A Study On development of Induction Welding of Thermoplastic Composites

P Velmurugan1, Janaki Manohar2, C Ramesh Kannan3, S Manivannan4, J Vairamuthu5, P and B Stalin6

1Department of Mechanical Engineering, School of Mechanical and Automotive Engineering, College of Engineering and Technology, Dilla University, Dilla, Ethiopia.
2Department of Mechanical Engineering, Sri Venkateswaraa College of Technology, Sriperumbudur, Tamil Nadu 602105
3Department of Mechanical Engineering, PET Engineering College, Tirunelveli, Tamil Nadu, India.
4Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore -21, Tamil Nadu, India.
5Department of Mechanical Engineering, Sethu Institute of Technology, Pulloor- 626 115, Kariapatti, Tamil Nadu, India.
6Department of Mechanical Engineering, Anna University, Regional Campus Madurai, Madurai-625 019, Tamil Nadu, India.

* Corresponding author: velmuruganp581980@gmail.com

Abstract. The inductive thermal method of welding has been used for heating metals most commonly by all the industries. This method of heating is actually a very efficient means of treating high speed fibre-reinforced thermoplastic composites over past years for enormous applications. The present research work clarifies the thermoplastic welding process. The primary goal is to explain the nature of the inductive welding process and to identify a broad variety of research efforts. The focus is on the method of heat generation dynamics during the inductive heating process and the parameters governing the welding process (frequency, power, stress, time of residence). The experimental methodology is often outlined with focusing on experimental set-up.

Keywords: Thermoplastic, induction welding process, frequency, power, stress.

1. Introduction
Duo-fibre-reinforced thermoplastic composites (CFRTPCs), due to their rising ability for high-performance applications, are becoming increasingly desirable in the industry. Matrix materials recently produced for the manufacture of thermoplastic composites (TPCs) have the same, if not stronger, yield materials with fundamental mechanical properties (stiffness) as thermosets (TS) [1]. Furthermore, TPCs have a range of benefits relative to TS, such as greater tolerance to the atmosphere (high temperature, humidity, hostile fluids), fast drying times, non-flammability and limitless shelf life. The likelihood of low cost fast development is one of their main advantages. The currently produced thermoplastic parts have a comparatively simple structure because of the limited deformation of reinforcing fibres, making it possible to integrate a crucial phase in the development of TPC's. Joints have proved vital when...
manufacturing products for thermoplastic composites (TPC), since they can create a variety of structural defects that weaken the material [2]. Normal joining procedures (mechanical fastening, adhesive fastening), although not suitable for TPCs, are necessary for metals and thermosets. There are several issues with mechanical attachment: inclusion of the stress loads in the components, drilling delamination, multiple thermal extension of the attachments in relation to the part; water interaction with the joint and the galvanic material are likely to deteriorate. It needs a rigorous planning of areas that are usually difficult to control and long-term adhesive curing (normally epoxy) in manufacturing environments. It may also be difficult to bind the chemical inert thermoplastic matrix [3]. A comprehensive summary of the induction welding process for TPCs is given in this article. The primary goal is to provide a deep and scientific study of the nature of the induction welding method by a wide variety of researchers. An overview of the experimental method with an emphasis on the experimental set-up is given after a review of welding protocol induction [4]. The main focus is placed on the heating forms occurring during induction heating processes and the parameters that govern welding processes (frequency, power, strain, residence time).

2. Induction welding
Induction welding is the only method where the induction coil or heat susceptor does not need contact and cannot be engineered so that no heat beyond the desired soldering area is generated. Heating systems have been more of a heating composite. Furthermore, this process is highly flexible for related thermoplastics and non-thermoplastic components that can be welded. The basis behind the method is clear as represented in figure 1 [5]. When an alternating voltage is applied on a conductive belt, an alternative current is formed. This alternating current induces a magnetic time variance field at the same frequency as it generates the alternating current. A magnetically receptive and conductive material creates eddy currents in the vicinity of the spool and the alternative magnetic field that are sensitive to the strength of the magnet [6]. One prerequisite is that closed loops are given to induce eddy currents. In the case of fibre enhanced thermoplastics, closed-loop networks shape in the shape of a conductive network. For many applications, the type of device necessary to work properly varies but typically the equipment may be divided in four parts [7]. First, the RF generator supplies the necessary current and voltage for the induction coil. The second is the thermal plant which covers the induction coil and creates the magnetic field needed to heat the material. Thirdly, the acrylic workstation, and fourthly, the secondary installations, such as the water cooling system and the fittings [8].

