VALIDATION OF A NEW NANO-MODIFIED ADHESIVE JOINING TECHNOLOGY TRIGGERED BY ELECTROMAGNETIC FIELD, BY TESTING OF A REAL COMPONENT

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Abstract

Nowadays, the importance of recycling and reuse of parts and materials is growing, and the automotive industry is asked to meet stricter and stricter criteria in vehicle design; as a consequence, more significance is given to assembling and disassembling processes. Studies have been carried regarding the possibility to use an innovative technology based on an electromagnetic field in order to join components for the automotive industry. This new method relies on nanoparticles embedded into a hot-melt adhesive matrix: these nanofillers respond to an electromagnetic field by heating and by allowing the adhesive to reach melting temperature, thus causing both the enhancement of polymerization while joining of the components and allowing disassembling of those components. Experimental results show that not only this process is simple, not time-consuming and flexible, but also that, once the components have been assembled, an equally easy disassembling procedure is possible by using similar equipment and operative conditions.

1. Introduction

Faced with growing concerns about the impact that automobiles have on our environment, the use of plastic in the automotive industry has increased significantly in recent years. As shown in a high number of studies, the use of polymeric materials leads to lighter-weight vehicles, lower fuel consumption and, therefore, reduction of emissions [1]. The European Union ELV Directive (End of Life Vehicles), which was created to promote recycling and provide incentives for environmentally-friendly vehicles, stipulates that, from January 2015, 85% of a vehicle must be retrieved for recycling and that another 10% should be available for energy-recovery processes [2].
With respect to recycling, the greatest opportunities for increased recovery rates necessary to meet these targets may involve polymers, glass, and electronic components of vehicles. Plastics, which comprise the largest proportion of currently non-recycled materials in vehicles, are a logical focus of research and development efforts directed toward vehicle recycling.

In order to optimize a product's end-of-life system, it is important to consider disassembling as well as assembling. The ability to select the appropriate joining process at every step of production, as well as the process to separate the components is critical and may influence the selection of the joint geometry, the materials to be joined, the functions required from the joint, and production conditions [3].
However, there is still a poor quantity of technical literature available dealing with development on disassembling of plastic and polymer matrix composites. Considering this stage, the development of a new assembling/disassembling technology can lead to enormous benefits including simplification of products, lower assembly and manufacturing costs, improved quality and reduced time to market.

2. Traditional and innovative joining technologies

The traditional methods for joining plastic can be divided into three fundamental categories: mechanical fastening, adhesive joining, and welding [4,5].
Traditional mechanical joining involves the use of fasteners such as metallic and polymeric screws, and offers the advantage to allow a rapid and effective disassembling process both for inspection and part substitution. Unfortunately, this type of mechanical joining is associated with an increase of the final weight.
Adhesive joining is a process whereby an adhesive is placed between the parts (adherends) where it serves as the material that joins the substrate and transmits the load through the joint. The principal benefits deriving from the use of adhesive joining involve: low cost, design flexibility, improved stiffness of the joint, ability to damp noise and vibrations, uniform distribution of stresses over the assembled areas, possibility to join dissimilar materials and no direct contact between parts.
In welding, the plastic materials are fused together by the proper combination of heat and pressure; heat is applied to melt the polymeric material on the joint surfaces, to enable polymer intermolecular diffusion across the interface and chain entanglements to give the joint strength, and surfaces are pressed together for polymer solidification and consolidation.
Both adhesive joining and welding are currently more frequently used for the assembling process, due to their process speed, weight saving, inferior material demand and cost effectiveness, but one of the critical problems related to these methods is that they do not allow easy disassembling processes of the components. Since reuse and recycling are two main issues of new EU regulations, it is essential to develop new joining technologies in order to facilitate ease of disassembly and optimize recycling processes.
Due to these reasons, adhesives and induction welding could be combined to achieve special benefits and obtain unique joining combination in a electromagnetically nano-activated adhesive for reversible assembling/disassembling technologies.

