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A highly efficient hybrid inductive joining technology for metals and composites

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ABSTRACT

A hybrid technology of inductive contact joining (ICJ) was developed to join fibre-reinforced thermoplastics (FRP) with metals by using a tool with single-sided heating. In comparison to conventional methods with separate heating, pressing and cooling, the unique new hybrid ICJ process is characterized by combining all three steps into one hybrid process. The maximum temperature is shifted toward the joining zone due to the direct cooling effect of the surface. FE simulations showed the temperature distributions within the joint. The performed experiments provided data for the temperature profile of the process and the resulting strength of the joint, type of damage and microstructural characteristics. Proven advantages include very short cycle time, competitive joint strength and limited influence on the mechanical properties of the metallic component.

1. Introduction

The successful use of fibre-reinforced polymer (FRP) composites in the aerospace, automotive and shipbuilding industries does not only depend on material cost and universal automation, but also greatly on a flexible and efficient joining technology [1]. In addition to the possibility of integrating FRP composites into existing process chains, decisive factors for their industrial application comprise the amount of investment, cost for joining elements and joining times. The joining process should also be suitable for limited accessibility e.g. for methods with one-sided accessibility [2]. Joining techniques, which are capable of joining metal and FRP, can be subdivided into mechanical, thermal, chemical and hybrid joining processes [3].

In thermal joining processes of thermoplastic FRPs, different physical principles can be used for heating such as radiation (e.g. laser), convection, and friction (e.g. ultrasound) as well as electromagnetism (e.g. induction heating) [4]. Induction heating represents an effective way of introducing thermal energy into the joining zone [5,6]. The direct heat generation in the metallic component is beneficial for the joining process in terms of time and energy efficiency [7,8]. Investigations on induction-based joining deal with continuous and discontinuous variants [9,10]. In discontinuous processes the required pressure between FRP composites and metal components is usually applied by a pressing tool. In terms of time and place, the entire joining process can be subdivided into heating, transport and force application. The individual steps run sequentially. Not only does this have a negative effect on cycle times, but also on flexibility and energy efficiency. The novel joining variant presented here combines the steps of heating, surface cooling and pressing in one process.

2. Physical background

An alternating electromagnetic field induces a voltage U_{ind} in an electrically conductive material. The resulting current I causes a heat flow $\dot{Q}_{el}$ mainly by the Joule effect (Eq. (1)), depending on electric resistance R over time in a cross section A. Additional heating occurs in ferromagnetic metals by magnetic hysteresis.

$$\dot{Q}_{el} = I^2 \cdot R = \int_A J^2 dA \cdot R \quad (1)$$

The spatial heat flow depends on the current density J in the workpiece, which can be described using

$$J(x) = J_0 \cdot e^{\left(-\frac{x}{\delta}\right)} \quad (2)$$

Here J_0 represents the current density at the workpiece surface. The current density decreases exponentially with the distance x from the surface due to the skin effect. J(x) is also determined by the penetration depth

$$\delta = (\pi \cdot f \cdot \mu \cdot \sigma)^{-1} \quad (3)$$

which represents the distance from the surface at which the current density has fallen to $1/e \approx 37\%$. In this area, approximately 86% of the electric energy is converted into heat. According to Eq. (3), the penetration depth depends on the material parameters of permeability μ, electrical conductivity σ and the frequency f of the electromagnetic field. In addition to material properties, the temperature distribution in the workpiece relates only to the process parameter of frequency

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[11,12]. In the described cases the heat generated in the material is mainly dissipated by convection $\dot{Q}_{conv}$ (Eq. (4)), conduction $\dot{Q}_{cond}$ (Eq. (5)) and radiation $\dot{Q}_{rad}$ (Eq. (6)) as follows

$$\dot{Q}_{conv} \approx 4 \cdot \sigma \cdot T_c^3 \cdot A \cdot (T_A - T_C) \quad (4)$$

$$\dot{Q}_{cond} = \frac{A \cdot \lambda}{d} (T_j - T_{A|B}) \quad (5)$$

$$\dot{Q}_{rad} = \varepsilon \cdot \sigma \cdot \left(T_B^4 - T_{amb}^4 \right) \quad (6)$$

The temperature values T_A and T_B are related to the joining partners A and B; thus, the heat sink with the temperature T_C is in contact with the joining partner T_A (Fig. 1). T_{amb} relates to the ambient temperature, T_j to the joining temperature, λ to the thermal conductivity, ε to the emission coefficient and d to the thickness of a joining partner.

3. Inductive contact joining (ICJ)

3.1. Process principle and variants

An inductor capable of applying a press force F is placed over the joining area (Fig. 1) to produce overlap joints between heterogeneous materials — among which at least one is electrically conductive. The applied alternating electromagnetic field immediately heats the electrically conductive joining partners by electric heating (Section 2). Due to heat conduction between the joining partners, the thermoplastic matrix melts and penetrates the cavities on the surface of the metallic joining partner. The subsequent solidification comprises cohesive bonding as well as mechanical clamping of the steel component with the thermoplastic contents and fibres. The water-cooled inductor serves as a heat sink and causes a reduction of the surface temperature by direct contact (Fig. 4). The inductor is removed after solidification of the thermoplastic.

