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Susceptor-assisted induction curing behaviour of a two component epoxy paste adhesive for aerospace applications

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A B S T R A C T

The curing behaviour and the mechanical behaviour of susceptor-assisted induction-cured adhesively bonded joints has been investigated. Induction Heating (IH) was established by mixing Iron particles into a two component epoxy paste adhesive. The effect of different process parameters, such as particle content, coupling distance and coil current, on the IH curing process was evaluated by experimental tests and simulation of the induction heating process in COMSOL multiphysics. The process simulation showed that hysteresis losses has a major contribution for the heat generation of IH using Iron particles. Differential scanning calorimetry (DSC) analysis was used to assess the effect of susceptor particles on the cure behaviour of the adhesive. The results showed that the Iron particles do not interfere with the curing process of the epoxy adhesive in scope.

The mechanical performance was evaluated through Single Lap-Shear (SLS) testing at different volume-percentages of Iron particles in combination with glass fibre reinforced plastic (GFRP) adherends. Induction-cured SLS samples were compared with conventional oven-cured SLS samples. In the oven cured samples, the addition of Iron particles resulted in a decrease in the lap-shear strength of 15% to 20%, even for a volume-percentage as low as 0.5%. An additional increase in particle content up to 7.5 v% did not show any additional reduction in the lap-shear strength. Furthermore, results show that when curing the adhesive layer from the inside, as in the susceptor-assisted induction heating, the lap-shear strength is 6% higher than in oven-cured samples (curing the adhesive layer from the outside).

1. Introduction

The autoclave curing process is known to be the current manufacturing technique that pro- vides the best quality of composite laminates and adhesively bonded joints in aerospace application. However, this process implies a high acquisition cost, high energy consumption and, hence, a large ecological footprint. Furthermore, with the current composite aircraft fuselages, it is in- feasible to use autoclave/oven curing processes to assemble large sections of an aircraft. There- fore, new manufacturing solutions must be developed in order to make composites and composite bonding cost-attractive, energy-efficient and applicable to large-scale assemblies, while deliver- ing at least the same product quality as the current autoclave/oven processes. This research addresses the challenge to explore an out-of-autoclave alternative curing process for adhesively bonded joints, based on Induction Heating (IH).

The principles of the IH theory have first been established by Michael Faraday [1]. By exposing a material to an alternating electromagnetic field, heat is generated either by Joule- or hysteresis heating. The latter requires the material to be ferromagnetic for hysteresis losses to occur. Joule heating on the other hand, based on generated Eddy currents, requires the material to be conductive. In comparison with other heat transfer methods, the IH technique's main advantages are high energy transfer intensity and low energy consumption [2,3].

As common paste adhesives are neither conductive nor magnetic, strategies have to be developed in order to apply induction heating on adhesively bonded joints. When working with conductive materials, such as aluminium or carbon fibre reinforced plastic (CFRP), heat can be generated by induction within the adherend, which is then conductively transferred to the bond layer. This is called susceptorless induction heating.

Sanchez C. et al. have established an induction curing process using CFRP adherends and a two-component epoxy paste adhesive [4–6]. Sanchez' curing process showed a reduction in energy consumption of approximately 25% when compared to conventional oven-curing, without any significant decrease in the mechanical performance of the adhesive. However, such an induction heating process is strongly dependent on the quality of the CFRP adherends in terms of fiber

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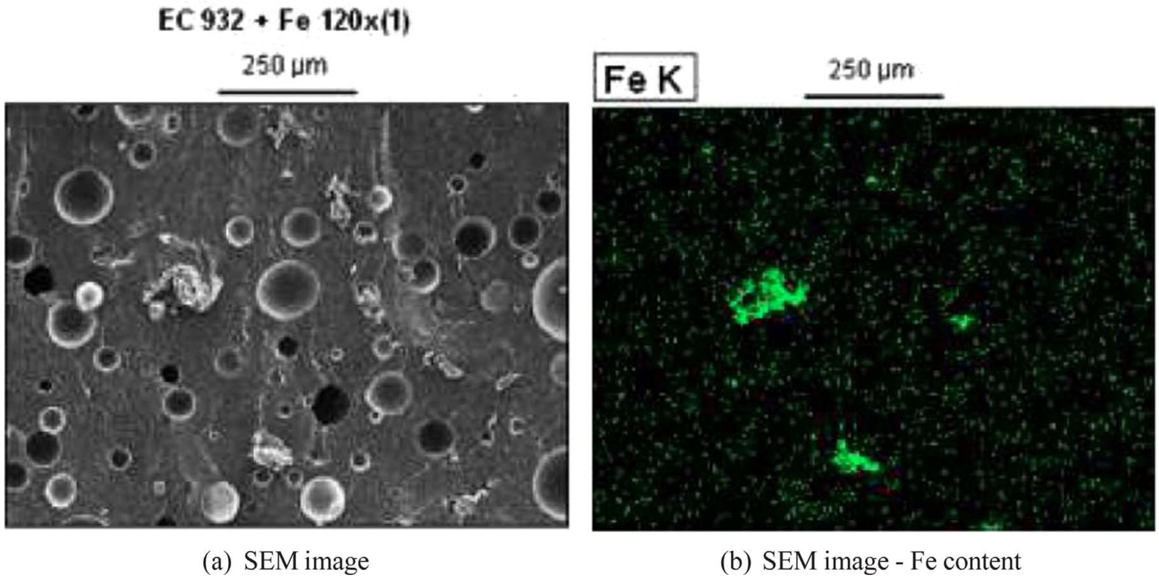

