

INTEGRATION OF COST MODELS AND PROCESS SIMULATION TOOLS FOR OPTIMUM COMPOSITE MANUFACTURING PROCESS

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Abstract

Manufacturing cost of resin transfer molded composite parts is significantly influenced by the cycle time, which is strongly related to the time for both filling and curing of the resin in the mold. The time for filling can be optimized by various injection strategies, and by suitably reducing the length of the resin flow distance during the injection. The curing time can be reduced by the usage of faster curing resins, but it requires a high pressure injection equipment, which is capital intensive. Predictive manufacturing simulation tools that are being developed recently for composite materials are able to provide various scenarios of processing conditions virtually well in advance of manufacturing the parts. In the present study, we integrate the cost models with process simulation tools to study the influence of various parameters such as injection strategies, injection pressure, compression control to minimize high pressure injection, resin curing rate, and demold time on the manufacturing cost as affected by the annual part volume. A representative automotive component was selected for the study and the results are presented in this paper.

1. Introduction

Structurally reinforced (SR) composites where a liquid-like resin is introduced by a pressurized injector and then penetrated within a preform lay-up of fibers in a mold at an elevated temperature are widely used in structural applications in aerospace and automobile industries [1]. This resin transfer molding process (RTM) can be utilized to manufacture large and complex geometries and allow consolidating multiple parts in a single part substantially reducing the cost of components of an assembly. Moreover, load-bearing property can be tailored by different strategies of lay-up built and a choice of a reinforcement material in the RTM process. Bader [2] compared several reinforcing fibers for mechanical properties versus the cost of their performance in the form of pregreg laminates, and concluded that the high strength carbon fibers were the best choice for cost efficiency and lowering mass. In the cost variants of different manufacturing processes, it is evident that a dominant cost factor comes from raw materials in making the composites parts. Akermo and Astrom [3] developed a cost model for different manufacture processes of reinforced composites compared to the metal-based stamping process. They found that the molded composite components were cost-competitive with the steel components in relatively small production volumes, because the higher cost of the raw materials in the composites components could be compensated by the expensive tooling.

The liquid composite molding process encompasses a series of manufacturing steps, namely injection, curing and demolding. During the injection stage, the viscous resin impregnates the preform under a thermal cycle in a heated mold. The filling time for the infiltrating formulated liquid resin can be adjusted by several operation parameters, such as permeability of fibers, viscosity of the infiltrated resin, injection pressure and curing temperature as well as the number of inlets and outlets of the mold. Verry *et al* [4] demonstrated that the effective cycle time was mainly driven by the different characteristics of curing/polymerizing processes when the floor pan was thermally molded with either the formulated thermoset resin or the activated monomers, which resulted in 22% increase of the part cost in case of the polymerized floor pan due to the longer thermal cycle time at the closed mold stage. Thus, a well characterized thermal cycle in the given operation window could be a key factor to manufacturing cost-competitive composite panels for high production volumes. In this paper, the cost models for several variants of resin transfer molding are developed and evaluated for difference manufacturing scenarios. In parallel, the PAM-RTM computer program was utilized as a predictive manufacturing simulation tool to optimize the processing parameters, such as injection pressures and injection locations for a representative automobile component and results are presented.

2. Methodology

Processing parameters in resin transfer molding (RTM)

RTM has a lot of advantages in several aspects. For example, a wide range of low viscosity resins and different fibers materials can be used for both small and large composite components. It is also beneficial for engineering designers to achieve complexity architectures, which often requires different surfaces finished at the end product. Moreover, a simple thermal molding process makes it easier to produce a constant quality of the end product [5]. However, poor processing parameters can result in the undesired thermal-mechanical problems, such as delamination and

warping of the components due to the mold deformation and inefficient heating and cooling systems [6]. Thus, optimizing process parameters is critical to minimize the development of internal residual stresses and maximizing the efficiency of thermal molding cycles.

Filling and curing time in RTM are regarded as key parameters directly influencing the cycle time that is substantially dedicated in the part cost. Conventional RTM, due to a lower injection capability, requires relatively longer time for filling the resin and thus the total cycle time increases. If fast curing resins are used, this can potentially increase a risk of the unfilled area obtained at the end of the process because of an existence of the partial cured resin at up-front. This obstacle, in some cases, can be overcome using a higher compression pressure of the hydraulic injection during the filling process. This improved capability in injection pressure can not only lead to a faster filling time. On the other hand, the HP- RTM process needs an expensive capital investment for the injection equipment and also requires a high capacity of press tonnage to use for large size components. An injection-compression resin transfer molding (C-RTM) is an attractive manufacturing process in reducing the fill times for the resin transfer and thus decreasing the total cycle time in pressing during an open-closed molding process. These continuous processes in resin transfer molding require optimizing processing parameters, such as gap size for injection, injection pressure, the tonnage to squeeze the resin into the preform, etc.

Cost modelling

The cost modelling used in this study was based on the total cost of manufacturing processes in which the costs of fixed and variable elements were estimated on a production volume of components. In the present cost modelling approach, every task in fabrication to be independently accounted into the cost variations. As a result, the input factors in the model, such as permeability, temperature and reaction kinetics as well as injection pressure, were considered as a root cause of the variables and fixed costs, which could result in determining the total cost of each equipment and tooling at each fabrication. Additionally, it was assumed that machinery, tooling and facility were linearly depreciated by a period of the usage and their costs were amortized over the life time of the product. In particular, the total tooling costs were calculated by the basis of one complete tool set, which was used over the total cycles time required for the production capacity. More detail of the fixed costs in the process based cost model was founded elsewhere and a summary of the general assumptions used in the cost modelling study were tabulated in Table 1.

