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RTM TECHNOLOGY IMPROVEMENT WITH TOOL SURFACE HEATING BY INDUCTION

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SUMMARY: With the goal of weight and cost reduction in the automotive industry, the need for technology capable to produce highly structural composite parts in a short cycle time is very important. This is the reason why RocTool adapted its tool surface heating technology to the RTM process. The inductive phenomena allows this technology to heat fast and cool down the tool surface quickly leading to many advantages for the RTM process such as overall cycle time reduction, filling time reduction and safer filling of the mould, warpage reduction because of extraction of cold parts, surface quality improvement.

Having shown the potential of this technology in a metal/metal tool configuration dedicated to RTM Class A application, a projection of this technology to another family of RTM techniques, using a flexible membrane, will be detailed. This new configuration will allow energy savings and better heating quality on the tool surface, keeping the objective of increasing and especially controlling the temperature ramps.

KEYWORDS: induction heated tool, RTM, vacuum bagging

INTRODUCTION

With the goal of developing innovative molding technologies for composite materials, RocTool has developed the Cage System® [1], a molding solution assisted by induction heating. To adapt this approach to complex parts, or more specifically to Resin Transfer Molding (RTM) process variants [2] such as Liquid Resin Infusion (LRI) or Resin Film Infusion (RFI), an adaptation of Cage System® was devised by incorporating a flexible membrane and/or a vacuum bag to the process. The objective of this article is to demonstrate the compatibility and interest of this new configuration for composite manufacturing by resin injection. Furthermore, it is important to illustrate the potential of this new approach in terms of production output and heating quality [3].

A NEW INDUCTION HEATING CONFIGURATION

Currently, the RTM process [4] is mainly driven by the injection, the curing and the extraction temperatures. In fact one has to find a compromise between the highest temperature acceptable to extract parts, the highest temperature acceptable for the resin injection and the lower one acceptable to reach a decent curing time for the resin. This statement leads to have thermally regulated mould at a medium temperature around 100°C (Fig. 1). Then the process is facing some difficulties; for the filling (because the mould is already hot when injecting the resin which could create some pre-curing problems and blocking the injection system); for the long cycle time (due to low curing temperature and then low curing speed); for the dimensional stability and part wrapping when extracted (due to high extracting temperatures leading to a complex conformer step after part extraction). These difficulties could now be overridden by using induction to heat the tool surface.

Fig.1 Conventional thermal cycle.

Tool Surface Heating Dedicated to RTM Technology

RocTool has developed a core technology dedicated to several processes which permits to transform plastics and composites very quickly. This Tool Surface Heating Technology uses an inductive phenomenon which heats mainly the tooling surface of the mould instantaneously. Hence, it permits to decrease a lot the energy consumption compared to the classical process which needs to heat the whole mould, and aborts all possibilities of cycle heating and cooling in an industrial configuration [5]. As seen previously, the lower the injection and extraction temperature and the higher the curing temperature, the better the RTM process would perform (Fig. 2). TSHT with its ability of heating and cooling the mould surface instantaneously allows having different temperature steps during the whole molding process [6].

Resin injection is carried out at a quite a low temperature, with no risk for resin pre-curing and injection system blocking, a good resin rheology optimization (due to a better and a faster filling of the mould) and enabling the use of very reactive resins. Once the mould is filled with the resin, thanks to the TSHT, the mould is heated at a high temperature to cure the resin with a reduced cycle time by fast resin curing (due to high mould temperature), and increases the flexural strain and at the same time decreases the residual styrene.

Then the mould is cooled down using water channels which are closed to the mould surface, there is no warpage as the part is cooled down in the mould, therefore no need for an expensive post-conforming machine. When the mould opens, the part is cold, ensuring a safe extraction of the part and a good surface quality as allowed by cold part extraction.

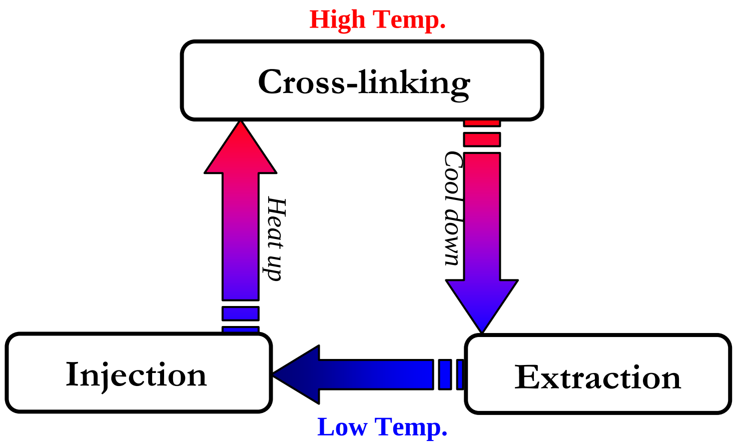

Fig. 2 New thermal cycle.

