Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 1291-1302

ECCOMAS
Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

NOVEL PROCEDURE OF INTEGRATING TRANSDUCERS TO THERMOPLASTIC COMPOSITE STRUCTURES BY INDUCTION HEATING FOR SHM

T. Sofi[1,2*], Maria. R. Gude[1], J. Avila[1] AND P. Wierach[2,3]

[1] Foundation for the Research, Development and Application of Composite Materials (FIDAMC)
Avda. Rita Levi Montalcini 29, Tecnogetafe, 28906 Getafe, Spain
https://www.fidamc.es/

[2] Institut für Polymerwerkstoffe und Kunststofftechnik,TU Clausthal
Agricolastraße 6, 38678 ClausthalZellerfeld, Germany
https://www.puk.tu-clausthal.de/

[3] German Aerospace Center (DLR)
Lilienthalplatz 7, 38108 Braunschweig
https://www.dlr.de/content/de/standort/braunschweig.html
*: Corresponding author

Abstract. A novel method of bonding special PZT transducers called Acousto-ultrasonic composite transducers (AUCTs) to high-performance thermoplastic (TP) composites was developed using induction heating. A TP adhesive film (TPAF) is placed between the AUCT and the host composite where a localized induction field is applied to generate heat, while the adherents are kept in contact by pressure until cooling to form a bond. The proposed method is a very fast, economical, and reparable bonding procedure while at the same time reducing the heat exposure of the host structure by using localized heating. Different types of susceptors were used to study if they can contribute to the overall heating of the TPAF. The results showed that the susceptors used in the study do not contribute positively to the heat generated and the best case would be not using a susceptor at all. The influence of various induction process parameters namely power, coupling distance, and time on temperature produced was studied. It was observed that power has the most influence on the temperature produced. Coupling distance is also a very critical parameter. These parameters can be used to get a better control of the process since it is very challenging to exactly control the heating or cooling cycle of the TPAF in an induction heating process. The bonding quality of the AUCTs bonded with induction heating was studied by electro-mechanical impedance (EMI) spectroscopy, it was seen that good bonding quality can be achieved. The mechanical performance of the induction bonded AUCTs was studied by 4-pt static flexural and tensile-tensile fatigue tests. From the static flexural tests, the critical strain measured at gauge for the two TPAFs used were: 0.6% for P45200 and 0.4% for T-Link. From the fatigue tests, it was seen that among the five TPAFs tested, only two do not have a good fatigue tolerance.

doi: 10.7712/150123.9876.446068

Key words: PZT Transducers, Thermoplastic Films, Induction Heating, Thermoplastic Composites, Structural Health Monitoring

1 INTRODUCTION

ENHAnCE is a H2020 project aimed at developing next-generation intelligent composite structures. The aim is to develop smart composite structures that can diagnose their current state of health as well as predict their future health. For diagnosis and prognosis of the structure permanently attached sensors are required which can continuously monitor the structure and provide timely updated data. This process of collecting and analyzing data from a sensor network that is integrated with a structure to obtain information about its health is known as structural health monitoring (SHM) [1]. One of the challenges in the advancement of the SHM is the manufacturing of composite structures with integrated sensors. The focus of this work is to develop new strategies for integrating PZT transducers with high-performance thermoplastic (TP) composites such as carbon fiber Poly-Ether-Ether-Ketone (PEEK) composites. The use of such TP composites has been growing in the aeronautical industry due to some of the advantages they have as compared to thermoset based composites such as easier recyclability, weldability, infinite shelf life and can be stored at room conditions.

To integrate the PZT transducers with composite structures two methods are used namely co-bonding and secondary bonding [2]. It is more challenging to integrate the PZT transducers with high-performance TPs composites because for one co-bonding is not possible due to the high processing temperatures of these materials and two, they have low surface energies. The current state-of-the-art of bonding the PZT transducers to TPs is through secondary bonding using epoxy adhesives. However, epoxy adhesives have some disadvantages such as difficult reparability, long curing cycles, and essential refrigeration. To overcome these disadvantages the use of TP adhesives is proposed. TP adhesives have lower processing cycles because they only need heat to reach the melting temperature and upon solidification, a bond is formed between the adherents which are kept in contact under pressure.

In the previous work [3], a conventional method of melting the proposed TP adhesives was investigated, in which the TP adhesive films (TPAFs) were melted in an oven to bond PZT transducers to TP composites and the bond durability was tested in aeronautical operational environmental conditions. In this work, a novel rapid adhesive bonding process of integrating the PZT transducers to TP composites with TPAFs using induction heating is proposed and investigated.

