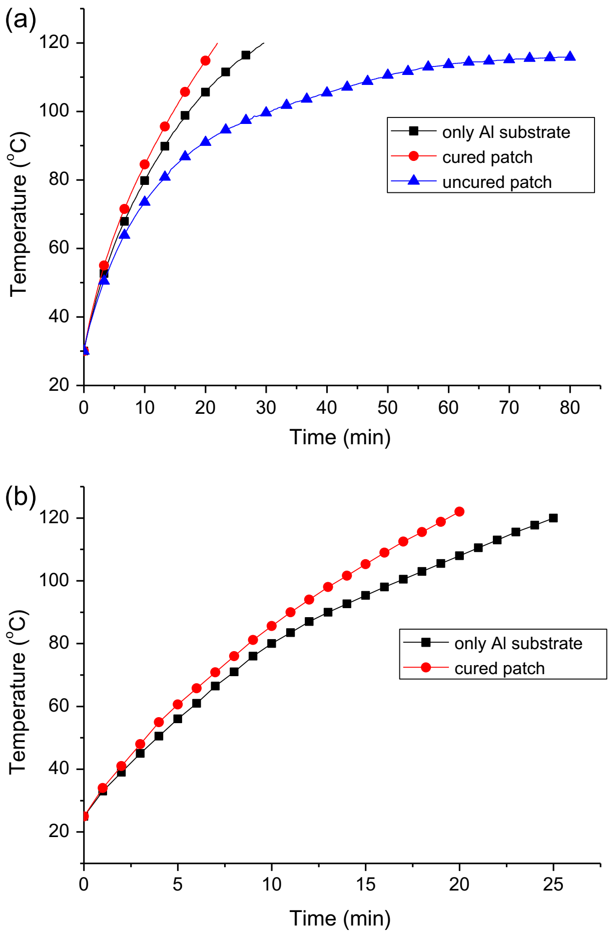

Figure 8. Temperature increase by induction heating: (a) experimental results (b) simulation results.

patch would not cover the aluminum substrate completely. In other words, part of the aluminum substrate would still be exposed directly to the induction heating coil, and its temperature could increase. This was also proven by the fact that we did not experience any difficulty in processing the DLS samples with the uncured patches using induction heating.

Numerical simulation

Simulation process. Numerical simulations were performed to elucidate further the effects of the composite patches on the temperature increase rate during induction

Table 3. Material property of simulation for induction heating.

	Air	Aluminum	Coil	Cured patch
Relative permeability	1	1	1	1
Resistivity (Ωm)	–	27e−9	17e−9	2.7e−4
Thermal conductivity (w/m °C)	–	165	401	0.3
Specific heat (J/kg °C)	–	875	385	1255
Density (kg/m^3)	–	2770	8300	1572

