EPOXY MATRIX TECHNOLOGIES ENABLE COST-EFFICIENT MASS PRODUCTION OF COMPOSITE LEAF SPRINGS

Sigrid ter Heide, Dr. Lars Moser, Dr. Ian Swentek
HEXION Inc.

Abstract

Composite leaf springs have been in use in the automotive industry for quite some time, examples include the GM Corvette, Daimler Sprinter and Volvo models from the new Scalable Product Architecture platform. Significant weight savings of 65 - 80% can be achieved compared with steel equivalents making composite leaf springs attractive solutions to comply with tightening fuel consumption and CO_2 emission reduction regulations. In addition, the weight reduction is realized in the unsprung mass leading to better driving behavior and vehicle responsiveness.

The development of optimized epoxy products for high pressure resin transfer molding (HP-RTM) technology allows large scale cost-effective production. In this paper, results of thick laminate molding demonstrate that a high conversion degree is reached with a short production cycle and post-curing can be eliminated. It is demonstrated that HP-RTM is a cost effective technology at large build rates.

Epoxy composites have gained substantial interest in aerospace, wind energy and automotive applications mainly due to their high strength, outstanding fatigue and corrosion resistance. Tests show that an optimized resin / fabric combination results in good static and dynamic mechanical properties required for the leaf spring applications. Extended tests have been performed at elevated temperature, higher humidity and in exposure to automotive fluids demonstrating that the excellent mechanical performance is maintained under application conditions. The high performance properties of epoxy matrix technology are discussed versus alternative materials.

Background

Epoxy composite leaf springs have a long application history that goes back to the first introduction in American sports cars, several generations of the General Motors Corvette have had epoxy composite transverse leaf springs in both front and rear suspensions. The use of transversal leaf instead of coil springs does not interfere with the engine packaging in the front and provides more trunk space in the rear of the car. Since 2006, epoxy composite transversal leaf springs have been successfully used in the front-axle suspension system in high volumes of the Mercedes-Benz and Dodge Sprinter and Volkswagen Crafter models (1). In 2014 Volvo introduced lightweight transverse leaf springs in the rear axle module of their luxury SUV. BENTELER-SGL mass-produces composite leaf springs for the new Volvo XC90 using Loctite Matrix resin from Henkel (2).

Due to their lightweight construction (65 – 80% weight reduction), composite leaf springs consume less fuel during vehicular operation and consequently, large energy savings can be obtained. Taking the recycling of steel and the energy recovery of the composite resin into account, the total energy consumption over the entire lifespan is much lower than of its steel counterpart as demonstrated with life cycle assessment (3) and shown in Figure 1. With the tightening CO_2 emission limits, this makes them attractive solutions for part producers and OEMs.

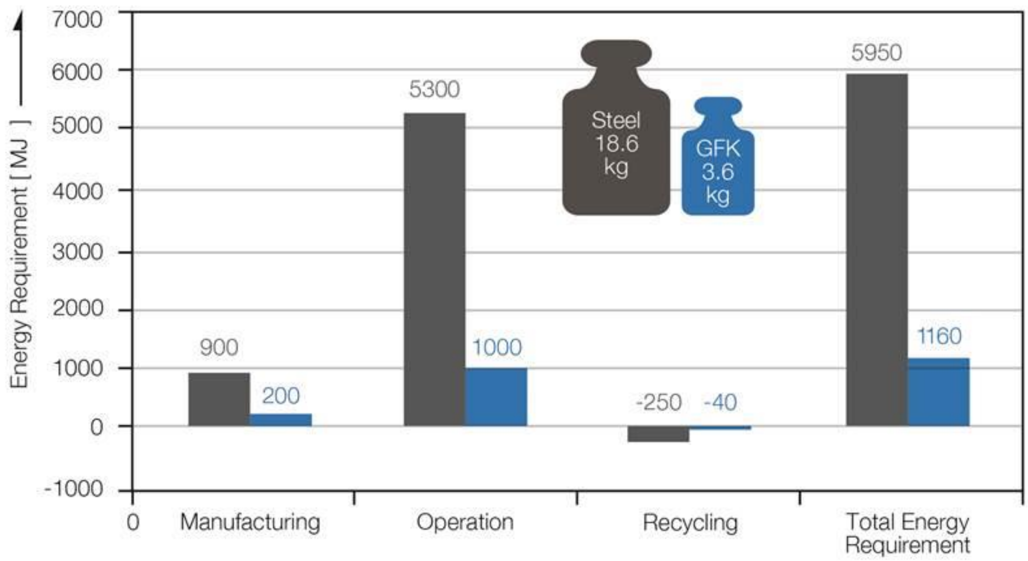


Figure 1 Overall energy balance: Comparison between steel and fiber reinforced epoxy composite leaf springs