Since the scope of this paper aimed to predict an optimization of processing strategies in correlation with cost-competitive fabrication parameters, we assumed in the cost model that the total manufacturing cost per part were only driven by a change of the manufacture processing factors. As a result, the total cost per part in the fabrication of RTM was significantly affected by the different processing variables in curing and filling the resin in the mold. For example, in the filling time, permeability and viscosity were a main factors driving the cost, which was coordinated with a mold geometry and an injecting pressure. On the other hand, in the curing time the reaction kinetics, i.e. activation energy and reaction rates, which were based on temperature and an efficiency of the catalysis, could play a significant role on determining a total time of the thermal cycle in mold and later influence to an optimal demolding process. Therefore, the time for either filling or curing resin was the primary variables to evaluate the different processing strategies and to validate the optimized injection strategies by comparing the cost per part from each strategy in injection location. The following paragraphs were more described in the

predictive manufacturing simulation of the injection locations with a representative automobile component.

Table 1: General assumptions in the cost modeling

PRODUCT	<ul style="list-style-type: none"> • Anneal production volume: 80,000 /year • Production operation life: 7 years
LABOR	<ul style="list-style-type: none"> • Working days: 250 day/year • Working hours: 21 hour/day • Working shift: 3/day
ENERGY	<ul style="list-style-type: none"> • Electricity cost: \$0.09/kWh • Electricity downtime/uptime usage: 80%
FACILITY&EQUIPMENT	<ul style="list-style-type: none"> • Idle space: 25% • Installation cost: 20% • Maintenance cost: 10% • Facility recovery life: 15 year
CAPITAL INVESTMENT	<ul style="list-style-type: none"> • Recovery rate: 15% • Recovery life: 10 year

Predictive manufacturing simulation

The predictive manufacturing simulation tool used was the PAM-RTM computer program. An automotive assembly of dimensions 2000 mm x 800 mm x 1.8 mm was chosen for study. The mold temperature was assumed to be 130°C and at this temperature the resin viscosity was assumed to be 0.015 Pa.s. The two layers of a preform [0/45/-45/90] were laid up to make a quasi-isotropic symmetric laminate. The permeability of the dry fabrics at the preform was assumed to be $3.5E-11$ m² isotropic in the plane of the laminate. The porosity of the preform was set to be around 50%. Different injection strategies were studied to analyze the processing conditions required for a successful molding. For conducting simulations with the PAM-RTM, a two-dimensional finite element models were developed and Darcy's equations were solved to study the resin fill time for the component.

The first design considered the injection gate on the shorter edge of the rectangular panel with a constant flow rate of 0.00004 m³/s (same as below). A perfect vacuum condition was assumed for the mold. Without considering the limitation of the pressure at the injection gate, the simulation predicts that the injection time is around 36 seconds and the maximum pressure during the injection can reach to a pressure of 237 bar. If we limit the maximum allowable injection pressure to only 20 bar and the flow rate is decreased to adjust to limit the maximum pressure, the time for filling the resin increases to around 215 seconds. The simulation results are shown in Figure 1.

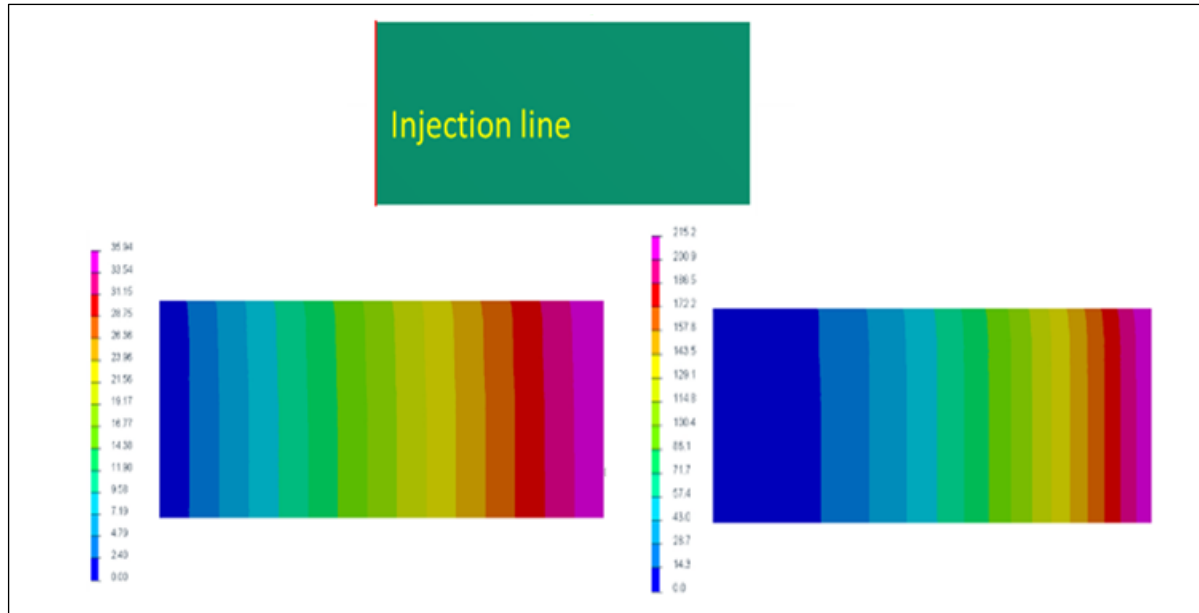


Figure 1. Injection line and the fill time contours of the panel with 237 bar and 20 bar (Injection design -1)

For the second design, the injection lines were defined on the longer side of the rectangle. As we can see in Figure 2, the fill time of the resin is around 36s without the limitation on the injection gate pressure and 44s if the maximum allowable gate pressure is limited to 20 bar. One can see clearly that the shorter distance between the injection gates and the vents, the shorter injection time needed for the full impregnation.