First, the influence of different susceptor types and not using a susceptor on the maximum achievable temperature was investigated. Then the influence of process parameters namely power, coupling distance (Cd), and time on the temperature generated was studied. From the results of these studies, it was found out whether using a susceptor would be beneficial or not and the right process settings that should be used to achieve a sufficient melting of the TPAFs. Following these results actual PZT transducers were bonded to carbon fiber PEEK composites and the bonding quality of the PZT transducers was checked through electro-mechanical impedance (EMI) spectroscopy. Finally, the bonded PZT transducers were mechanically tested through 4-pt static flexural and tensile-tensile fatigue tests to find their ultimate strain and behavior in fatigue respectively.

2 MATERIALS AND METHODS

2.1 Materials

To study the influence of different susceptors on the temperature and process parameters on the temperature produced, woven carbon fiber PEEK (HTA-40) two different panels were manufactured with a layup of [0/90/0/90/0/90/0]. One panel with dimensions 80x80x2.17 mm^3 is named 'panel-1' and the second panel with dimensions 150x80x2.17 mm^3 is named 'panel-2'. An induction equipment from Ambrell with a solenoid-shaped coil was used to generate the induction field. The Solenoid shape was chosen because the induction field is a mirror of the coil shape, so it provides localized heating in a small area that fits best to the application. The temperature was measured with an E-type thermocouple and data logger supplied by OmegaTM, while the temperature field was recorded with an IR camera from FLIR.

Five different TPAFs and six different types of susceptors were used as shown in Table 1. The PZT transducers, namely DuraActTM were supplied from PI Ceramic®. These are special piezoceramic transducers embedded in a ductile polymer and provided with a mechanical precompression to form an acoustic-ultrasonic composite transducer (AUCT) [4]

Table 1: TPAFs and susceptors used for studying susceptor and process parameter influences.

Thermoplastic adhesive films		Susceptor	
Name	Supplier	Material	Type
P22100	Pontacol	Copper	Very fine mesh
P45200		Copper	Coarse mesh
P22110		Steel	Very fine mesh
P22400		Copper-TPAF integrated	P22100- very fine mesh
T-Link	L&L products	Copper-TPAF integrated	P22100- coarse mesh

2.2 Influence of susceptors and process parameters

To study the influence of the susceptors on the temperature generated, strips of different susceptors and the TPAFs were cut according to the dimensions of the AUCT in consideration. The strips of the susceptors and those of the TPAFs were then placed over each other at three different locations on panel-1: at the center and between the center and edges of the panel as shown in Figure 1. To measure the temperature, thermocouples were placed between the composite panel and the strips at each of these three locations. The IR camera was also used to record the temperature field and the focus was mainly on the area where the induction field was applied at any given time. The whole setup is shown in Figure 1. The measurements were repeated with two different TPAFs namely P2100 and T-Link for each type of susceptor. The process parameters were fixed during this study, a power of 165 Ampere, Cd of 5 mm, and time of 35 seconds was used where Cd is defined as the distance between the outer edge of the coil and the panel.

To study the influence of the process parameters, a single thermocouple without the susceptor or the TPAF was placed at the center of panel-2, while the IR camera was recording the temperature field. The process parameters investigated are listed in Table 2. These values were chosen after trial and error and the criterion was set that the temperature produced should be around 100°C to 200°C.

Table 2: Process parameters used to study their influence on the temperature generated.

Process parameters	Unit	Values		
Coupling distance	mm	3	5	7
Power	Amp	120	130	140
Time	Sec	25	30	35

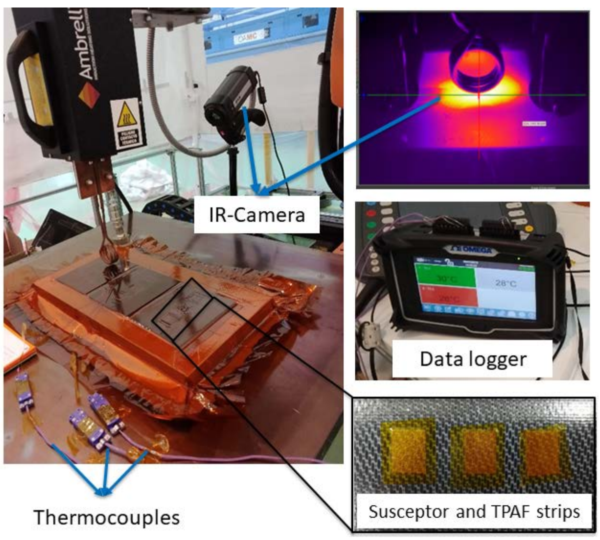


Figure 1: Temperature measuring setup for studying the influence of different susceptors and process parameters.

