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On the Assessment of Susceptor-Assisted Induction Curing of Adhesively Bonded Joints

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1. Introduction

The autoclave/oven curing process is known to be the current manufacturing technique that provides the best quality of composite laminates and bonded joints. However, this process implies high acquisition cost and a large ecological footprint. Furthermore, with the current complete aeroplane composite fuselages, it is infeasible to use autoclave/oven curing processes to assemble large sections of an aircraft. Therefore, 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 delivering 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 bonded joints, based on induction heating.

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. In comparison with other heat transfer methods, the induction heating technique's main advantages are high energy transfer intensity and low energy consumption [1, 2].

As common paste adhesives are neither conductive nor magnetic, strategies have to be developed in order to apply induction heating on adhesively bonded joints. If non-conductive adherends are used, such as Glass Fiber Reinforced Polymers, the adhesive must be modified in order to be able to generate heat by induction, so-called susceptor-assisted induction heating.

Most of the available research focuses on the effect of different process- and material parameters on the induction heating process, and the achievable temperature at a certain set-up [3, 4]. However, little research has been done on assessing the effect of susceptor- assisted induction heating on the actual cure behaviour and mechanical performance of adhesively bonded joints.

The purpose of this research is to develop additional insights in the field of susceptor-assisted, induction-heated adhesive bonding. The aim is to assess the impact of susceptor-assisted induction heating on the curing and mechanical performance of adhesively bonded joints.

2. Materials and Specimens

Materials

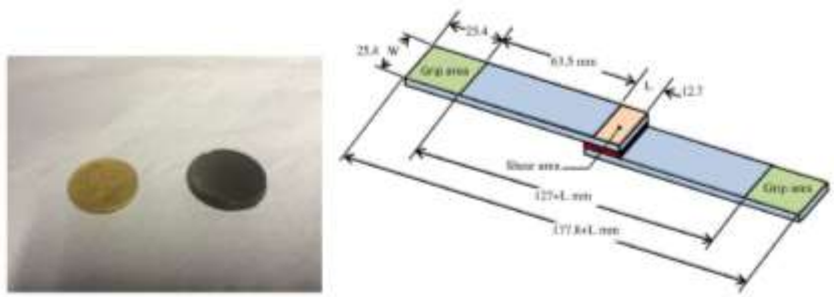
The structural adhesive used for this project is the two component epoxy paste adhesive EC9323-B/A produced by 3M. This adhesive has been selected because of its wide application within the aerospace industry. The manufacturer's recommended cure cycle for this adhesive is two hours at 65 °C.

The chosen susceptor particles are Iron particles, produced by Acros Organics, with an average size of 200µm. 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 [5, 6].

Glass fibre reinforced plastic (GFRP) was used as an adherend material for the lap shear specimen. This material does not generate any heat when exposed to the electromagnetic field. The adherends consist of eight layers of 0°/90° glass fiber fabric and HEXION RIM 235 epoxy resin. The GFRP coupons were produced by vacuum infusion and cured at RT for 24 hours.

Specimens

The effect of different induction heating process parameters on the heat generation has been evaluated on coin-sized coupons (mixed paste adhesive and Iron particles (Figure 1(a)). The specimens had a diameter of 27 mm and a thickness of 2.95 mm. The particle content was varied from 1 to 5v%. Susceptor particles were manually mixed into the adhesive.
The effect on the mechanical performance was evaluated, by testing single lap shear (SLS) specimens, with dimensions in accordance with ASTM standard D5868 [5], shown in figure 1b. The volume-percentage of Iron particles was varied between 0.5 and 7.5v%.



(a) (b)

Figure 1. *Coin- sized specimen (left) and single lap shear specimen (right).*

3. Experimental campaign

The experimental program consists of three phases. An evaluation is made on the heat-generating characteristics of the EC9323 epoxy paste adhesive [6] mixed with- and without different types of susceptor particles. Then the impact of the best performing particles (the Iron particles) on the cure chemistry of the adhesive is evaluated through DSC analysis. Finally, the mechanical performance and production cost aspects of the induction-cured compared to oven cured adhesive is assessed by single lap shear specimens.

Cure Performance

All samples have been cured at the manufacturer's recommended cure cycle of two hours at 65°C. Oven- cured samples were manufactured in a Heraeus T6030 oven. The used induction heating equipment is an EasyHeat- LE 10 kW unit, made by Ambrell. Induction-cured samples had to be manufactured with 7.5v% of Iron particles at a coil current of 175 A in order to obtain a cure temperature of 65◦C for two hours without overheating the system.