TSHT Improved to Flexible Membrane Processes

For some RTM applications the flexible membrane processes may be preferred [7]. We have found interest in this transformation of the TP configuration for small and medium size series [8]. The advantages of these « closed moulds » solutions are in the fact that, to have clean process and limited styrene emission. They noticeably reduce the cost of tools while realizing better parts from the compression point of view and from the transformation point of view with an a void content level, far superior to the traditional RTM methods. At last, such a device allows realizing parts of complex shape, notably non developable geometries, thus ensuring a more homogeneous pressure control.

The Cage System® has therefore been orientated to integrate a flexible membrane system, while conserving its principal advantages as written earlier, to propose a new attractive and compatible solution with the specifications of the RTM process.

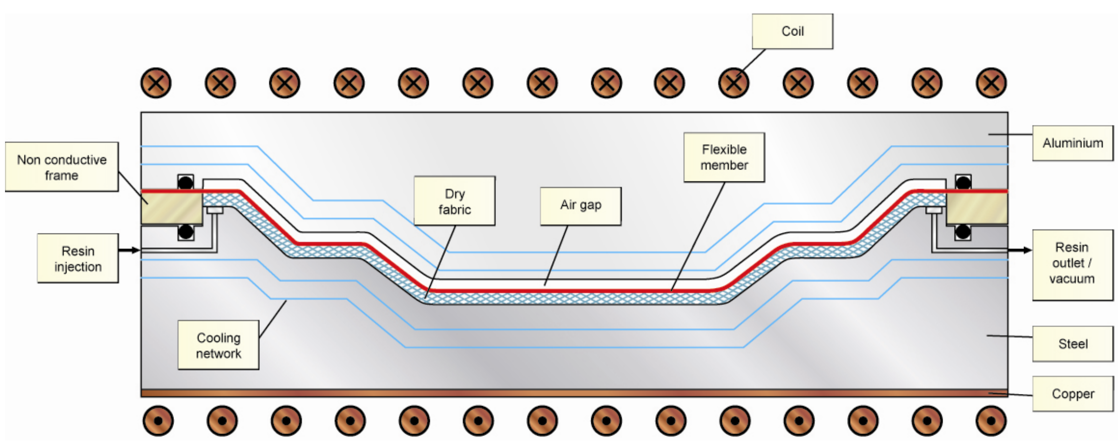

Fig. 3 New configuration.

As described in Fig. 3, as a substitute to the traditional core made out of steel, an aluminium core which generates an air-gap far superior to the previous configuration and avoids the moulding role, allowing to integrate a flexible membrane system. With a simple design, this aluminium tool has little reaction to induction, therefore keeps its electro-conductive effect and its role in the air-gap. Therefore, we consider the output to be around twice that of a steel/steel configuration.

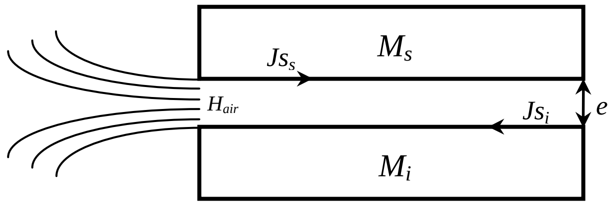

Fig. 4 One zone fundamental schematic.

Fig. 4 shows a top M_s and bottom material M_i respectively defined by their electrical resistivity ρ and relative magnetic permeability μ_r. Also represented in this diagram, the surface current densities that circulate on the body surfaces, M_s and M_i, are denoted by Js_s and Js_i respectively. The magnetic field in the air is H_{air}. If we translate the magnetic flux conservation in the air-gap between these two bodies M_s and M_i, we can write:

$$\mu_s.\delta_s.Js_s + B_{air}.e + \mu_i.\delta_i.Js_i = Cste \quad (1)$$

With μ_s, the magnetic permeability that represents the product of the magnetic permeability in air μ_0, by the relative magnetic permeability to the concerned bodies μr_s. In the end, δ_s, the electromagnetic skin depth, represents the penetration of the magnetic field and the location of induced currents. The magnetic induction, B_{air} , is the product of the magnetic permeability in air μ_0 by the magnetic field in the air-gap H_{air}:

$$\mu_s = \mu_0.\mu r_s \quad (2)$$
$$\mu_i = \mu_0.\mu r_i \quad (3)$$
$$B_{air} = \mu_0.\ H_{air} \quad (4)$$