2.3 Induction heating bonding process

The basic principle of bonding AUCTs to a composite coupon is that a TPAF is placed between the AUCT and the host where a concentrated localized induction field is applied and the adherents are kept in contact by vacuum or roller pressure as shown in Figure 2. Due to the joule effect the conductive carbon fiber generates heat, which melts the TPAF, and after cooling a bond is formed between the AUCT and the composite. Since induction heating is a non-contact process, it reduces the equipment and the consumables needed. It is economic, easier, and faster to reduce the bonding time from hours to a few minutes as compared to bonding with epoxy or TPAF but melted through other methods.

After the bonding process, the bonding quality was checked by EMI spectroscopy which is a method to check the health and bonding condition of a PZT [2, 5, 6] In addition, guided waves were sent and received to check the bonding of the AUCTs, which can be also a good indicator to check the bonding condition of a PZT [7, 8]

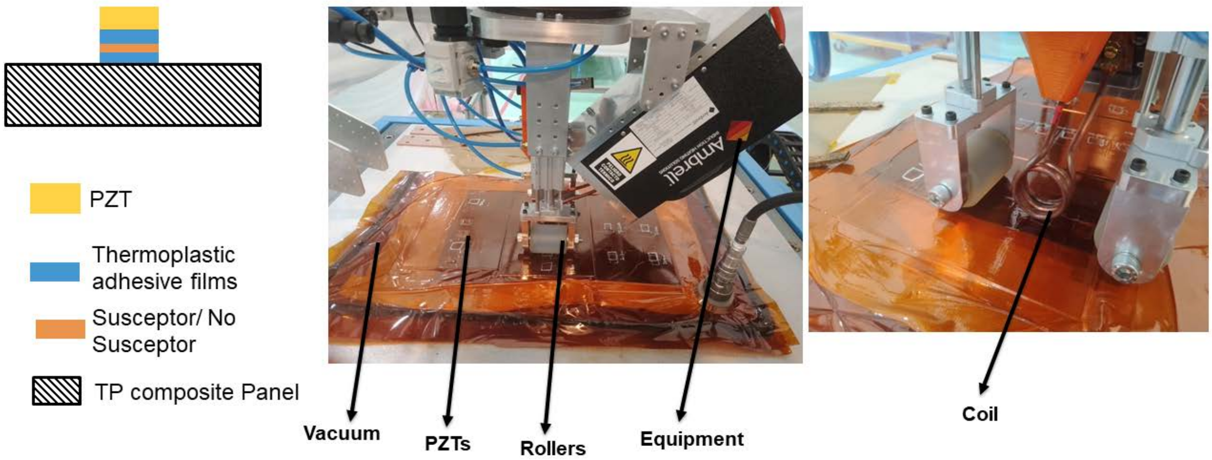
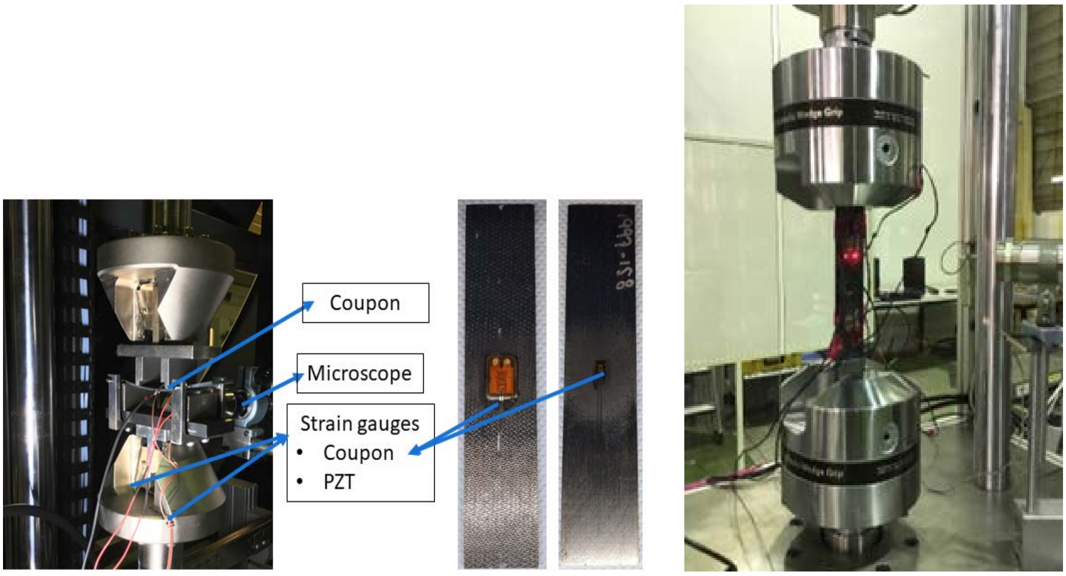


Figure 2: Bonding of AUCTs by induction heating setup.