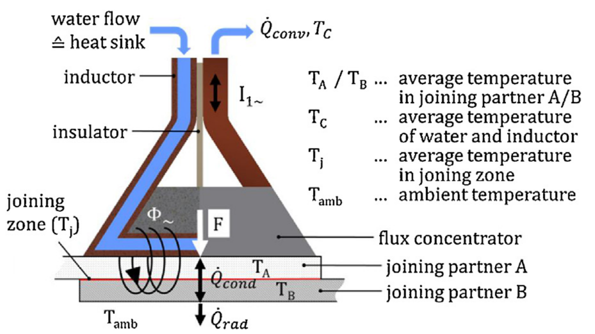

Fig. 1. The hybrid Induction Contact Joining (ICJ) tool and main parameters.

Research in metal and FRP joining processes applying inductive [9] and conductive heating [13] show that the process steps of heating and pressing run separately, both in terms of time and position. The polymers were molten indirectly by thermal conduction (phase I). After heating, the joining partners were moved (phase II) and the joining pressure was applied by means of a press tool. In phase III, the joining partners were cooled down under pressure and consolidated.

In inductive contact joining (ICJ), phases I and III run simultaneously (Fig. 2). The intermediate transport (phase II) is no longer necessary.

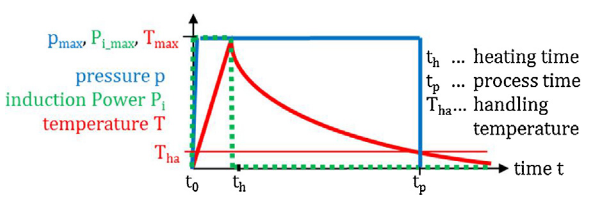

Fig. 2. Schematic diagram of the pressure, temperature and induction power in the joining zone during the ICJ process.

As the inductor's cooling effect speeds up the cooling and consolidation of the parts to be joined, the handling temperature can be reached more quickly. This advantage is also demonstrated by energy savings.

3.2. Process variants

Depending on the position of the induction tool relative to the joining partners, two process variants can be distinguished:

Variant 1 — inductor-composite-metal: With the inductor placed on the composite, Joule heat is immediately generated in the surface of the metallic component facing the joining zone. A higher frequency linked to a lower penetration depth (Eq. (3)) is beneficial to reach the joining temperature faster.

Variant 2 — inductor-metal-composite: With an inductor positioned on the metallic joining partner, Joule heat is mainly generated in the surface of the metallic component and is subsequently transferred into the composite. Due to the strong temperature difference between metal and inductor (heat sink), convection plays a dominant role in the heat dissipation (Eq. (4)). By direct cooling with the inductor, the temperature maximum is moved towards the contact area of the joining partners, thus preventing unintentional overheating of the metal component. By applying a lower frequency of the electromagnetic field in variant 2, the penetration depth (Eq. (3)) is increased, resulting in a more direct and rapid heating of the joining zone. In principle, both joining processes are feasible at the same frequency.

4. Experimental setup and procedure

4.1. Simulation of the inductive contact joining process

Regarding the mechanical behaviour, the inductor must bear the load during pressing while providing a maximum contact area with a homogenous pressure distribution. The hollow inductor was designed as a rectangular profile of E-Cu ($R_{p0.2}$ = 160 MPa). A finite element analysis was performed in ANSYS to obtain the stresses within the inductor under a pressing force of F = 1 kN, in accordance to the joining force used by Velthuis [9].

A frequency-transient study was applied in the electromagnetics AC/DC Module of COMSOL Multiphysics to predict the temperature distribution during the process. Simplifications have been made regarding the thermal and electrical contacts and the temperature difference between water and inductor. Since the surfaces had been cleaned and the geometry of the setup was flat, the contact between the components was assumed to be perfect. Due to the constant water temperature and water pressure of $p \approx 12$ bar as well as the inductor's wall thickness of $w_t = 1$ mm, a homogeneous inductor temperature of $T_C = 20\,^{\circ}\mathrm{C}$ equal to water temperature and the ambient temperature T_{amb} was assumed. The material models of the steel and the composite include verified data of temperature-dependent material properties such as thermal conductivity, specific heat capacity and thermal expansion coefficient.

4.2. Equipment and process parameters

The geometry of specimens and the procedure to test single-lap joints was performed in accordance with DIN EN 1465. The dimensions of the samples were 100.0 mm × 25.0 mm with an overlapping area of 12.5 mm × 25.0 mm. Tensile shear tests were carried out with a Hegewald & Peschke Inspekt 150 universal testing machine. The digital microscope VHX-600 by KEYENCE was used to analyse fractured surfaces. An EMAG eldec simultaneous dual frequency generator providing medium- and high-frequency ranges of $8 < f < 25$ kHz and $140 < f < 350$ kHz was applied for supplying the electrical power of the process. For variant 1, the high frequency range of f_1 = 288.0 kHz was chosen. As a higher penetration depth is beneficial for variant 2, the experiments were conducted in the medium-frequency range resulting in an applied frequency of f_2 = 14.1 kHz. In both cases, the experimental setup, the inductivity