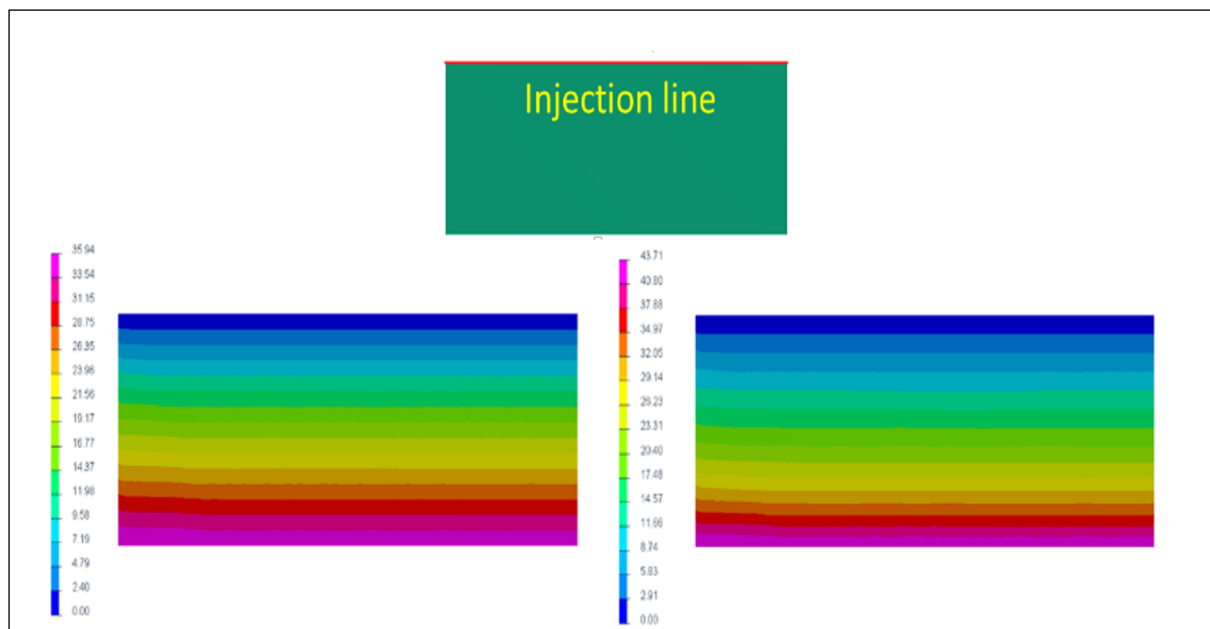


Figure 2. Injection line and the fill time contours of the panel without pressure limitation and limiting the pressure to 20 bar (Injection design -2)

An optimal injection design should strategically shorten the distance between the injection gates and the vents. For this rectangle geometry, two center lines as the injection gate runners might be an effective choice. To study this case, simulation was conducted for this injection gate design, the simulation predicts the fill time is as short as 36 seconds with a maximum pressure of 36.8 bar. When the injection pressure is limited to be only 20 bar, the fill time has increased very slightly.

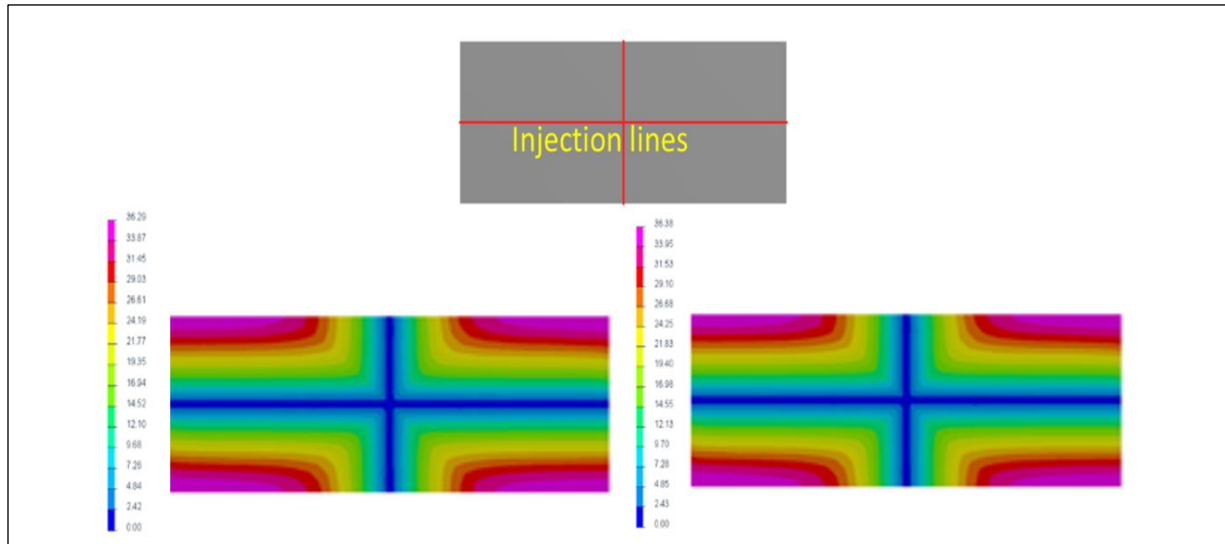


Figure 3. Injection line and the fill time contours of the panel without pressure limitation and limiting the pressure to 20 bar (Injection design -3)