Hexion's epoxy GFRP leaf springs have superior mechanical performance

Though different manufacturing methods can be applied for molding composite leaf springs, High Pressure -RTM (HP-RTM) is most cost efficient at high build rates. The RTM technology has a proven robustness in commercial applications and is suitable due to the availability of fast-cure resin systems and compatible internal mold release agents and preform binders.

Opposed to other materials, such as polyurethanes, Hexion's fast cure epoxy systems for suspension applications feature a unique set of properties which enables fast and robust processing. Cure times down to 5 to 7 minutes, depending on the part geometry, ensure high productivity. These fast-cure epoxy systems developed for HP-RTM processing exhibit thermo-latent behavior: the extended period of time for a mixed epoxy at the cure temperature to maintain a low viscosity. A large amount of resin is injected at low viscosity and after impregnation, rapid curing of a three-dimensional cross-linked network takes place. This allows large, multi-cavity tools to maintain the low effective curing time per part. Internal mold release agents guarantee good demolding behavior and make the per-shot application of external mold release agents unnecessary. Also, epoxy resin systems are insusceptible to humidity, which significantly contributes to robust processing. An example of an in-house molded, 30 mm thick laminate is presented in Figure 2.

Figure 2 Representative thick-sectioned HP-RTM leaf spring demonstrator

Binder stabilized fabrics are easier to handle and position in the mold which is particularly important when large ply stacks need to be handled like in the manufacturing of leaf springs. Depending on the required level of fabric stabilization, Hexion offers both non-reactive and reactive epoxy binders fully compatible with fast-cure epoxy systems.

Additional benefits of epoxy systems are the absence of GADSL-listed materials, low VOC, and long shelf life in the range of 2 - 3 years. Epoxy systems can be designed with a higher T_g for applications where the mechanical performance must be maintained under elevated temperature conditions. Table 1 shows the fast cure properties of the Hexion TRAC 06150 system comprised of EPIKOTE™ Resin TRAC 06150 and EPIKURE™ Curing Agent TRAC 06150. It can be seen that the system allows for fast conversion out of the mold eliminating the need for post cure. In a typical production setting with a multi-cavity tool, this translates to per-part cure times well below one minute.

Table 1 Conversion of glass fiber reinforced Hexion TRAC 06150 epoxy resin in thick components (30 mm)

Conversion of Hexion TRAC 06150 system (glass fiber, 58%vol.)		
Molding temperature [°C]	Cure time [s]	Degree of conversion [%]
105	600	98.5
120	300	99.2

Epoxy systems offer high levels of corrosion and chemical resistance. Cost savings can be made in comparison with metal leaf springs through elimination of anti-corrosion treatment and maintenance. In a Hexion internal study, the TRAC 06150 epoxy system was tested for stability in automotive fluids. Four millimeter thick specimens were tested according to ISO 62 and ISO 178. In short, the samples were stored in an acclimatized room for 112 days, fully immersed in a variety of automotive fluids (4). In all media, except for motor oil at 100°C, the system registered no major change in strength. In general, it can be considered that this epoxy system will maintain its mechanical properties in case of contact with automotive fluids, humidity and temperature. The static properties of glass fiber reinforced laminates are given in Table 2.