This innovative technology is based on the embedding of electromagnetically active susceptors in an adhesive matrix. Suitable choices are iron particles, iron oxide, stainless steel, ceramic, ferrite or graphite [6]. Once an alternating electromagnetic field is applied, the magnetic particles within the adhesive activate and rapidly heat: the amount of the generated heat depends on the nature, the quantity and the morphology.
The increasing temperature is thus able to melt the thermoplastic adhesive matrix and the assembling process of polymer-made automotive components is possible. Once the joint is created, it can also be disassembled quickly and effectively by simply using the same apparatus and conditions.

In a previous work it was demonstrated that this innovative adhesive is also able to bestow attractive mechanical properties on the new joint [7].
The physics of electromagnetic induction describes the susceptor magnetic heating as the combination of magnetic effects (hysteresis losses) and heating by Joule effect (eddy current losses). In ferromagnetic materials based on iron, both mechanisms of magnetic hysteresis and eddy currents contribute significantly to the heating. Furthermore another effect can occur in particles embedded in the adhesive causing ferromagnetic/ferrimagnetic domain wall motion and domain realignment losses [8], which lead to an additional heat generation.
The frequency of the primary alternating current, along with the permeability and resistivity of the material, decide the depth that the eddy currents are able to penetrate and therefore the distribution of heat within the work piece. It is worth noting that the plastic materials being joined are totally transparent to electromagnetic waves, consequently the adhesive electromagnetic activation is a highly selective process that avoids any modification of the chemical or mechanical properties of the assembled elements [9].
One of the most promising adhesive types that can be considered as eco-friendly and cost-effective is a hot-melt thermoplastic adhesive. In light-weight design the use of this kind of adhesives has become increasingly popular because of their short treatment time and thermal reversibility at high temperature. By taking into consideration their reversibility at high temperature, studies have been done on selected hot-melt adhesives and thermoplastic substrate materials.

3. Materials and methods

The structure under study is the low tail gate of a vehicle rear door; this component consists of a homopolymer polypropylene (PP) 10% talc filled reinforcer, at present linked to the vehicle door frame through rivets, and an external skin in polypropylene too, adhesively joined to the reinforcing structure.
The geometry of the low tail gate is given in Figure 1. The total length of the part is about 1.2 meters.

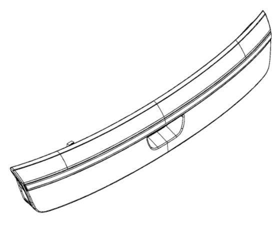


Figure 1. Low tail-gate

The adhesive system used in this investigation was a synthetic polypropylene-based hot-melt adhesive, largely used in automotive application.
The magnetic susceptors chosen were iron-based nanoparticles: magnetite (Fe_3O_4), a magnetically soft ferrite powder obtained from Sigma-Aldrich [10]. The particles were mostly spherical with average size smaller than 50 nm in diameter.
The magnetic adhesive was fabricated by incorporating magnetite powder into the polyolefinic hot-melt adhesive at 5, 10 and 30 percent by weight. The mixing was done by hand, on a hot plate, at 180°C for 10 minutes.
For the deposition of the modified adhesive on the component to be joined, a hot-melt Nordson Durablue extrusion gun was used. The modified adhesive was manually spread at

200°C, trying to apply a uniform and adequate bead of adhesive onto the full perimeter of the tail gate inner panel.

The main goal of the activity was to investigate whether the experimental data obtained on standard specimens via induction heating are still meaningful for a more complex geometry.
In a previous work [7], five different types of ferrite nanoparticles were chosen and embedded into the hot-melt adhesive to investigate their thermal response while they were subjected to external electromagnetic field using induction heating process. Based on the found results, magnetite nanoparticles were chosen, since they showed the best heating performance.