3. Result and discussion

From the literature, we can observe that the manufacturing cost of the structurally reinforced composites are generally lower than that of the metal based counterparts at a relatively low volume of production. This is mainly because less expensive initial capital investments are used in the case of composites manufacture and the costs are amortized over a lifetime of production. Inevitably, at high production volumes the additional equipment and tooling have to be implemented in order to meet the required production capacity, which results in the fact that the expenses of the additional equipment and tooling are added to the total cost per part. On the other hand, manufacturing cost of the metal based counterparts are noticeably reduced over the production operation lifetime, even more effectively decreased when it is in a series of high production volumes in cases of the stamped steel-based parts, despite of the fact that the initial capital investments are much higher. Thus, it is very critical to address all aspects of the manufacturing cost at the beginning of the development of composite parts to minimize the additional costs at a high production volume. The resin transfer mold (RTM), which is the interest of current study, can produce a higher quality of the parts, which strongly relies on the manufacturing processing strategies. For example, the filling and curing time, as stated in the

previous section, are significantly affected by permeability and temperature, respectively. Moreover, the property of permeability can mainly result from the different stacking sequences of the fabrics plies, which eventually alters to a change of flow direction through the thickness. This results in the different filling time. In the present study, we have a different approach to address the filling time by different injection pressures, injection locations and mold temperatures. Therefore, in the cost model that we developed in this study, both permeability and flow rate are the given factors. The time to cure a resin, another important processing variable, is strongly dependent of temperature and the reaction rates for formulated resins with an optimized curing agents, which is defined of how fast the filled resin is cured in the mold. Therefore, in order to demonstrate how to alter both the filling and the curing time for cost aspects, we choose two different resin systems in a coefficient of the reaction rate and we assume that the slow curing resin system is 10 times slower than the fast curing resin system for curing, which can lead to the different cost variations in the cost model. Moreover, the demolding time is another factor for the curing time to be affected significantly, which will be addressed in the next section. For the analysis of the cost modelling in a chosen geometry, the given input parameters of the RTM manufacturing process are tabulated in Table 2.

Table 2: RTM manufacturing processing parameters.

➤ Input Parameters:	
•	Flow rate: 0.00004 m ³ /s
•	Viscosity : 0.015 Pa.s
•	Permeability : 3.5E-11 m ²
•	Porosity : 50 %
•	Total Volume: 1.44E-03 m ³
•	Total Weight: 7.186 kg
•	Degree of Curing at Demold : 95%

Cost variations of the slow/fast curing resin systems in constant flow rate (CFR)

For the case of modeling in the mode of the constant flow rate, it was assumed that the resin flow was driven by a local difference in injected pressure during the filling process so that the time for filling a nominal part with a resin was a function of the permeability, which was constant in the cost model. As a result, the filling time was 18 seconds at either the slow curing or the fast curing resin system. Thus, the total time for the throughput cycle was mainly influenced by the time of curing resin. Figure 4 shows the curing time plotted on a logarithm scale on Y-axis with temperature on X-axis. On the same plot, the manufacturing cost also plotted on the Y-scale using a dot-line curve. It can be seen that at 110°C, the fast curing resin cures in about 300 seconds while the slow curing resin requires around 3000 seconds. This large reduction in the curing time for the fast curing resin can result in a sufficient cost saving per part. The manufacturing cost per part can be reduced from \$160 to \$60 and more cost saving per part for the fast curing resin can be achieved by switching the mold temperature from 110°C to 130°C. Moreover, from the figure an interesting feature can be seen that a relatively large reduction in the cost per part is obtained

in the slow curing system in comparison with that from the fast curing resin, although the curing time for the slow curing resin is still required over 1500 seconds even if the mold temperature is increased from 110°C to 130°C. This cost variations can be explained by the fact that the fixed costs of the slow curing resin at 110°C is dramatically reduced by the little increase in the curing temperature, which is shown in Figure 5. This reduction from the fixed costs is mainly achieved from a decrease of the cycle time.

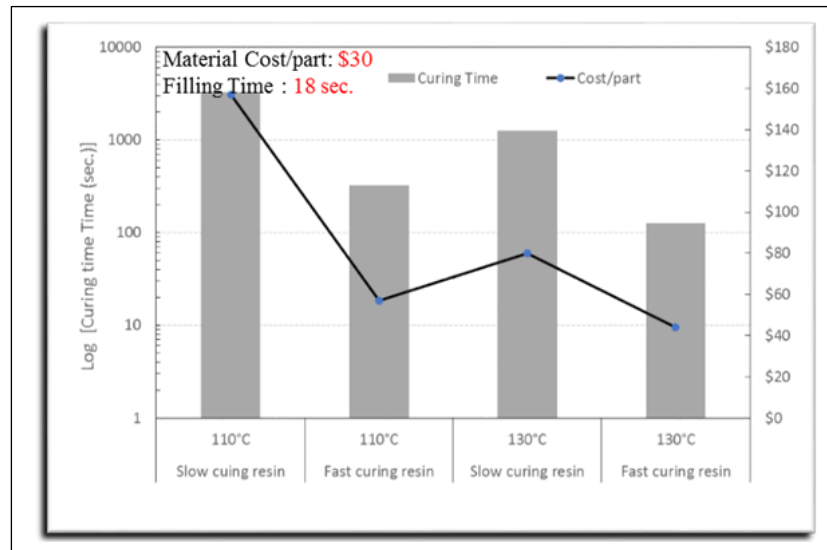


Figure 4. Curing time vs curing temperature and cost/part in CFR.