Therefore, if we integrate (2), (3) and (4) in (1), we obtain:

$$\mu r_s.\delta_s.Js_s + H_{air}.e + \mu r_i.\delta_i.Js_i = Cste \quad (5)$$

Knowing that the electromagnetic skin depth expresses itself according to the frequency F, the electrical resistivity ρ and the relative magnetic permeability μr, as follows:

$$\delta \sim (1/F)^{1/2}.(\rho\,/\mu r)^{1/2} \quad (6)$$

By incorporating (6) in (5), we get:

$$(\rho_s.\mu r_s)^{1/2}.(1/F)^{1/2}.Js_s + H_{air}.e + (\rho_i.\mu r_i)^{1/2}.(1/F)^{1/2}.Js_i = Cste \quad (7)$$

Therefore we discover the term source, H_{air}, as well as the electromagnetic definition of a material that we will call M, defined as the square root of the electrical resistivity by the relative magnetic permeability:

$$M_s \, . \, F^{-1/2} \, . \, Js_s + H_{air} \, . \, e + M_i \, . \, F^{-1/2} \, . \, Js_i = Cste \qquad (8)$$

Let us analyze this relationship. If the air-gap is reduced, we obtain a higher magnetic field H_{air}. If we work at a higher frequency F, a higher magnetic field effect is created since the magnetic field is concentrated in a lower magnetic skin depth.

Finally, if we put in place a configuration with two materials which both possess electromagnetic properties M_s, low as aluminium, compared with a material with electromagnetic properties M_i, high as magnetic steel, we will obtain a strong magnetic field effect H_{air}, and on material M_i a good output. This improves the output of this configuration, compares to the two magnetic steel configuration ($M_i = M_S$).

Effect of a Variable Air Gap

However to reduce the cost of a tool significantly, this offers more potential for the adjustment of the process and for obtaining a good heating quality. The internal surface of this aluminium core does not have a moulding function, neither from the mechanical nor the thermal points of view. Therefore one can work out a more flexible strategy to obtain an even surface heating.

As observed in Fig. 5 with inductive surface heating, one must consider a double effect on the geometrical shape. A thermal effect which has the tendency to accentuate surface heating on the convex radii, concentrating on the thermal diffusion throughout the surface around the moulds interior, but we must integrate a stronger local inductive effect, a stronger concentration of the magnetic field on the same convex zones, the magnetic field will follow the shortest path possible. The inverse phenomenon can thus be explained, with a thermal effect on the concave radii, naturally and easily dissipated within the mould, to add a weaker concentration of the magnetic field locally. Thus, one can conclude quickly on the different under-heating and over-heating that one may observe along a given geometry.

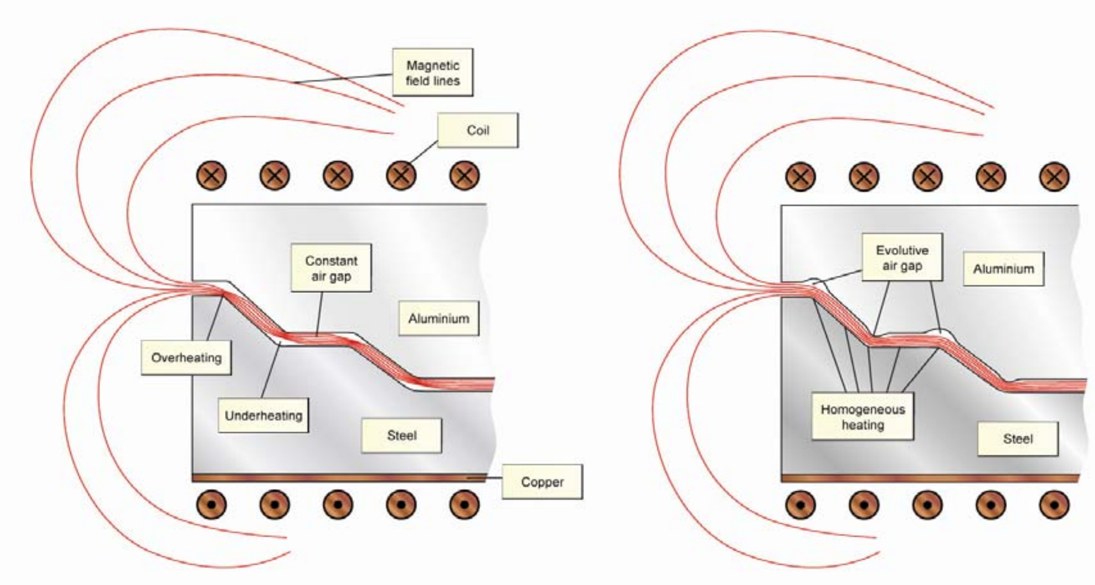

Fig. 5 Effect of air-gap on the magnetic field.

Therefore, to detail the relationship (8), in generating variable air-gaps, at our convenience we can, measure the magnetic field effect to return a homogenous thermal response to the surface of a tool, while applying a term source superior to the one applied on the straight zones, on the radii naturally under heated and inversely a term source inferior on the zones naturally under heated (Fig. 5). Therefore the air-gap effect, which is not simply linear, is to integrate in a body of other parameters as describes hereafter in the Fig. 6.

