A inductive joining technology for production of hybrid material composites

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***Abstract*— In this paper, the new process of "inductive contact joining" (ICJ) for the production of hybrid material composites is introduced and the results of investigations using glass and carbon fiber reinforced polyamide matrix composites are presented. Finite element simulations as well as joining experiments were conducted.**

Keywords*— *Induction joining, composite materials, simulation

I. Introduction

The importance of lightweight constructions in aerospace, automotive production and shipbuilding will increase significantly in the coming years due to rising energy and fuel prices [1], [2]. As a result, the number of lightweight constructions, particularly fiber-reinforced plastic components, in the aforementioned product areas will also increase enormously. In order to reach wide sales markets in the future, it is necessary to reduce the currently high costs for lightweight materials. Flexible, efficient and cost-effective joining techniques for producing hybrid material composites with sufficiently high strength will be also required. The possibility of integrating new joining technologies into existing process chains, the level of new investments, the costs for the joining elements as well as the joining times are decisive factors for a wide industrial application. The joining method should also be applicable in case of restricted, e.g. one-sided, access to the joint. The manufacturing of lap joints between thermoplastic fiber reinforced composites and metals can be realized by mechanical, thermal, chemical and hybrid joining processes [3]. The novel thermal joining process with inductive heating presented here meets the aforementioned requirements and thus offers the potential for an efficient industrial application.

II. Technical Background

In thermal joining processes, the heat generation in the joining zone can be realized by taking advantage of different physical principles such as radiation (e.g. laser, infrared radiation), convection (e.g. gas phase convection, liquid phase convection), friction (e.g. ultrasonic) and electromagnetism (e.g. induction heating) [3]. Therefore, the choice of energy input depends mainly on the material properties of the components to be joined and their geometry.

Due to the fast heating rates that are achievable and the very low energy losses, an energy efficient way of introducing thermal energy into electrically conductive components is induction heating [4], [5]. Another advantage is the direct heat generation in the electrically conductive components [5], [6]. Furthermore, by adapting the process parameters, the location of heat generation can be limited.

III. Inductive Contact Joining (ICJ)

The technology of ICJ, which was originally developed for the joining of fiber-reinforced plastics and metals, uses induction heating to generate heat locally limited at the joining zone [7]. The process sequence is as follows. The components to be joined are positioned in overlap condition. The inductor that is geometrically adjusted to the overlap joint and the geometry of the parts to be joined is placed on the plastic component above the joining zone and the joining force F is applied. When the joining process is started, the alternating electromagnetic field immediately heats the electrically conductive metallic joining partner by resistance heating of induced eddy currents. Due to the heat conduction between the joining partners, the thermoplastic matrix of the fiber reinforced plastic melts in the area of the joining zone and spreads over the metal part. During subsequent solidification, the solidifying polymer matrix and the roughness profile of the metallic component are mechanically interlocked. In addition, adhesive bonding between plastic and metal part is established, i.e. the polymer melt acts as an adhesive. As the copper-coil is water-cooled, in direct contact with the joining partners and positioned close to the joining surface, it constitutes an effective heat sink. The resulting heat flow towards the induction coil causes a rapid temperature reduction in the joint, limits the heating to the joining area and reduces the thermal load of the parts. After the thermoplastic melt has solidified, the inductor can be removed. Compared to conventional processes with spatial and temporal separation of the process steps heating, pressing and cooling, the ICJ process is characterized by the combination of all three steps in one hybrid process. Figure 1 depicts a schematic representation of the ICJ process.

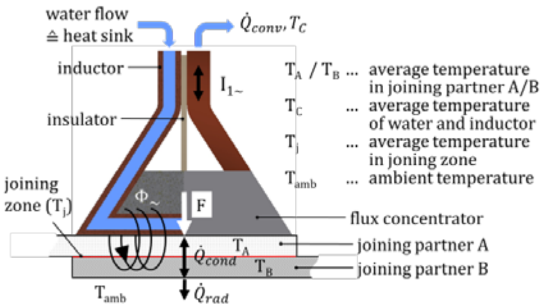

Fig. 1: Schematic principle of the inductive contact joining process [7].

Due to the electrical conductivity of carbon fibers, they can also be inductively heated. As a result, it is possible to join carbon fiber reinforced composites with each other or with other thermoplastic polymer matrix composites. Through the inductive heating of the carbon fibers, the heat thus generated is transferred to the polymer matrix of both components so that they can melt. The plastic melts in the joining zone are mixed and during the cooling step, a firm bond as well as a force-locked joint is established. In this paper, the joining of two fiber-reinforced plastic components, of which at least one component contains carbon fibers, will be investigated. Figure 2 shows the experimental setup for the inductive contact joining of a carbon fiber reinforced sheet (bottom) with a glass fiber reinforced sheet (top).