Cure Behaviour Analysis of adhesive including Iron particles

Figure 2 shows the heat flow graphs obtained from the DSC experiments. Heat flow data is normalized by dividing the total measured heat flow by the sample's weight. Both samples obtain a full cure in two hours, as both graphs reach a residual heat flow of zero at that time. The initial negative heat flow peak noticed in the first five minutes of curing was found to be a measurement error, and not related to the actual cure chemistry of the adhesive.

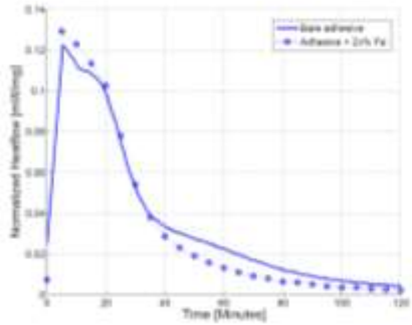


__Figure 2.__ Heat flow curves obtained from the DSC analysis at 65 °C for susceptor- assisted (2v%) and pure adhesive

As shown in Figure 2, both the susceptor-assisted and pure adhesive show comparable heat flow trends over the curing process. Additionally, the total area underneath both curves, representing the total cure energy, is also comparable.

Mechanical Joint Performance

Single lap shear tests were performed in order to obtain the influence of both the particle content as well as the influence of induction-curing on the adhesive performance in comparison to the oven cured adhesive. Figure 3 shows the test results on the performance of induction-cured samples, containing 7.5v% of Iron particles. The addition of Iron particles reduces the overall mechanical performance, independent of the type of curing process. Though in comparison to oven-cured samples with the same amount of susceptor particles, the lap shear strength of the induction-cured samples show a slight increase of 6%.

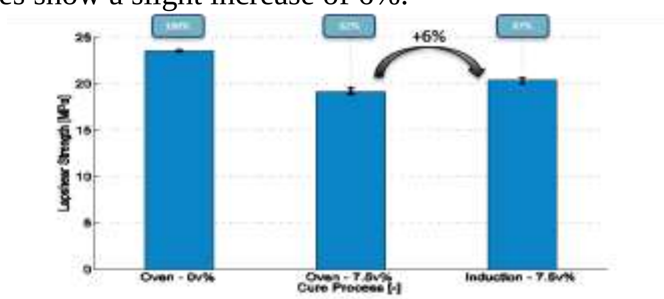


__Figure 3.__ The average lap shear strength of induction- and oven cured samples with 0v% and 7.5v% of Iron particles

4. The Comparison of Oven Curing vs. Conduction curing

The influence of the bonding parameters and curing equipment

Induction heating: When trying to generalize the relation between bonded area, the induction heating equipment’s rated power and its energy consumption, one has to realise that the link between those parameters is much more complex than for oven-curing. As increasing the equipment’s rated power is commonly used for generating larger coil currents, and thereby denser magnetic fields, rather than increasing the coil size.

Oven heating: Based on the findings of the research, the energy consumption of an oven can be roughly estimated from its maximum rated power. For small-scale ovens, up to a volume of $5m^3$, the relation between rated power and volume is almost linear.

Process Costs

When looking at the investment- and process costs, calculations show that applications having a bonded area of less than 50 cm^2, but requiring an oven-volume of more than 0.8 m^3 for the curing process, could be processed more efficiently by susceptor- assisted induction- curing. The reason is that the costs related to susceptorless induction-heating are less product size dependent, when only small sized curing areas are of main interest.

5. Conclusions

The curing behaviour and mechanical performance of induction-cured bonded joints, as a possible alternative to traditional oven-cured processes has been evaluated. Heat was generated from the inside of the adhesive layer, by adding ferromagnetic susceptor particles to a two component paste adhesive, in order to cure bonded joints of non-conductive adherends. The main conclusions from this research are:

- Adding Iron particles does not influence the curing behaviour of the studied paste adhesive;
- Adding Iron particles to the adhesive results in a reduction of the lap shear strength of 15%, even at a small particle content as 0.5v%. A further increase in particle content, up to 7.5v%, does not result in any additional decrease in lap shear strength;
- Curing the adhesive layer from the inside-out, as in susceptor-assisted induction heating, results in an increase in lap shear strength (6%), compared to oven-cured samples (cured outside-in)
- When small sized bond areas have to be cured, susceptor-assisted induction curing can be more cost-effective than oven curing.

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