2.4 Mechanical testing

After successfully bonding the AUCTs to the composite panels two types of tests were carried out to study the mechanical performance of the bonded AUCTs. A 4-pt static flexural test was employed to find the critical strain of the AUCTs bonded with two different TPAFs namely P45200 and T-Link using induction heating. The dimensions of the coupons were 140x30x2.2 mm^3 with a single AUCT bonded at the center. During the bending tests, a strain of 0.1% to 0.8% measured at gauge in steps of 0.1% was put on the coupons, while the charge and the voltage generated by the AUCTs were recorded. After each stain cycle, the EMI of the AUCTs was measured as well. The charge, the voltage plots, and the EMI spectra are used to characterize the health of the AUCTs and hence to find the critical strain of the AUCTs [5]. Furthermore, after each strain cycle, a microscopic image of the AUCTs was taken to see if any cracks were formed. Tensile-Tensile fatigue was carried out to find the fatigue behavior of the AUCTs bonded with TPAFs using induction heating. The AUCTs were bonded with five different TPAFs. The dimensions of the coupons for the fatigue tests were 300x55x2.2 mm^3. The coupons were fatigued for a total of 2x105 cycles with a frequency of 10 Hz and a r-ratio of 0.1 with 10 kN being the maximum load. The EMI of the AUCTs were measured after a particular number of fatigue cycles to check if any degradation has occurred on the AUCTs. The mechanical test setup is shown in Figure 3a for static flexural test and for fatigue test in Figure 3b.



(a) (b)

Figure 3: Mechanical testing setup (a) static flexural test and (b) fatigue test.

3 RESULTS

3.1 Influence of susceptors and process parameters

The maximum temperatures produced at the center of panel-1 for different susceptor types and when no susceptor was used, with a power of 165 Ampere, Cd of 5 mm, and time of 35 seconds as process parameters are plotted in Figure 4. It was seen that among all the cases the highest temperature produced was in the case when no susceptor was used. Although, this is not expected because generally, the susceptor should contribute positively to the overall temperature. However, considering the size of the susceptors in our study they are so small that the joule effect is very small and in place of contributing to heat generation, they are acting as a heat sink because of their high thermal conductivity.

Similarly, the same results were obtained when comparing the temperatures measured at the other two locations on panel-1, where the experiments were repeated by using different susceptors and no susceptor, i.e., the maximum temperatures were achieved in the case where no susceptor was used.

If the three locations on the panel where the induction heating tests were carried out are compared among themselves, it was observed that the higher temperatures are generated at the center of panel-1 as compared to the other two positions. This is shown in Figure 4, where temperatures generated at the center and at one of the two positions relatively close to the edge of the panel are plotted. The lower temperature at the locations relatively close to the edges is due to edge effects in induction heating where lower temperatures are generated near the edges rather than away from the edges because at edges there is a large area for eddy currents to flow resulting in lower current densities and less heat is generated [9].

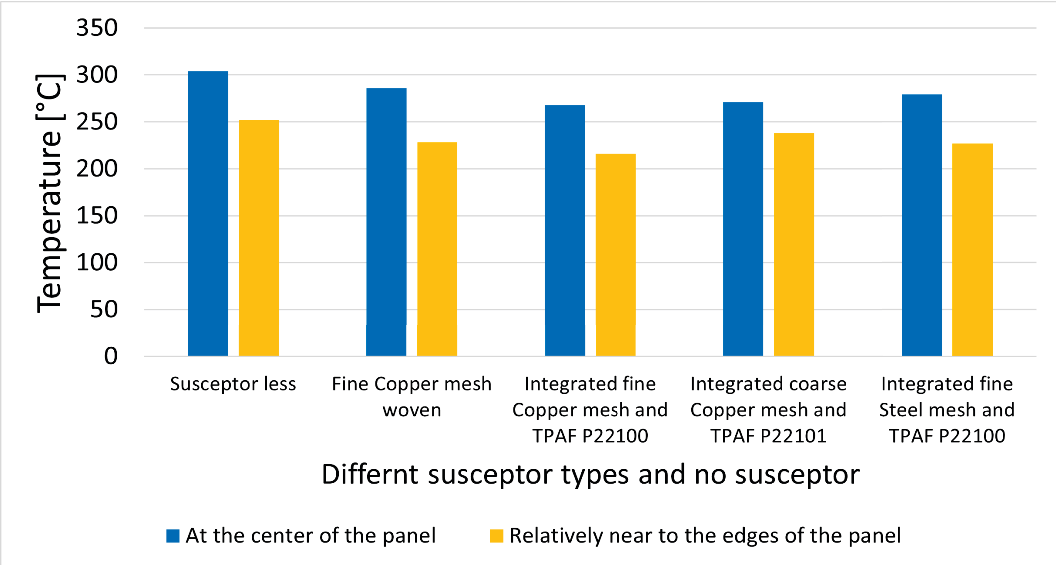


Figure 4: Temperature generated for different susceptor types and no susceptor at the center and relatively near to the edges of the panel-1.