Special set up was designed in order to manufacture joints by new assembling technology. The equipment was composed of a generator and an inductor. The study used an Egma 30DR induction unit, provided by KGR and designed for the exclusive use in the automotive industry, which operates at frequencies between 30 and 300 kHz.
As shown in figure 2, to avoid a reduction in the magnetic flux density, metal components near the work coil were properly shielded, in order not to allow heat subtraction by metallic parts.

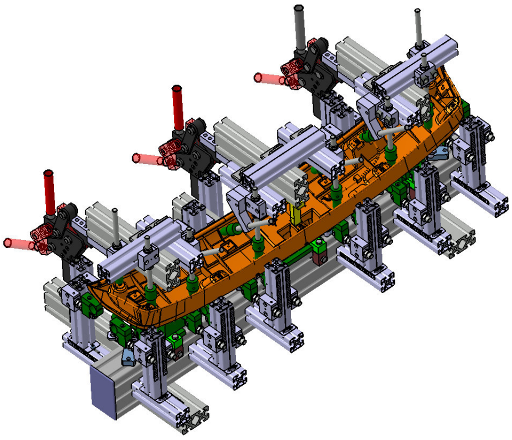


Figure 2. Location and position of the low tail gate during processing.

The coil used on the induction unit was obtained from a 1 cm diameter copper tubing shaped as the component's geometry. The solenoid was about 30 cm wide and 140 cm long, water cooled (figure 3). This specific design allowed to process the entire component simultaneously.
The density of the induction field can be controlled through Ferrotron 559H high frequency flux concentrators fixed along the inductor perimeter.

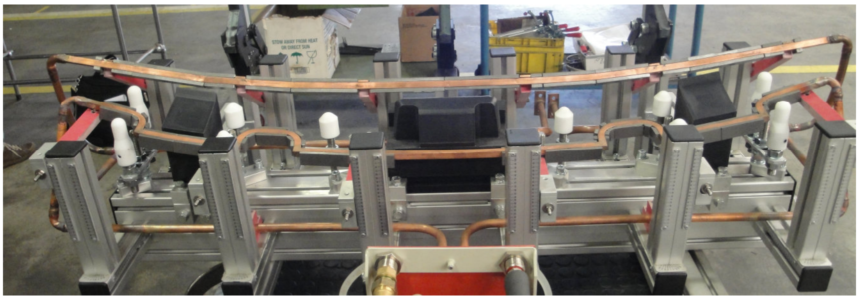


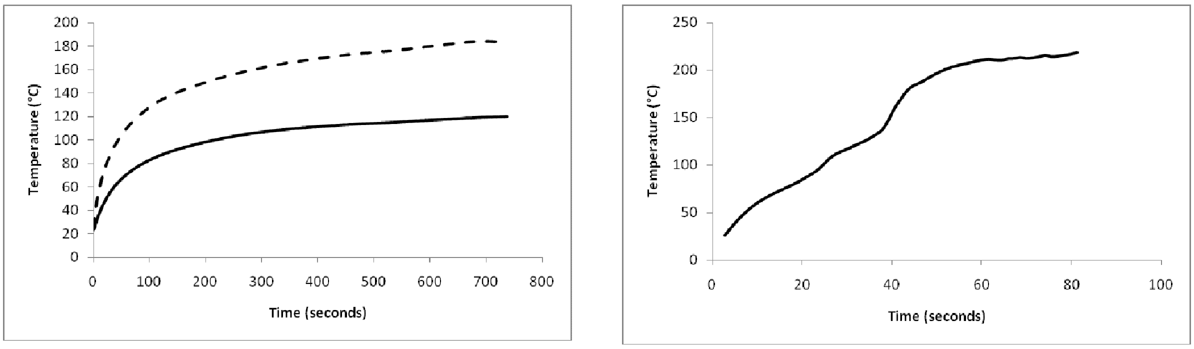
Figure 3. Induction coil

A thermocouple could not be used as a temperature sensor since it consists of metallic wires which are sensitive to the applied induction heating. In order to obtain accurate temperature data, adhesive heating profile was measured using a opSens fiber optical sensor model OTG-M170. In order to get a heating map of the modified adhesive, the measurement zones of the sensor were embedded in the middle of the adhesive layer, along the perimeter, in two parallel positions.