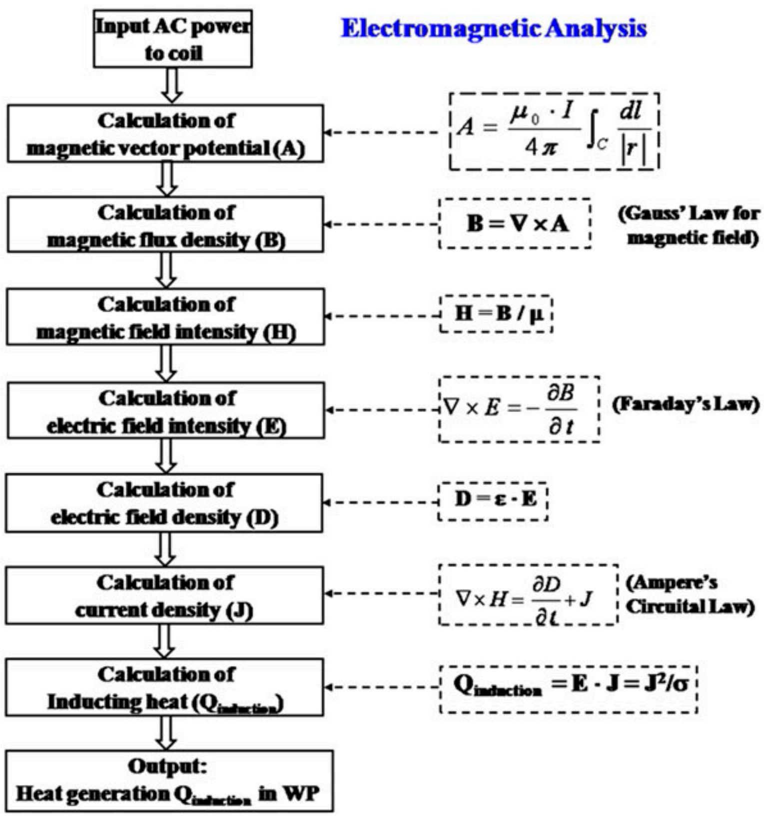

Figure 9. Flow of simulation of induction heating.

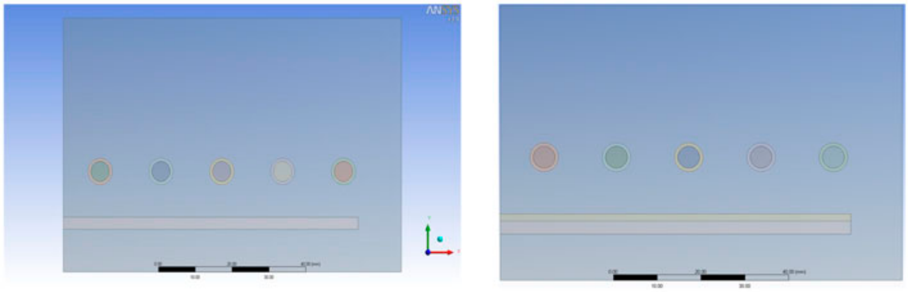

Figure 10. Two-dimensional axi-symmetric model: aluminum substrate only (left), precured patch on aluminum substrate (right).

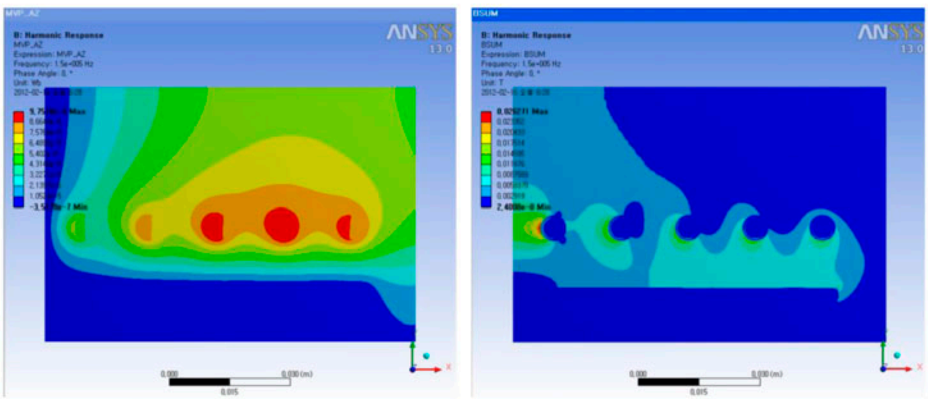

Figure 11. Magnetic flux and density of only Al substrate.

heating. The simulations were performed using the commercial simulation software ANSYS®. The numerical model was designed to imitate the experimental setup. The induction coil was placed 11 mm above the aluminum plate. We simplified the model to a two-dimensional axi-symmetric one to reduce the simulation time. The material properties used for the simulation are listed in Table 3.