The maximum temperature produced for various process settings is shown in Figure 5. Among the different process parameters, namely power, Cd, and heating time, the power has the highest influence on the generated temperature. The Cd has also a significant effect on the temperature produced or heat generated, however not as significant as power, while the heating time has the least influence on the temperature produced among the three parameters. To give an example, an absolute change of 16.7% (120 to 140 Amp) in power produces a change of 24.1% in the temperature, while a higher absolute change of 66.7% (3 to 5 mm) in the Cd changes the temperature by 15.6% and changing the time by 20% (25 to 30 mm) causes a mere change of 4.96% in the temperature.

The right combination of power as well the Cd cannot only be used to generate the right temperature to melt the TPAFs but these parameters can also be used to control the heating as well as the cooling cycle of the TPAF which is very important to good bond strength. In this study, the Cd has been chosen as a controlling parameter because of its limited range as compared to the power. The Cd can be changed during the induction heating process to control the heating as well as the cooling cycle. In particular, controlling the cooling cycle has been demonstrated which is very difficult to control in an induction heating process but is important for the crystallization of the polymer to form a high strength bond.

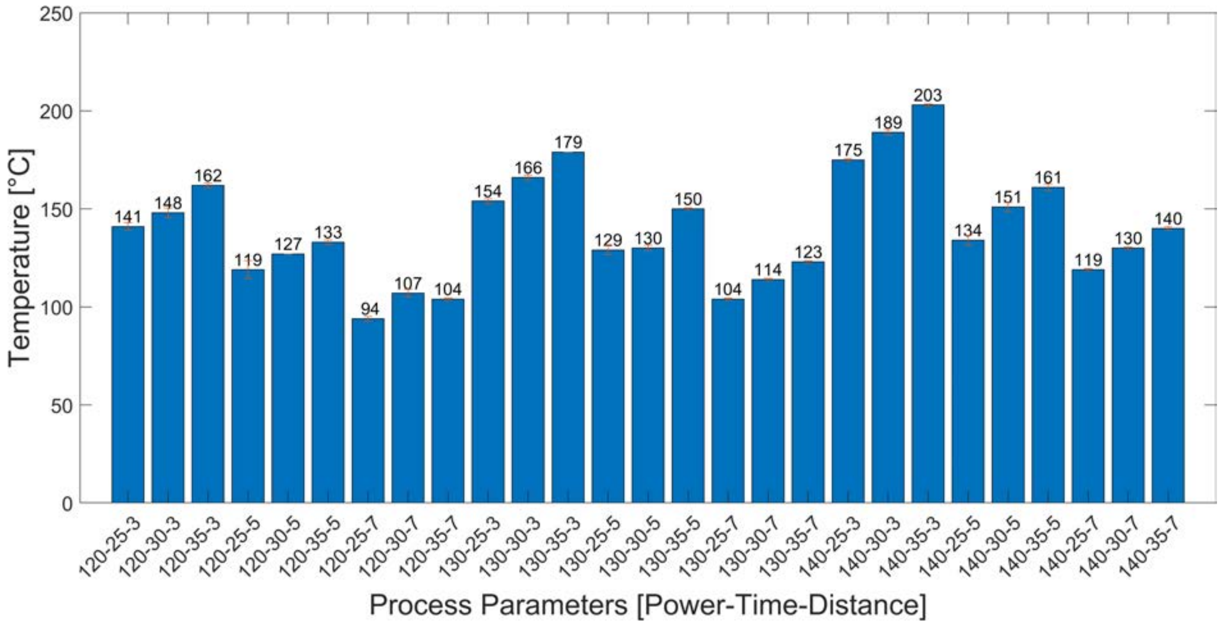


Figure 5: Temperatures produced for different process parameter combinations.

In Figure 6, three heating cycles are shown to heat the TPAF. The first case is where fixed process parameters have been used throughout the whole induction heating cycle with a power of 150 Ampere, Cd of 7 mm, and heating time of 35 seconds. The temperature reaches a maximum of around 150 ° C which is the required temperature to melt the TPAFs and then drops at a very fast rate. Therefore, having fast heating and cooling rates. The second case is where process parameters are also fixed but a low power of 70 Ampere and Cd of 3 mm and heating time is the time it takes to reach 150 ° C. Although, in this case, the heating cycle can be controlled in a better way, and the temperature can be maintained at the melting temperature for a specific time to allow proper melting of the TPAF, but the cooling rate is still very fast which will not allow the melted TPAF to form a proper semi-crystalline structure after cooling. This can lead to lower mechanical properties of the adhesive bond. In addition, this type of cycle is time-consuming and less efficient. The third case is where the process parameters are not fixed during the induction heating cycle. Initially, a faster heating cycle has been applied by using high power (130) and low Cd (3 mm) and once the required temperature has been reached the Cd is changed to 7 mm so that the temperature is approximately maintained at the melting temperature of the TPAF for a specific time to allow proper melting of the TPAF, then the Cd is changed in steps from 10 mm to 20 mm to obtain a gradual cooling of the TPAF as compared to the previous two cases as shown in Figure 6. This slow cooling rate allows the TPAF to form a proper semi-crystalline structure after cooling and hence better mechanical properties of the adhesive bond can be achieved.