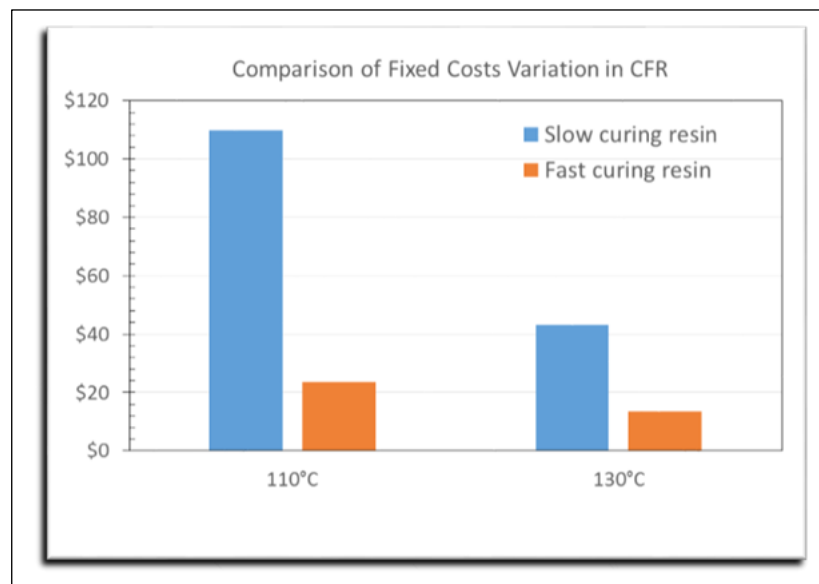


Figure 5. Comparison of fixed costs variation in CFR.

Cost variation of the slow/fast curing resin systems in constant pressured filling (CPF)

In contrast to the constant flow rate, in this section, we studied the filling of the resin by the constant pressure. In the cost model, the amount of the resin flow was only dependent of how much pressure was used for injection so we assumed that the slow curing resin was injected at 2 bar and the fast curing resin was injected at 80 bar, which could mean that the slow curing resin had less expensive injection equipment and the longer time was required to inject the resin. On the other hand, for the case with a shorter resin fill time, the fast curing resin was expected to be injected at a high pressure provided by the more expensive injection equipment. As we can see in Figure 6, the time for filling the slow curing resin increases from 18 seconds to about 110 seconds with the curing time being same as before. This would cause an increase of the cost/part if other costs are remain constant within the thermal cycle. However, as seen for the cost/part from Figure 6 and Figure 7, the cost decreases from \$160 to about \$110. This may imply that the mold tonnage required to fill the slow curing resin within 18 seconds at the constant flow rate is much higher than that required at 2 bar injection pressure in the mode of the CPF. Thus, the fixed costs is noticeably reduced from \$110 to \$65, which is shown in Figure 5 and 7. This effective fixed costs become highly cost-competitive when the slow curing resin is cured at 130°C, where the fixed costs of the slow curing resin is lower than that of the fast curing resin at 110°C. The smaller fixed costs can lead to the fact that by switching from CFR to the CPF in resin flow mode, the cost/part of the slow curing resin at 130°C is reduced from \$80 to about \$60 and then becomes closer to the cost/part of the fast resin cured at 110°C in CPF.

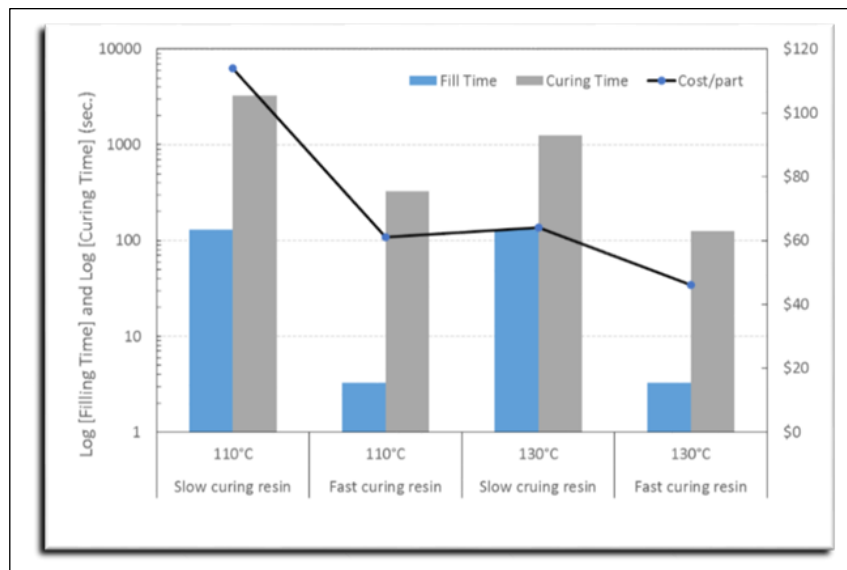


Figure 6. Curing time vs curing temperature and cost/part in CPF.