![Figure 1. Induction welding technique](image)

3. Heating process
The composite workpiece generates heat as a reaction to the magnetic field but how and where the heat is created depends on the material properties. The substance itself will serve as a weakness because it is
advantageous that the bond line lacks a contaminant insert that will undermine your bond’s mechanical power [10]. A welding insert may also be used as a way of producing and concentrating heat inside the weld zone even though the adhesives are magnetically susceptible [11]. Three types of heating mechanisms, namely Joule loss, crossover heating and hysteresis loss have been established. Heating fibres, due to the intrinsic strength of the fibres, is the product of Joule loosing and hence depends on the fibre length, resistivity and cross section area [12]. Where the attachments are not magnetically vulnerable or where there is a need for managed and localised heating, the heating elements are used as inserts in the solder [13]. Two principal heating factor forms, common to all electromagnetic soldering forms and in the form of a powder or mesh, are available for the inductive welding process.

4. Induction heating parameters

4.1. Frequency
This is a critical parameter because eddy currents are produced by means of the alternating magnet field in the laminate and always affect the reference depth, the higher the frequency the lower the reference depth [14]. Rudol et al. has tested that, with increasing frequency at optimal temperature, the time taken to heat a composite laminate decreases. For greater energy generation inside the laminate, therefore a higher frequency is needed. This then contributes to a shallow reference depth and fits any circumstance [15].

4.2. Power
The input of power is one of the most critical process parameters, provided that it is proportional to the amount of power produced in a particular area of the material. The heat generated by the workpiece is also commensurate with the squared frequency as represented in figure 2 [16]. This causes the reduction in producing capacity to be offset by an increase in frequency as the magnetic field amplitude decreases away from the work piece’s spiral. Power has an average effect on heating time. Short processing times, hence heating times, are required for useful welding applications [17]. As explained, however, the consistency of the suds must be accounted for and a solution must have obtained. The heat time can be used to measure the necessary power in the design of the device since other parameters such as resistivity and real heat apply to the material and differ beyond broad limits [18].

4.3. Pressure
For high quality consolidation, adequate pressure application is essential as it makes good intimate communication and it is shown in figure 3. But Rudolf concluded that the strain to be exerted has a functional limit. During examination of the continuing softening of carbon fibre-enhanced
thermoplastics, higher pressures have resulted in lower soil content. This is because the welding matrix has been further squeezed out, and a sufficient intimate touch to squeeze out polymer has to be reached [19].

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Effect of pressure in induction welding [20]}
\end{figure}

4.4. Voids
There are many explanations why the presence of voids has a clear connexion to the dismantling of the matrix material. Elastic energies as fibre bundles are deformed by heat and strain, gas-captured gas bubble, air pocket crashes, injection sets and heated stresses are all adding to the output of vacuums by eliminating pressures before cooling down to below the necessary temperature [21]. The roughness of the surface is an important parameter when air bubbles are stuck. In order to avoid voids, the high surface smoothness and high soldering pressure are necessary to remove the incidence of voids. The high pressure limit can contradict the low pressure in order to prevent folding and flicking, which is mentioned below. Another effect of vacuum formation is delamination [22]. The delamination is due to intense deconsolidation much of the time. In this case the matrix material contains relatively large air pockets which separate one layer from another in the laminate and thus destruct the interaction between the layers [23].

4.5. Folds and flashes
These flaws are caused by misalignment and inadequate pressure application. If the pressure is divided unequally over the soldering field, the matrix material on the sides will be squeezed out, causing flashes or forcing the laminate to collapse at the edge of the pressure tool. Folding can contribute to buckling of fibres [24]. It is necessary not to apply a high soldering pressure to stop these flashes. The substance is pushed out of the welding field through extremely high pressure. It is necessary to avoid plugging, because an uneven plate will push the brid into the laminate while adding pressure [25].

4.6. Residence time
The moment the workpiece is exposed to the induction field is the moment of residence which causes the motion of polymer molecules through the solder. Generally, a long stay contributes to better weld efficiency, since more polymer chains can be passed around the welding interface [26]. If the frequency, force and pressure of the welding parameters are assumed stable, there will be three welding regimes for the residential and temperature resulting; non-weathering, uniform fusion and deterioration. Inadequate soldering times and therefore low temperatures contribute to poor weathering and low soldering power [27]. A uniform fusion cycle ensues, after which the solder efficiency increases as it surpassed by the residence time and temperature. This makes the optimal welding time and temperature range and thus the optimum operation window [28]. Finally, once inside the workpiece temperature
reaches the normal polymer solder temperature, thermal Polymer degradation and corresponding surface strength decrease.