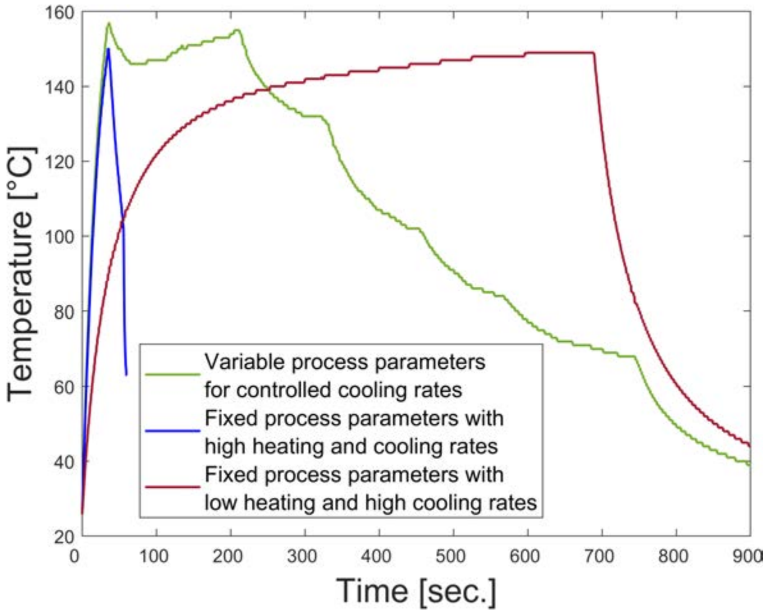


Figure 6: Heating and cooling cycles for fixed and variable process parameters.

3.2 Mechanical testing

The static flexural tests were carried out for two TPAFs only namely P45200 and T-Link so that one case of both semi-crystalline and amorphous TPAF can be studied. Figure 7a shows the voltage over time for each strain step of 0.1% for AUCTs bonded with the TPAF P4500. It can be seen that when the strain reaches its critical value, the AUCT breaks, and as a result, a large and fast deformation is experienced by the PZT material which results in a significant change in the voltage signal at that moment. The EMI spectra measurements for the same TPAF after each strain step are shown in Figure 7b. These measurements also show that when the critical strain is reached a significant change is observed in the EMI spectra due to the change in the AUCT stiffness. The changes are particularly evident in the second resonant frequency around 490 kHZ. The frequency shifts to the left and the amplitude decreases significantly which indicates that major degradation has occurred on the AUCT. Similarly, these tests and measurements were carried out for AUCTs bonded with T-Link. From these two methods, the critical strain of P45200 was found to be 0.6% while that of the T-Link was 0.4%. The critical strain for similar AUCTs which were either co-bonded or bonded with epoxy adhesives on composite coupons has been reported to be 0.58% [5], 0.5% [6], and 0.58% [10]. Therefore, the AUCTs bonded with the TPAFs using induction heating have a good critical strain. Hence bonding with TPFs is an alternative and efficient method of bonding PZT transducers to composite structures.

For fatigue tests, the AUCTs were bonded to a single coupon with different TPAFs. In total five different TPAFs were used as shown in Table 1. The EMI spectra of P22100, P22110, P45200, and T-link after a certain number of fatigue cycles is shown in Figure 8. For P22100, P22110, and P45200 there is a very small change in the EMI spectra after the completion of the fatigue tests. In the case of P22400 the EMI, spectra showed a somewhat noticeable change after 100000 cycles and for T-Link there is a significant change in the EMI spectra after the 80000 cycles. Hence it can be concluded that AUCTs bonded with P22100, P22110, and P45200 have very good behavior in fatigue, with P22400 has a good behavior and with T-link did not show good fatigue characteristics.