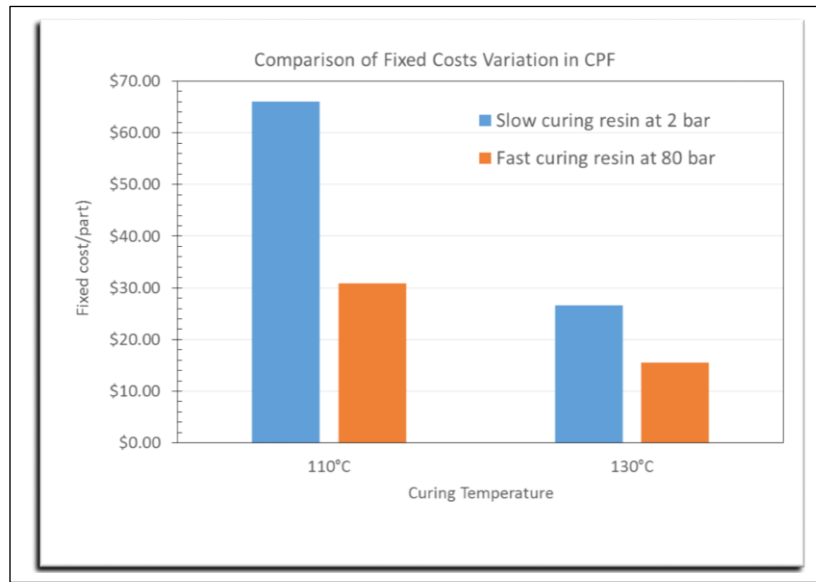


Figure 7. Comparison of the fixed costs variation in CPF.

Cost variations of the slow/fast curing resin systems with various production volumes

Although we showed in the previous section that the slow curing resin system was cost-competitive when it was injected at the lower pressure and higher curing temperature, the fast curing resin system could be highly cost-effective in high production volumes in the mode of the CPF. In order to demonstrate this notion, we conducted a study with our cost models to determine the cost variations including the production volume as a variable. The material costs of the preform fabrics were constant when either the slow curing resin or the fast curing resin was used. Figure 8 presents the cost/part for the two resins systems under study at different molding temperatures. One can see that as the production volume is gradually increased to 15k, the cost/part reduces. At all the production volumes, the fast curing resin system is cost-competitive over the slow curing resin system. Moreover, the variations of the cost/part are fairly constant over the series of the production volumes, except the one from the slow curing resin system cured at 110°C. In the case of the slow curing resin system cured at 110°C, the time for curing is high and to meet higher production volumes, more tool sets are needed and thus increases the manufacturing cost from the fixed elements, such as machinery, tooling and overhead labors. The difference in the cost/part between the slow curing resin and the fast curing resin when they are cured at the lower temperature is much higher than that in the two resin systems cured at the higher temperature. Additionally, the magnitudes of the difference between the two cured resin systems at the lower temperature gradually increase as the production volume is increased, which is shown in Figure 9. Therefore, the fast curing resin system is cost-competitive in cost/part in the series of high production volumes in the mode of the constant pressured injection.

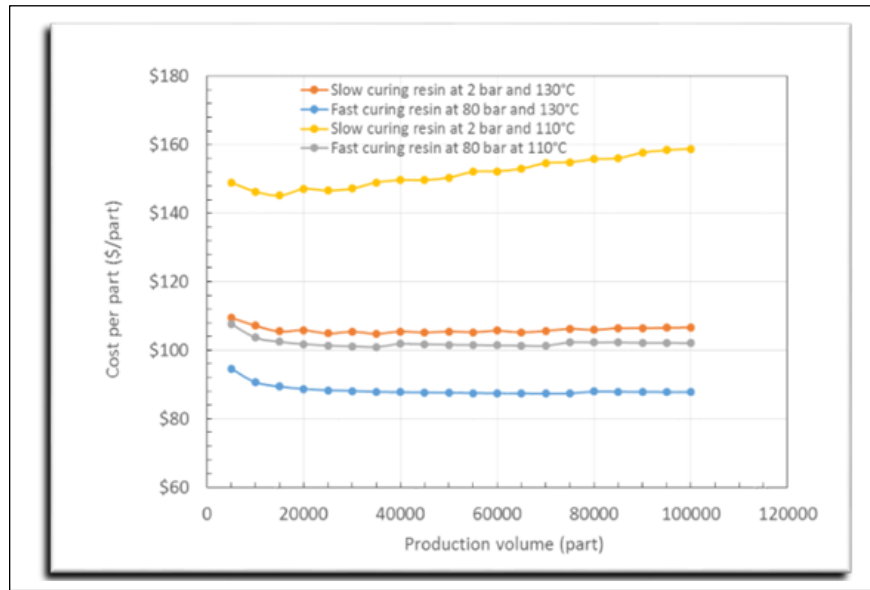


Figure 8. Cost/unit vs production volume with the slow/fast curing resins systems in the mode of the CPF at different curing temperatures.