Fig. 1. SEM image taken from a sample with 2 v% of iron particles.

alignment, lay- up and manufacturing, which can significantly compromise the quality of the bonded joint. Furthermore, such curing process are limited to conductive adherends.

If non-conductive adherends are used, such as Glass Fiber Reinforced Polymers, the adhesive can be modified in order to be able to generate heat by induction, so-called susceptor-assisted induction heating. This manufacturing has some interesting advantages over conventional oven- curing and susceptorless induction curing. First, it allows the application of induction curing on adhesively bonded joints having non-conductive adherends. Secondly, it provides the ability to generate heat locally, reducing the overall thermal stresses that occur when the complete structure needs to be heated (such as in an autoclave or oven process). Lastly, the fast increase of temperature within the bondline could enhance gas liberation, possibly resulting in a reduction of void formation and thus improved mechanical performance of adhesively bonded joints.

However, susceptor-assisted IH requires that the bondline has conductive or magnetic properties, by adding either a mesh or particles. Rudolf (2000) has established a susceptor-assisted induction curing process by adding a steel mesh to the bondline [7]. However, poor adhesion between the mesh and the adhesive resulted in a reduced mechanical performance of the joint. A different strategy, used today in biomedical applications for cancer treatments, is to mix ferro- magnetic nano-particles within the material to be heated, which generates heat through hysteresis losses of the particles [8]. Research has shown that different susceptor particles show different heating characteristics [9]. Also susceptor-size and weight percentage have a significant impact [10,11]. In general, smaller sizes and higher particle content increase heat generation. Several studies also investigated the effect of adding different nano-particles on the performance of epoxy resins or adhesives. In general, the lap shear strength and peel strength increase to small amounts of particle content ($< 5\,wt$%), but a further increase in the particle content leads to a decrease in lap shear strength [12–15]. However, research is mostly focused in using the particles to reinforce the adhesive or composite resin. Few studies have been found on using the particles for IH curing. One of them is Hartwig (2009) which investigates selective heating of adhesives using superparamagnetic nano particles. The study shows that the heating rate increases with the adhesive thickness and decreases with the thermal conductivity of the adherends. The best heating rate was obtained with Glass fiber Reinforced Polymers (GFRP) when compared to polycarbonate.

Despite having the mentioned advantages and showing promising results, susceptor-assisted IH adhesive bonding is yet to be established in aerospace industry as a reliable and cost-effective alternative to autoclave/oven curing. A study which compares oven-cured with susceptor assisted IH-curing for aerospace application is still missing.

The purpose of this research is to develop additional insights in the field of susceptor-assisted, induction-heated adhesive bonding using an aerospace certified epoxy adhesive. The aim is to assess the impact of susceptor-assisted induction heating on the curing of the epoxy and on the mechanical performance of composite bonded joints. The conventional oven curing process will be used as reference.

2. Materials and specimens

2.1. Materials

The structural adhesive used for this project is the two component epoxy paste adhesive EC9323-B/A produced by 3 M@ (St. Paul, USA). This adhesive has been selected because of its wide application within the aerospace industry. The manufacturer's recommended cure cycle for this adhesive is two hours at 65 °C.

The susceptor particles are Iron particles, produced by Acros Organics, with an average size of 200 µm. These particles have been chosen because of their superior heat-generating properties compared to other susceptor materials, such as Nickel or Magnetite, as found in literature [10,16].

Glass fibre reinforced plastic (GFRP) was used as adherend material for the lap- shear spec- imen. This material does not generate any heat when exposed to the electromagnetic field and thereby does not interfere with the heat generation through the susceptor particles. Aluminium or Carbon Fibre Reinforced Polymer adherends were not chosen since they would shield the iron filled adhesive from the electric field. The adherends consists of eight layers of $0^{\circ}/90^{\circ}$ glass fibre fabric and HEXION RIM 235 epoxy resin (E_t = 3.0–3.2 GPa, σ_{tu} = 65–70 MPa and ε_{tu} = 6–8% according to Technical Data Sheet). The GFRP coupons were produced by vacuum infusion and cured at room temperature for 24 h.

2.2. Specimens

The effect of different induction heating process parameters on the heat generation has been evaluated on coin-sized coupons of a mixture of the paste adhesive and Iron particles, as shown in Fig. 2(a). The coin-