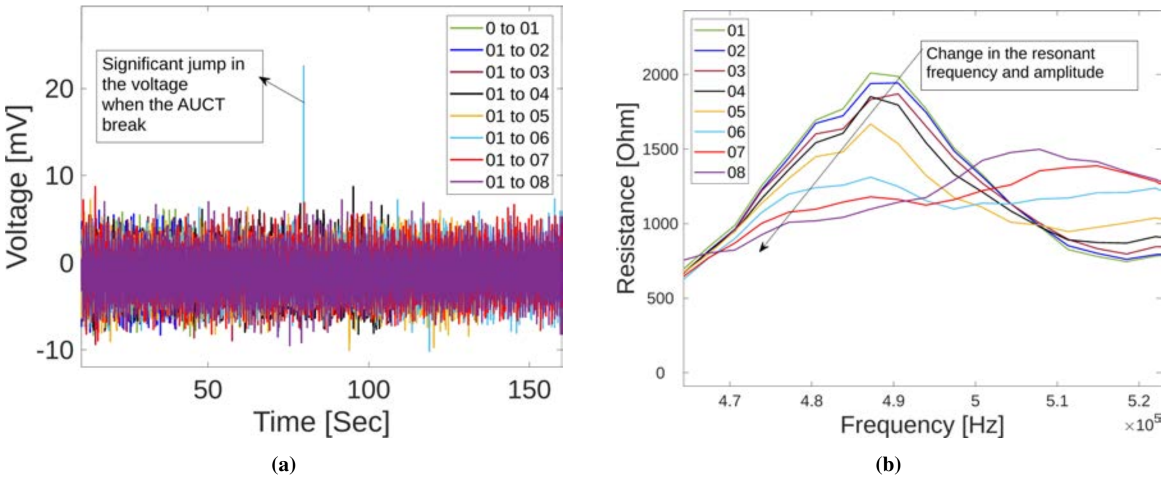


Figure 7: After each strain cycle for TPAF P45200 (a) Voltage-time signal and (b) EMI spectra.

4 CONCLUSION

In this work, a novel and rapid method of bonding PZT transducers to high-performance TP composite structures has been developed by using induction heating. The bonding process was demonstrated and verified by EMI spectra measurements. The influence of different susceptors was investigated and it was concluded that not using a susceptor would be the optimal case. The influence of the process parameters was also studied and based on the results a controlled heating and cooling cycle for the TPAF was developed and demonstrated.

The AUCTs bonded with different TPAFs were tested to study their mechanical performance. During the static flexural tests, it was demonstrated that AUCTs bonded with some of the TPAFs have very good critical strain at which they failed e.g., AUCTs bonded with P45200 failed at an average strain of 0.6% measured at gauge. From fatigue tests the performance of the AUCTs was also studied and most of the TPAFs used in this study passed the fatigue test. Hence, from these two tests, it has been demonstrated that the AUCTs bonded with this new method are durable and reliable.