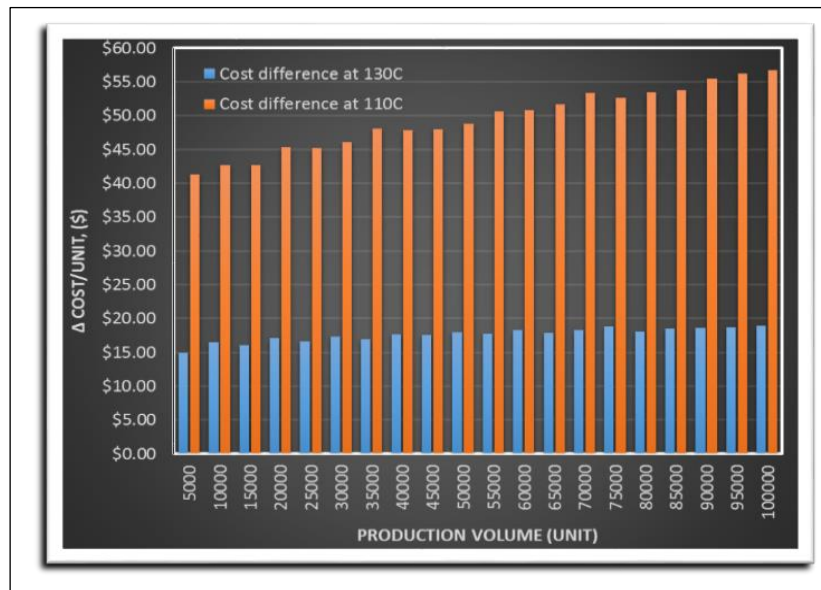


Figure 9. The difference in cost/unit vs production volume with the slow/fast curing resins systems in the mode of the CPF at different curing temperatures.

Manufacturing cost in the ratios of demolding time to curing time

The demolding process is one of the important thermal cycle steps during the molding. The time at which demolding is done is directly relevant to the total cycle time and thus throughput. The degree of curing resin can be adjusted by a relation between the curing time and the demolding time during the molding process. Lowering the demolding time can reduce the thermal cycle time and increase throughput, but less cured resin can pose serious challenges in integrity and handling. Thus, the optimization of the demolding process is a critical aspect to either the cured integrity or the mold maintenance. In this section we explore an optimizing relationship of the ratios of the demolding time to the curing time. The estimate of cost variations from the different ratios at the different curing degrees are presented in Figure 10 and Figure 11. From the figures, we can see that the highest cost/part is obtained when it is at the ratio of 0.9 in any curing degrees for either the slow curing resin or the fast curing resin. Additionally, in the case of the slow curing resin system, the cost variations become steep as both the degree of the curing and the ratio of demolding/curing time increase. For the fast curing resin system, the cost variations are marginally increased until the degree of curing is 90%. After that, we can still see an increase of the cost/part at 95% and 98% curing degrees but their cost variations are fairly narrow within the three different ratios. These cost variations of the two resins systems in the different rates of curing are more clearly seen in the average of the cost/part at the three different ratios, which is shown in figure 12. In the figure, the average cost/part in the slow and fast curing resins are relatively constant until 80% curing degree. For the slow curing resin system, the average cost/part increases steeply compared to the fast curing resin system after the 80% curing degree. This demonstrates that the fast curing resin system is much less cost-sensitive to the demolding process compared to the slow curing resin system.

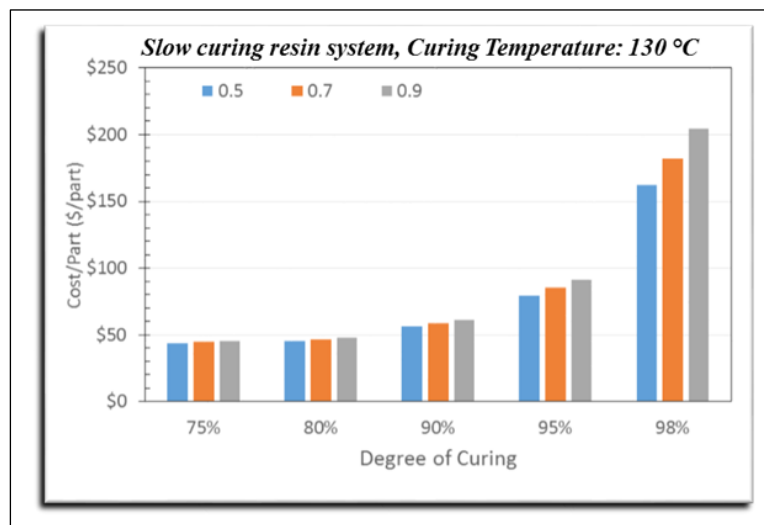


Figure 10. Cost/part vs the degree of curing at curing temperature 130°C in the slow curing resin system with the different ratios of the demolding time/curing time.

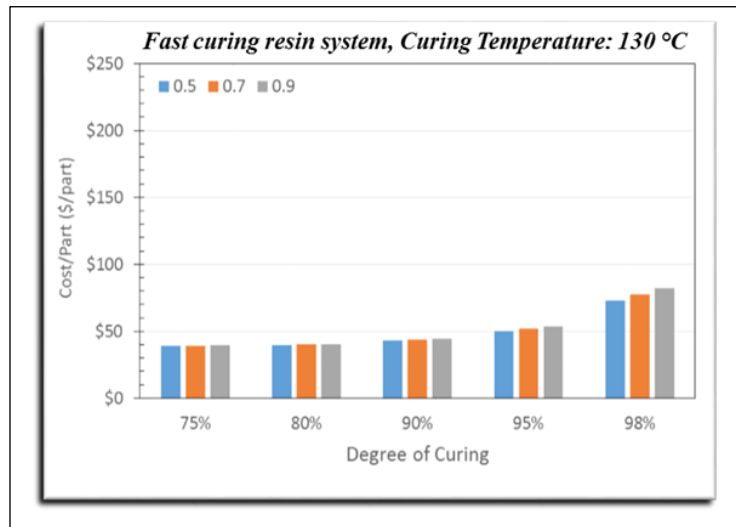


Figure 11. Cost/part vs the degree of curing at curing temperature 130°C in the fast curing resin system with the different ratios of the demolding time/curing time.