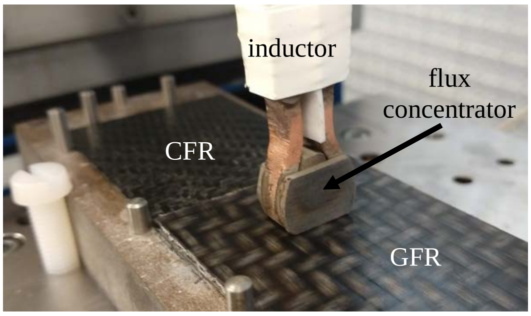

Fig. 2: Experimental setup for the inductive contact joining of a carbon fiber reinforced sheet (CFR, bottom) with a glass fiber reinforced sheet (GFR, top).

IV. Experiments

In a first step the process of ICJ was simulated with the software COMSOL Multiphysics 5.4 by using the AC/DC module. The main target of the work on the simulation model was the development of a valid analogous material model that represents the thermal behavior of polyamide matrix composites with carbon fiber or glass fiber fabrics under direct and indirect inductive heating. It was analyzed which frequencies of the magnetic field were necessary to heat the carbon fibers with a very large aspect ratio so that sufficiently high temperatures were reached to melt the matrix. The analyses were performed as a function of temperature and time, using material data from the COMSOL software database. On the basis of geometry and material of the inductor (m_{Cu} = 99.9 wt.%), an specific electromagnetic field is generated which penetrates the parts to be joined. The formation of this magnetic field can be determined by simulation. The heat generated by induction in the electrically conductive component is determined on the basis of permeability, relative dielectric constant and geometry of the components as a function of magnetic flux density and field strength. The induction coil temperature was assumed to be constant at T_C = 20 °C as in reality it is water-cooled and does not act as an additional heat source by means of conductive heating during the joining process. In a further step, the inductor geometry was virtually modified in order to adapt the geometry of the electromagnetic field to the geometry of the joining partners and to achieve a homogeneous heat development in the joining zone.

The simulative investigations were supplemented by joining tests methods according to DIN EN ISO 14273. For this purpose, glass fiber reinforced polyamide matrix plastic material was chosen as the lower joining partner and carbon fiber reinforced polyamide matrix plastic material as the upper joining partner. The dimensions of both sheets were V = 100 × 50 × 1 [mm³] each. The overlap area was selected to be A = 35.0 × 50.0 [mm²]. A joining force of F = 4450.0 N was applied to the inductor. The joining test was then started. A heating time of t = 2.0 s and a generator output of P = 3.5 kW was applied. These process parameters were determined during prior tests and allowed for melting the polyamide matrix without decomposing it and giving the melt enough time to spread over the metal sheet's surface.

V. Results

The manufactured joints were tested in lap shear tests using a Hegewald & Peschke universal testing machine Inspekt 150. Additional microscopic analyses of the fracture surfaces of the tested samples allowed for an analysis of the bonding mechanisms as well as the failure mechanisms. After measuring the maximum tensile force and the effective joined area, a maximum lap shear strength of τ ≈ 34 MPa could be determined.

VI. Conclusion

The investigations show that joints between heterogeneous materials can be realized without additional joining elements or filler material, with heating as well as holding times of only a few seconds, whereby only one-sided accessibility to the joint is required. The thermal load on the parts is minimized and the surfaces as well as the structure of the metallic joining partners are only slightly affected. This makes the new hybrid technology of ICJ both efficient and highly flexible. In addition, this new joining process can be used for a wide range of applications.

[1] An analysis of European plastics production, demand and waste data, Plastics-The facts 2019, PlasticsEurope, p. 14, 2019.

[2] L. Ickert, D. Thomas, L. Eckstein, T. Tröster, Beitrag zum Fortschritt im Automobilleichtbau durch belastungsgerechte Gestaltung und innovative Lösungen für lokale Verstärkungen von Fahrzeugstrukturen in Mischbauweise, FAT-Schriftenreihe,2012.

[3] F. Podlesak, Entwicklung und Verifizierung eines vorlochfreien mechanischen Fügeverfahrens zum Verbinden von Leichtmetallen und Faser- Kunststoff-Verbunden, Dissertation, TU Chemnitz, 2016.

[4] T. Bayerl, M. Duhovic, P. Mitschang,D. Bhattacharyya, The heating of polymer composites by electromagnetic induction - A review, Compos. Part A Appl. Sci. Manuf., vol. 57, pp. 27-40, 2014.

[5] Z. Huang, S. Sugiyama, J. Yanagimoto, Adhesive-embossing hybrid joining process to fiber-reinforced thermosetting plastic and metallic thin sheets, Procedia Eng., vol. 81, pp. 2123–2128, 2014.

[6] K. Mizukami, Y. Mizutani, A. Todoroki, Y. Suzuki, Detection of delamination in thermoplastic CFRP welded zones using induction heating assisted eddy current testing, NDT E Int., vol. 74, pp. 106-111, 2015.

[7] Kräusel, A. Fröhlich, M. Kroll, P. Rochala, J. Kimme, R. Wertheim, A highly efficient hybrid inductive joining technology for metals and composites, CIRP Annals, vol. 67, issue 1, pp. 5-8, 2018