Table 2 Hexion TRAC 06150 system neat resin and composite static mechanical properties

	Neat resin	Composite (E-glass, unidirectional, 58%vol.)	Composite Hot/Wet (70°C/75% rH)
Flexural modulus [GPa]	3.0	42.0	42.5
Flexural strength [MPa]	130	1250	950
Interlaminar Shear Strength [MPa]	-	73	49

It can be seen that in addition to the outstanding processing properties of epoxy composites the mechanical behavior is most suitable for suspension applications. The generally known excellent hot/wet properties of epoxy composites can also be seen as the drop in flexural strength and ILSS is very reasonable and the modulus remains unchanged. Figure 3 illustrates the fitness of glass fiber reinforced epoxies for dynamical loading conditions. The particularly flat slope of the S-N curve shows a relatively mild decay of the static properties up to high numbers of cycles, which is critical for suspension applications.

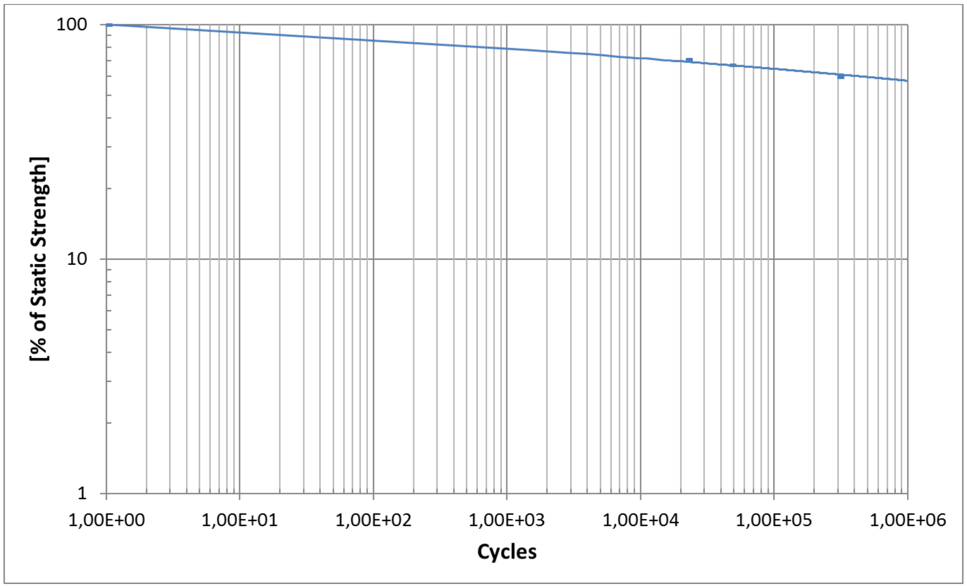


Figure 3 Fatigue performance of glass fiber epoxy composite (Hexion TRAC 06150 system)

HP–RTM technology enables cost-efficient processing of composite leaf springs

A detailed, analytical cost model was constructed to analyze the cost-saving potential of the high pressure resin transfer molding process as compared to conventional prepreg compression molding (PCM) for epoxy GFRP leaf springs. This model included pre-processing steps such as fiber preforming for the HP-RTM process or prepreg consolidation in the PCM process. Trimming and finishing operations were also included in the cost model to capture the all-in costs for each process. The processes are assumed fully automated, minimizing direct labor costs.

The analysis is based on available models from literature (5-7) under the assumptions indicated. It can be concluded that the raw material and tooling costs contribute most to the total leaf spring cost. Factors that directly affect these costs are the resin chemistry and corresponding scrap and rejection rate. The tooling costs are quite significant because only specialized toolmakers can fabricate the highly complex HP-RTM tool sets. Figure 4 shows a typical cost structure for a composite leaf spring produced in HP-RTM equipment. Case study assumes a suspension element suitable for a light-duty truck with a moderate production rate of 250k units per year with two springs per vehicle.