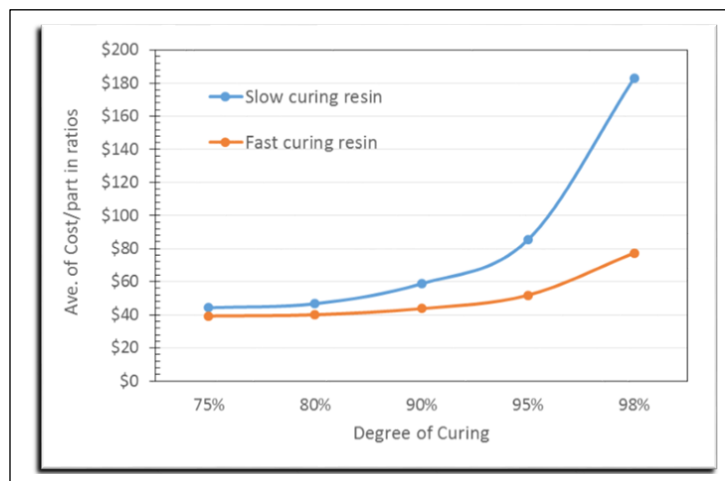


Figure 12. Average of cost/part vs the degree of curing at curing temperature 130°C for the two curing resins systems.

Cost variations of the three simulation strategies in injection location

In this section, we studied the influence of the injection strategy on the manufacturing cost. In the injection simulation model at the methodology section, the maximum injection pressure was dictated by the geometry of the component and the maximum pressure allowed for injection relied on the injector capacity of the equipment. Figure 13 presents the cost/part for the three different injection strategies, namely short-edge injection, long-edge injection and center injection. We can see from the results that in the case of the injection from the short-edge location, the cost/part in

the mode of the CFR is higher than that from the 20 bar of the CPF due to the higher costs added in the equipment and tooling compared to some cost penalty added from the longer filling time. Moreover, the cost variations of the short-edge injection are much higher than those of either the long-edge injection or center injection strategy because of the higher costs of the fixed elements and an increase in time for filling the resin.

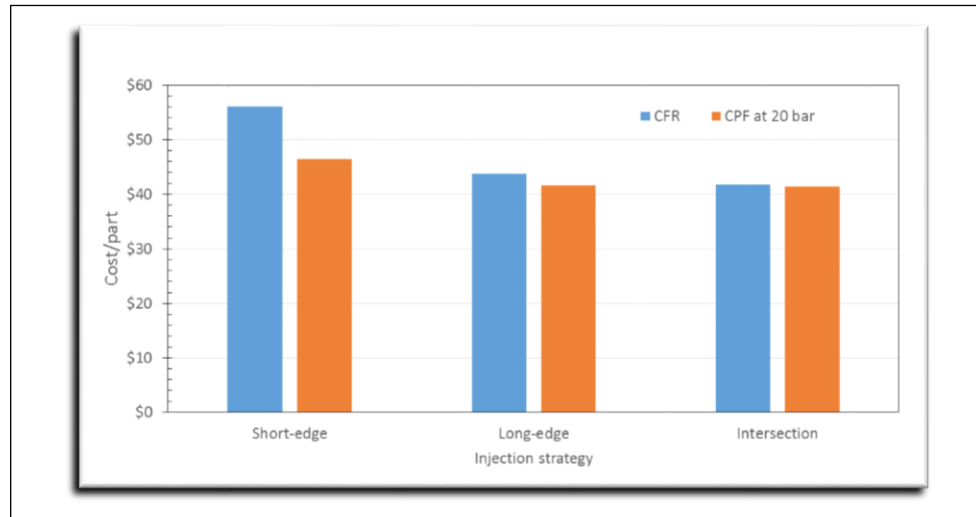


Figure 13. The cost variations of the three injection strategies in the representative automobile component.

4. Conclusions

- Integrating the cost models and the process simulation tools to study the manufacturing cost of a representative automotive composite part molded using resin transfer molding (RTM) was found to be very informative. A fast curing resin as well as a slow curing resin were considered for the study.
- Increasing the mold temperature of fiber reinforced thermoset composites reduced the curing time and thus lowered manufacturing cost. As expected, the slow curing resin showed a more favorable cost reduction with temperature compared to the fast curing resin.
- Fast curing resins were cost competitive across all the production volumes studied. For the lower production volumes, even though an expensive injection equipment was needed for injecting the faster curing resin, the capital cost was compensated by the reduction in the total cycle time.
- Reducing the demolding time had a significant reduction in the manufacturing cost for the slow curing resins. For the fast curing resins, the cost reduction was marginal.
- The process simulation tools can help to determine the best injection strategies to reduce the time for filling the resin into the mold, thus helping in a significant way to reduce the

manufacturing cost. Also, the process simulation tools might guide to select the best liquid transfer molding process between HP-RTM, C-RTM and the traditional RTM with optimum processing parameters.

Acknowledgements

The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Number DE-EE0006826. The information, data, or work presented herein was funded in part by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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