The parameters considered during the simulations were the initial current density in the coil, the heating time, and the frequency of the current. The induction output conditions employed in the simulation were the same as those used in the experiments: a coil current of 70 A at a frequency of 150 kHz and an application of 30 min. The numerical simulation process, including the governing equations used for the analysis, is shown in Figure 9. As mentioned previously, the analysis domain was simplified using a two-dimensional axi-symmetric model in which the heating section was considered to be rotationally symmetric. Figure 10 shows the two-dimensional axi-symmetric model used. Simulations involving an aluminum substrate alone and those involving an aluminum substrate with a precured patch on top of it and heated using an induction were performed under similar conditions. Numerical simulations of an uncured patch placed on an aluminum substrate were not performed since the model used would not have accounted for the curing kinetics of the uncured patch; this will be the focus of a future

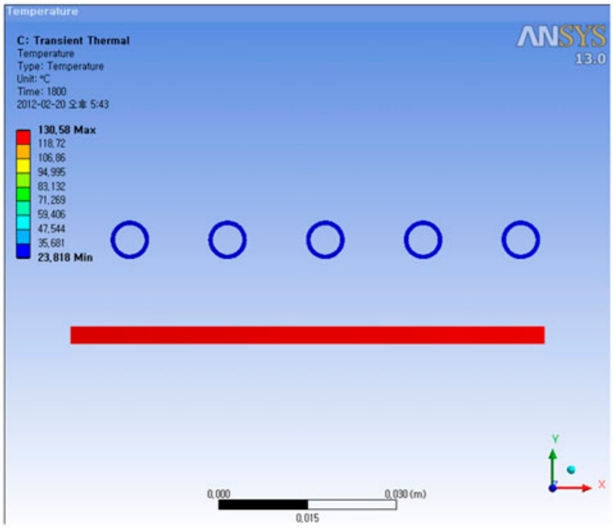

Figure 12. Temperature of only Al substrate.

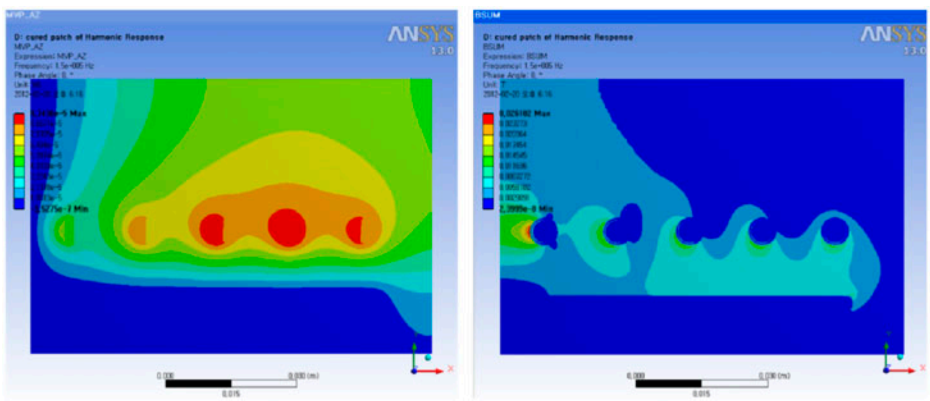

Figure 13. Magnetic flux and density of precured patch on Al substrate.

study. The temperature increase rate was determined for a heating period of 30 min in each case. The magnetic field intensity and temperature are related to the magnetic permeability while the temperature is also related to the specific heat, thermal conductivity, and electrical resistivity.

Simulation results. Figure 11 shows the distribution of the magnetic flux and magnetic density in the heating section in the case of the aluminum substrate without a patch. In this case, the magnetic field is concentrated around the inner coil. Figure 12 shows the temperature distribution in the case of the aluminum substrate without a patch. At the end of the heating stage (i.e. at 30 min), the temperature of the surface aluminum substrate was 130.6 °C.