5. Applications of induction welding

Induction can also be used where the plastic is either doped with ferromagnetic ceramics (in which magnetic hysteresis provides the heat needed) or by metallic particles. Current produced by a tube runs along the open seam and heats the edges and leads to a sufficiently high welding temperature [29]. The seam edges are pulled together at this stage and the seam is offered. While the RF current can be transferred through brushes through the tube, it remains the same as the current is flowing in the open seam and heating it. The conductive wire feeding stock and the shielding gas are fed through a coiled nozzle in the rapid induction printing metal additive process, which subject the feedstock to the heating induction and ejection of the tin as a liquid, while refusing to shape three-dimensional metal structures under shielding [30]. Compared to other manufacturing methods such as selective laser sintering which supplies heat to materials using a powerful laser or electron beam, the key advantage of the proceeding use of induction heat in this process is significantly higher energy and material efficiency.

6. Conclusion

Induction heating has been an appropriate and reliable method especially for thermoplastic composites. The flexibility of the physical method and the detailed study of numerical modelling of the heating mechanism made improving the welding process simpler. The induction welding capability of composite thermoplastic structures has been seen clearly by various studies. The shear strength offered is equal than oven-curated, bolted or welded-resistant joints. Besides the industry’s intrinsic inertness when it comes to modern technology, there are many difficulties that prohibit induction welding on a wide scale, including edge-effect and the local heating effect. The induction heating parameters are discussed in detail to improvise this technology to wide range of applications.

7. Reference

[1] O’Shaughnessey, Patrice Gouin, Martine Dube, and Irene Fernandez Villegas. "Modeling and experimental investigation of induction welding of thermoplastic composites and comparison with other welding processes." J Compos Mater 50, no. 21 (2016): 0021998315614991.
[2] Farahani, Rouollah Dermanaki, Mathieu Janier, and Martine Dubé. "Conductive films of silver nanoparticles as novel susceptors for induction welding of thermoplastic composites." Nanotechnology 29, no. 12 (2018): 125701.
[3] Lionetto, Francesca, Silvio Pappadà, Giuseppe Buccoliero, and Alfonso Maffezzoli. "Finite element modeling of continuous induction welding of thermoplastic matrix composites." Materials & Design 120 (2017): 212-221.
[4] Farahani, Rouollah Dermanaki, and Martine Dubé. "Novel heating elements for induction welding of carbon fiber/polyphenylene sulfide thermoplastic composites." Advanced Engineering Materials 19, no. 11 (2017): 1700294.
[5] Banik, Nabanita. "A review on the use of thermoplastic composites and their effects in induction welding method." Materials Today: Proceedings 5, no. 9 (2018): 20239-20249.
[6] Rahim, Nur Aida Abdul, Jaspreet Pandher, Nicholas Coppola, Vivek Penumetsa, and Michel van Tooren. "In-Situ Monitoring and Control of Induction Welding in Thermoplastic Composites Using High Definition Fiber Optic Sensors." (2019).
[7] Schieler, Oliver, and Uwe Beier. "Induction welding of hybrid thermoplastic-thermoset composite parts." Applied Science and Engineering Progress 9, no. 1 (2016): 27-36.
[8] Bhudolia, Somen K., Goram Gohel, Kah Fai Leong, and Aminul Islam. "Advances in Ultrasonic Welding of Thermoplastic Composites: A Review." Materials 13, no. 6 (2020): 1284.
[9] Costa, Anahi Pereira da, Edson Cocchiere Botelho, Michelle Leali Costa, Nilson Eiji Narita, and José Ricardo Tarpani. "A review of welding technologies for thermoplastic composites in aerospace applications." Journal of Aerospace Technology and Management 4, no. 3 (2012): 255-265.
[10] Sun, Jianliang, Shuo Li, Chouwu Qiu, and Yan Peng. "Numerical and experimental investigation of induction heating process of heavy cylinder." Applied Thermal Engineering 134 (2018): 341-352.

[11] Meitei, RK Bhogendro, Pabitra Maji, Ashutosh Samadhiya, Ranit Karmakar, Subhata Kumar Ghosh, and Subhash Chandra Saha. "An Experimental Investigation on Joining of Copper and Stainless Steel by Induction Welding Technique." International Journal of Precision Engineering and Manufacturing (2019): 1-9.

[12] Pánek, David, Václav Kotlan, Roman Hamar, and Ivo Doležel. "Novel algorithm for modeling combined laser and induction welding respecting keyhole effect." Applied Mathematics and Computation 319 (2018): 254-263.