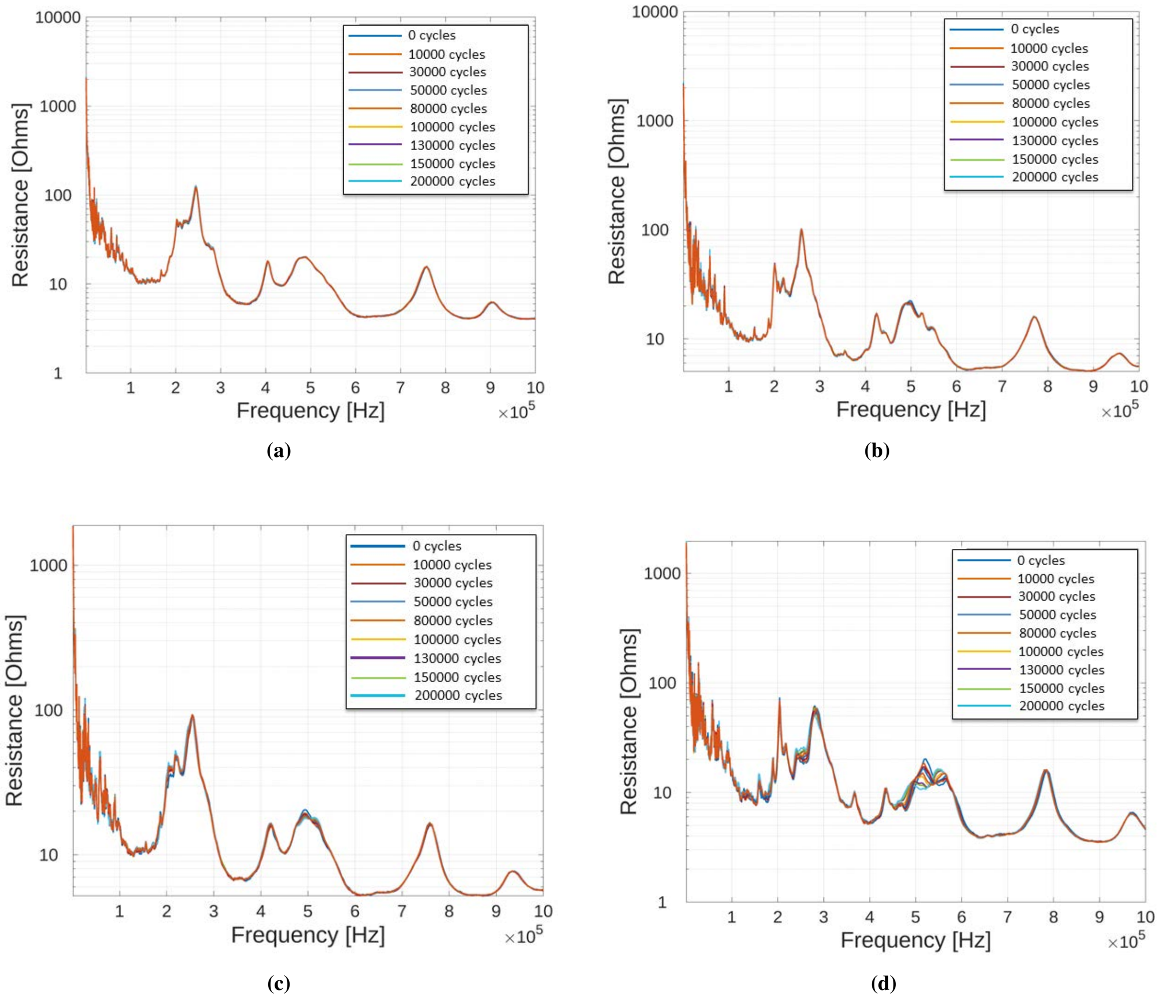


Figure 8: EMI spectra of AUCTs after a particular number of fatigue cycles, bonded with (a) P22100 (b) P22110 (c) P45200 (d) T-Link.

From these results, it can be concluded that the proposed method is a fast, economical, and reliable method of bonding PZT transducers in particular but sensors to composite structures in general. However, more work needs to be carried out therefore the extension of the study would be developing a more controlled induction heating and cooling cycle for the processing of the TPAFs; studying the adhesive bond line with micro-graphs; additional mechanical testing of the induction bonded AUCTs and using guided waves to study the performance of this newly developed method.

5 ACKNOWLEDGMENT

This paper is part of the ENHAnCE ITN project funded under the Marie Skłodowska-Curie grant agreement No. 859957.

REFERENCES

[1] X. Qing, W. Li, Y. Wang, and H. Sun, "Piezoelectric transducer-based structural health monitoring for aircraft applications," *Sensors*, vol. 19, no. 3, 2019.

[2] N. Yue, Z. S. Khodaei, and M. H. Aliabadi, "An innovative secondary bonding of sensors to composite structures for shm application," *Key Eng. Mater.*, vol. 774, pp. 516–522, 2018.

[3] T. Sofi, "Durability of Piezoelectric Transducers in Aeronautical Environmental Conditions Bonded with an Efficient Procedure for SHM of Thermoplastic Composite Structures," Palermo, Italy, Jul. 05, 2022.

[4] P. Wierach, "Electromechanical functional module and associated process," Patent US Patent 6,930,439 B2, 2005.

[5] M. Moix-Bonet, I. Buethe, M. Bach, C.-P. Fritzen, and P. Wierach, "Durability of co-bonded piezoelectric transducers," *Proc. Technol.*, vol. 15, pp. 638–647, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212017314001406

[6] I. Mueller and C.-P. Fritzen, "Inspection of piezoceramic transducers used for structural health monitoring," *Materials*, vol. 10, no. 1, p. 71, 2017. [Online]. Available: https://www.mdpi.com/1996-1944/10/1/71

[7] M. S. Salmanpour, Z. S. Khodaei, and M. H. Aliabadi, "Airborne transducer integrity under operational environment for structural health monitoring," *Sensors*, vol. 16, no. 12, p. 2110, 2016.

[8] N. Yue, "Stochastic analysis of guided wave structural health monitoring for aeronautical composites," Ph.D. dissertation, Imperial College London, 2019. [Online]. Available: http://hdl.handle.net/10044/1/81725

[9] T. Ahmed, D. Stavrov, H. Bersee, and A. Beukers, "Induction welding of thermoplastic composites—an overview," *Composites Part A: Applied Science and Manufacturing*, vol. 37, no. 10, pp. 1638–1651, 2006. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1359835X05003957

[10] I. Buethe, M. Moix-Bonet, P. Wierach, and C.-P. Fritzen, "Check of piezoelectric transducers using the electro-mechanical impedance," in *7th European Workshop on Structural Health Monitoring, Nantes, France*, 8-11 July 2014. [Online]. Available: https://hal.inria.fr/hal-01020432