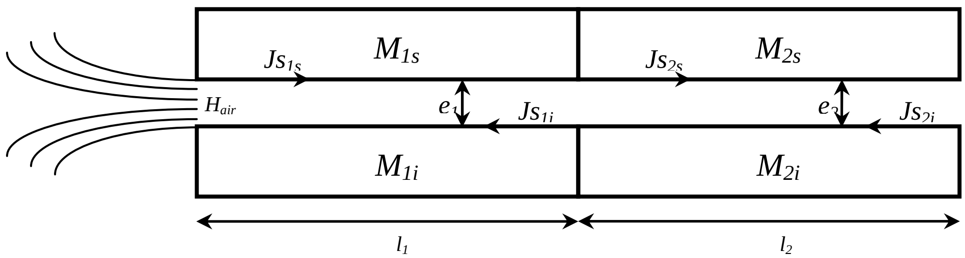

Fig. 6 Two zone fundamental schematic.

Let us write Ampere's theorem for this configuration:

$$Js_{1i} = Js_{1s} \tag{9}$$

$$Js_{2i} = Js_{2s} \tag{10}$$

As well the total current injected is defined by:

$$Js_{1i} \,.\, l_1 + Js_{2i} \,.\, l_2 = I_0 \tag{11}$$

The defining relationship (11) represents in this case the magnetic flux conservation from zone 1 to zone 2. It can be formulated in analogy to relation (1), having after integrated this term on the boundary $Js_{1i} = H_{air}$:

$$\mu_{1s} \,.\, \delta_{1s} \,.\, Js_{1s} + B_{air}.e_1 + \mu_{1i}.\delta_{1i}.Js_{1i} = \mu_{2s} \,.\, \delta_{2s} \,.\, Js_{2s} + B_{air}.e_2 + \mu_{2i}.\delta_{2i}.Js_{2i} \tag{12}$$

Thus, while substituting (9) and (10) in the equation (12), we obtain a first simplified expression:

$$Js_{1i}\,(\mu r_{1s} \,.\, \delta_{1s} + e_1 + \mu r_{1i}.\delta_{1i}) = Js_{2i}\,(\mu r_{2s} \,.\, \delta_{2s} + e_2 + \mu r_{2i}.\delta_{2i}) \tag{13}$$

At last, we determine a complete form of Js_{1i} and Js_{2i} by substituting (11) in (13), where A is an inversely proportional variable to the frequency:

$$\mathrm{Js}_{1i} = \frac{I_0\left(A\left(M_{2i} + M_{2s}\right) + e_2\right)}{l_2\left(A\left(M_{1i} + M_{1s}\right) + e_1\right) + l_1\left(A\left(M_{2i} + M_{2s}\right) + e_2\right)} \tag{14}$$

$$\mathrm{Js}_{2i} = \frac{I_0\left(A\left(M_{1i} + M_{1s}\right) + e_1\right)}{l_2\left(A\left(M_{1i} + M_{1s}\right) + e_1\right) + l_1\left(A\left(M_{2i} + M_{2s}\right) + e_2\right)} \tag{15}$$

To explain these relationships, we simply (14) and (15) for the aimed configuration, in other words, an aluminium core positioned in front of a magnetic steel cavity ($M_{1i} = M_{2i} = M_i$ and $M_{1s} = M_{2s} = M_s$), with two zones of the same length ($l_1 = l_2 = l$), but the air-gap e_2 will be five times larger than e_1 ($e_2 = 5\ e_1$ with $e_1 = e$ given as reference in the straight zones). Thus,

$$s_{1i} = \frac{I_0\left(A\left(M_i + M_s\right) + 5e\right)}{l\left(2A\left(M_i + M_s\right) + 6e\right)} \quad (16)$$

and

$$Js_{2i} = \frac{I_0\left(A\left(M_i + M_s\right) + e\right)}{l\left(2A\left(M_i + M_s\right) + 6e\right)} \quad (17)$$

Therefore

$$Js_{1i} > Js_{2i} \quad (18)$$

This increased control of heating process, allows, after a numerical simulation stage to validate a rough analytical analysis, to define the outline of the aluminium core, generated from the air-gap variables, with the objective of obtaining a thermal fine optimized response.

CONCLUSIONS

This reflexion, initially based on a thermal analysis, presents for all heating and/or cooling processes with a thermal response that is coming from a given geometrical shape. It is necessary at the end, to apply all different source terms to obtain an identical thermal response, by freeing itself with thermal diffusion effects in the tool.

This new configuration should allow, while using a purely inductive effect, to optimize the RTM processes, because if the cross-linking and cooling times are optimized, with a gradient of temperature in surface as reduced as possible, it will have a positive impact on the intrinsic quality of the part.

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