The induction heating apparatus was used to fix the inner panel with the outer panel of the low tail gate, providing the necessary heat for the adhesive to melt and go from a solid to a viscous state.
After the adhesive was spread, the external skin was placed on the reference equipment and the inner component was manually laid upon it and locked with three automatic non-magnetic push rods to have a uniform compressive force and a good overlapping during the exposition to radio frequencies.
In order to perform assembling tests a 5.3 kW electromagnetic field with 65.5 kHz frequency was applied. It is worth noting that cycle time changes depending on the type of adhesive used and on the structural features of all the elements involved.

4 Experimental results

The experimental tests were carried relying on an experimental procedure already optimized in a previous work [7].
The temperature response as a function of time for each modified adhesive (5-10-30 weight percent of magnetite) is shown in Figure 4a (5 and 10% modified adhesive) and 4b (30% modified adhesive). The two figures were split since the time scale was very different, and the 30% curve would be less visible.
All of the thermal profiles follow a similar pattern: we can see an initial portion where the temperature grows linearly with time, later an increase in temperature with a slightly smaller slope and, finally, a region where the temperature is constant (*plateau*).
The slope of the linear region, the plateau temperature and the time needed to reach the plateau phase depend on the magnetite percentage in the adhesive: if the amount of nanoparticles is increased, the initial slope is steeper, and a higher plateau temperature is reached in a shorter time.
Since the adhesive has a softening temperature of about 150-160°C, and the joining cannot be created before the adhesive is fluid, we can state that a sample that did not reach at least the softening temperature via induction heating is not a successful one.
As can be seen in figure 4, the 5% sample reached a plateau temperature of 120°C, the 10% adhesive reached 185°C, and the 30% adhesive reached 212°C: as a consequence, the first sample did not become fluid, thus not allowing the formation of the joint, while the other two samples, richer in magnetite, were able to soften and create adhesion.



(a) (b)

Figure 4. Thermal profiles of modified adhesives once the electromagnetic field is turned on; 5% and 10% samples are shown in portion (a) (continuous line is related to 5% adhesive, dashed line is related to 10% adhesive), 30% sample is shown in portion (b).

A growing quantity of susceptors is able to speed up the kinetic of the heating process, as can be seen on the steeper slope of the graphs in figure 4, thus allowing the sample to reach plateau phase in a shorter time: the automotive industry would greatly benefit from this feature, since it would allow to save production time.
As a result, in only 45 seconds the 30% in weight modified adhesive was able to reach the softening temperature and to create the joint between the two sections of the low tail gate.

As in a previous work [7], disassembling tests were performed exposing the joint to the same apparatus and setup used for the assembling process: a 5.3 kW power and a 65.5 kHz frequency RF field was able to activate the modified adhesive allowing, applying a weak tensile force, the joint dismantling. Experimental results showed that, when working at these conditions, the disassembling test requires an average time of 15 seconds.

The disassembled low tail gate is visible in figure 5:

Figure 5. Disassembled low tail gate

5. Conclusions

The application of the electromagnetic joining technique has been investigated for the low tail gate of a vehicle rear door.
The assembly/disassembly test using an electromagnetic field on the final prototype has allowed to evaluate the validity of this process. Even though a few improvements in lay-out and materials are still needed, this new technology shows a very high potential to allow rapid

and easy assembling and disassembling on automotive components, which can improve repairing and recycling routines.
The next goal is the optimization of the nanoparticles percentage and the equipment lay-out, in order to fully reap the benefits of this joining technique, such as a reduction in cycle time and costs compared to the standard industrial process. It can be estimated that the total time, starting from the positioning of the low tail gate in the apparatus until its final extraction, will amount to 60 seconds or 5 minutes, depending on the particles percentage chosen (30% and 10%, respectively).

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