[13] Baek, Inseok, and Seoksoon Lee. "A Study of Films Incorporating Magnetite Nanoparticles as Susceptors for Induction Welding of Carbon Fiber Reinforced Thermoplastic." Materials 13, no. 2 (2020): 318.

[14] Ghaaffarpour, Morteza, Davood Akbari, Hasan Moslemi Naeeni, and Sajad Ghanbari. "Improvement of the joint quality in the high-frequency induction welding of pipes by edge modification." Welding in the World 63, no. 6 (2019): 1561-1572.

[15] Dede, Enrique J., José Jordán, and Vicente Esteve. "The practical use of SiC devices in high power, high frequency inverters for industrial induction heating applications." In 2016 IEEE 2nd Annual Southern Power Electronics Conference (SPEC), pp. 1-5. IEEE, 2016.

[16] Ma, Wanping, Xiaoqiao Zhan, Hongyan Yang, Hengchang Bu, Yun Li, and Feiyun Wang. "Study on the interface morphology in the induction welding joint of PEEK plate at low power." Journal of Polymer Engineering 40, no. 5 (2020): 432-439.

[17] RK, Bhogendro Meitei, Pabitra Maji, Ashutosh Samadhiya, Subhata Kumar Ghosh, Barnik Saha Roy, Alak Kumar Das, and Subhash Chandra Saha. "A study on induction welding of mild steel and copper with flux under applied load condition." Journal of Manufacturing Processes 34 (2018): 435-441.

[18] Schieler, Oliver, Uwe Beier, and Peter Mitschang. "Control of the through-thickness temperature distribution in carbon composite aerospace parts during induction welding." Journal of Thermoplastic Composite Materials 31, no. 12 (2018): 1587-1608.

[19] Roelofs, Zachary Odel, Airton Martins, Ross Evers, and Oscar Garza. "Hybrid induction welding process applied to piston manufacturing." U.S. Patent 9,909,527, issued March 6, 2018.

[20] Troughton, M. J. "Chapter 11—Induction Welding." Handbook of Plastics Joining, 2nd ed.; William Andrew Publishing: Boston, MA, USA (2009): 113-120.

[21] Flanagan, M., A. Doyle, K. Doyle, M. Ward, M. Bizeul, R. Canavan, B. Weafer, C. M. Ó Brádaigh, Noel M. Harrison, and J. Goggins. "Comparative manufacture and testing of induction-welded and adhesively bonded carbon fibre PEEK stiffened panels." Journal of Thermoplastic Composite Materials 32, no. 12 (2019): 1622-1649.

[22] Weidmann, S., M. Hümbert, and P. Mitschang. "Suitability of thickness change as process control parameter for induction welding of steel/TP-FRPC joints." Advanced Manufacturing: Polymer & Composites Science 5, no. 2 (2019): 55-68.

[23] Shi, Huajie, Irene Fernandez Villegas, and Harald EN Bersee. "Analysis of void formation in thermoplastic composites during resistance welding." Journal of Thermoplastic Composite Materials 30, no. 12 (2017): 1654-1674.

[24] Jahromi, Allen. "Simulation of induction welding process for glass fiber thermoplastic composites in aerospace applications." (2019).

[25] Duhovic, M., P. L’Eplattenier, and I. Caldichoury. "Advanced 3d finite element simulation of thermoplastic carbon fiber composite induction welding." In ECCM 16–European conference on composite materials. 2014.

[26] Hassani-Gangaraj, Mostafa, David Veysset, Keith A. Nelson, and Christopher A. Schuh. "Melting can hinder impact-induced adhesion." Physical review letters 119, no. 17 (2017): 175701.
[27] Thompson, M., J. P. Puaux, A. N. Hrymak, and A. E. Hamielec. "Modeling the residence time distribution of a non-intermeshing twin screw extruder." International Polymer Processing 10, no. 2 (1995): 111-119.

[28] Wolf, David, and William Resnick. "Residence time distribution in real systems." Industrial & Engineering Chemistry Fundamentals 2, no. 4 (1963): 287-293.

[29] Kagan, Val A., and Russell J. Nichols. "Benefits of induction welding of reinforced thermoplastics in high performance applications," Journal of reinforced plastics and composites 24, no. 13 (2005): 1345-1352.

[30] Kagan, Val A., and Russell J. Nichols. Recent Advances and Challenges in Induction Welding of Reinforced Nylon in Automotive Applications. No. 2004-01-0733. SAE Technical Paper, 2004.