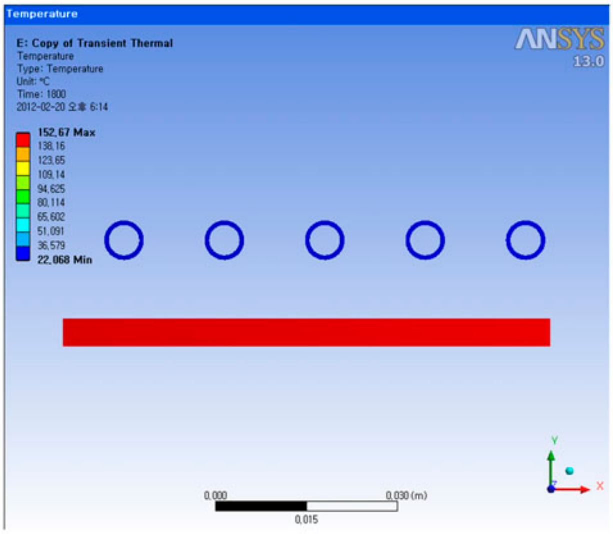

Figure 14. Temperature of precured patch on Al substrate.

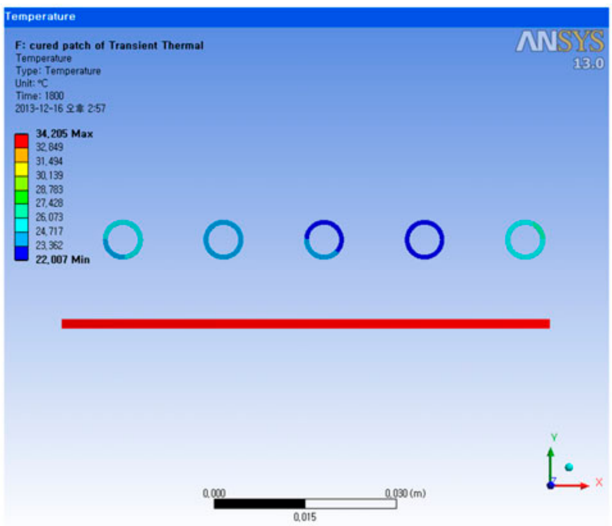

Figure 15. Simulation result in case of precured patch only.

Figure 13 shows the distribution of the magnetic flux and magnetic density in the heating section in case of the assembly consisting of a precured patch on an aluminum substrate. Figure 14 shows the temperature distribution in case of this assembly. At the end of the heating stage (i.e. at 30 min), the temperature of the surface of the aluminum substrate was 152.6 °C. As a comparison, simulation result in case of precured patch only is shown in Figure 15. In this case, the temperature reached only 34.2 °C in 30 min.

The results of the simulations confirmed that the effect of composite patches on the induction heating of aluminum substrates was minimal and that they did not restrict the magnetic flux from passing through them. In addition, the aluminum substrates with a precured patch exhibited a higher temperature increase rate since the patch kept the aluminum substrates warm, as was seen during the experiments as well. A comparison of the experimental results and the simulation results is shown in Figure 8. The simulation results were almost similar to the experimental results. The cause of the differences is the error in the simulation of induction heating, because only the effects of eddy currents were taken into consideration during the simulation, while those of hysteresis loss were ignored. This was because eddy currents form the basis of induction heating.

Conclusions

We investigated the feasibility of using induction heating as a means of curing adhesives and patches in composite bonded joints. It was found that the induction-cured DLS samples exhibited bond strengths very similar to those of the corresponding oven-cured samples; this was true for both baseline as well as CNT-reinforced samples. Therefore, induction heating can be considered an effective technique for curing adhesives and patches during composite patch repairs.

The bond strengths of the DLS samples were also found to depend on the fabrication method used. Cocured patch samples (fabricated by oven or induction curing) exhibited higher bond strengths than those of the corresponding precured patch samples; this was true for both baseline and CNT-reinforced samples. The cocured patch samples had a more undulated bondline profile than did the precured patch samples. It is believed that an undulated bondline profile results in greater bond strength. Therefore, the bond strengths of the cocured patch samples were higher than those of the corresponding precured patch samples.

For both the precured and the cocured samples, it was shown that the dispersion of 0.5 wt% CNTs in the adhesive improved bond strength. The CNT-reinforced samples exhibited slightly higher bond strengths than did the baseline samples. When CNTs are inserted on both sides of the adhesive layer, the strength of the adhesive interface layer between the adhesive and the substrates is enhanced.

Finally, it was shown experimentally that the uncured patches decreased the temperature increase rate during induction heating. However, this should not be a critical issue in real-life applications. With regard to the induction heating of an aluminum substrate alone as well as the heating of an assembly consisting of a precured patch and an aluminum substrate, the experimental results and those of numerical simulations were similar. The temperature of the aluminum substrates increased more rapidly in the case of precured patches than in the case of cocured patches. Thus, it can be concluded that induction curing and the cocuring method are sound and efficient techniques for the bonding and repair of metallic aircraft structures.

Funding

This work was supported by the Basic Science Research Program through the National Research Foundation (NRF) of Korea funded by the Ministry of Science, ICT, and Future Planning, Korea under Grant [NRF-2012R1A1A1044253].

References

[1] Ricci F, Franco F, Montefusco N. Bonded composite patch repairs on cracked aluminum plates: theory, modeling and experiments. In: Attaf B, editor. Advances in composites materials - ecodesign and analysis. InTech; 2011. p. 445–464. ISBN: 978-953-307-150-3. Available from: http://www.intechopen.com/books/advances-in-composite-materials-ecodesign-and-analysis/bondedcomposite-patch-repairs-on-cracked-aluminum-plates-theory-modeling-and-experiments.
[2] Alan Baker FR, Jones R. Advances repair metallic aircraft structure. Vol 1. Oxford: Elsevier Science; 2002.
[3] Mahdi S, Kim HJ, Gama BA, Yarlagadda S. A comparison of oven-cured and induction-cured adhesively bonded composite joints. J. Compos. Mater. 2003;37:519–542.
[4] Tsamasphyros GJ, Prassianakis I, Christopoulos I, Kanderakis G, Kalkanis K. Non destructive testing of bonded composite repairs using embedded metallic grids–numerical analysis. Prague: NDT for Safety; 2007.
[5] Baker AA, Callinan RJ, Davis MJ, Jones R, Williams JG. Repair of Mirage III aircraft using the BFRP crack-patching technique. Theor. Appl. Fract. Mech. 1984;2:1–15.
[6] Schubbe J, Mall S. Investigation of a cracked thick aluminum panel repaired with a bonded composite patch. Eng. Fract. Mech. 1999;63:305–323.
[7] Yarlagadda S, Kim HJ, Gillespie Jr. JW, Shevchenko NB, Fink BK. A study on the induction heating of conductive fiber reinforced composites. J. Compos. Mater. 2002;36:401–421.
[8] Mathur R, Advani SG, Yarlagadda S, Fink BK. Genetic algorithm based resistive susceptor design for uniform heating during the induction bonding process. J. Thermoplast. Compos. Mater. 2003;16:529–550.
[9] Kwon YW, Slaff R, Bartlett S, Greene T. Enhancement of composite scarf joint interface strength through carbon nanotube reinforcement. J. Mat. Sci. 2008;43:6695–6703.
[10] Zhao DL, Qiao RH, Wang CZ, Shen ZM. Microstructure and mechanical property of carbon nanotube and continuous carbon fiber reinforced epoxy resin matrix composites. Adv. Mater. Res. 2006;11–12:517–520.
[11] Burkholder GL, Kwon YW, Pollak RD. Effect of carbon nanotube reinforcement on fracture strength of composite adhesive joints. J. Mater. Sci. 2011;46:3370–3377.
[12] Kwon YW, Marrón A. Scarf joints of composite materials: testing and analysis. Appl. Compos. Mater. 2009;16:365–378.
[13] Srivastava VK. Effect of carbon nanotubes on the strength of adhesive lap joints of C/C and C/C–SiC ceramic fibre composites. Int. J. Adhes. Adhes. 2011;31:486–489.