PART SPECIFICATIONS		
Volume fraction	58%	
Maximum Wall Thickness	28.0	mm
Projected Area	0.069	sq m
Untrimmed Weight	3.83	kg
PRODUCTION COST FACTORS		
Annual Production Volume	500	(000)/yr
Product Lifetime	7	yrs
Dedicated Equipment	1	(1=Y;0=N)
Direct Wages (w/ benefits)	$32.50	/hr
Working Days/Yr	240	
Working Hours/Day	22.5	
Capital Recovery Rate	10.0%	
Capital Recovery Period	8	yrs
Working Capital Period	3	months
Price of Building Space	$1,600	/sq m
Building Recovery Life	25	yrs
Price of Electricity	$0.126	/KWh
Fixed Overhead	22.5%	
Auxiliary Equipment Cost	12.2%	
Maintenance Cost	3.0%	
Gang molding	8	#

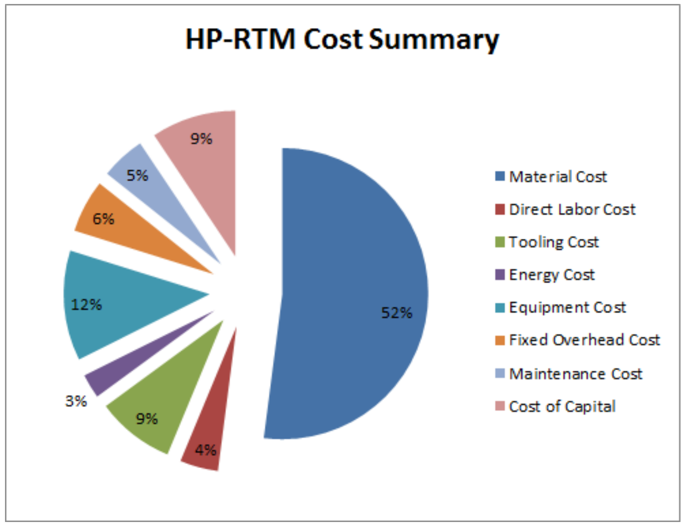
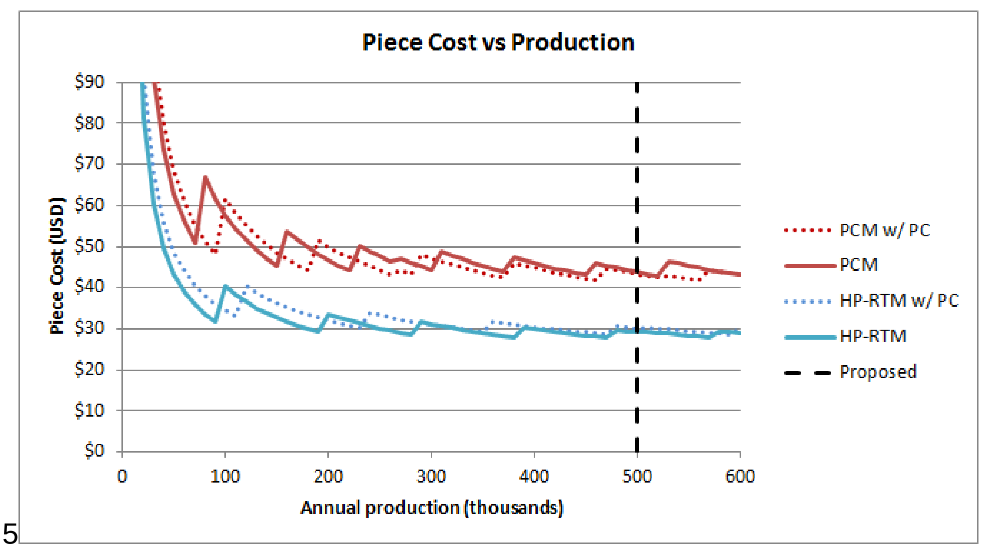


Figure 4 Cost summary composite leaf spring produced with HP-RTM according to the indicated tool specifications and production cost factors

To compare both HP-RTM and PCM on a level playing field, it was assumed that the prepreg was produced in-house with the same set of production cost factors as used for the HP-RTM analysis. The results are summarized in Figure 5, presenting the piece cost, and Figure 6, presenting the capital investment.

At low production volumes, it is proper to expect that prepreg would be the most economical production method since manual labor and cheaper tooling options can be utilized. This analysis was restricted to high-volume, fully automated implementations, and is thus less accurate below production volumes of 25k parts per year. Additionally, one common method to improve the production efficiency is to demold parts early and apply a post cure (PC). The result is a complicated relationship between the cycle time, capital investment, and resulting piece cost.



5

Figure 5 Piece cost comparison for HP-RTM and PCM over annual production volume with dedicated equipment

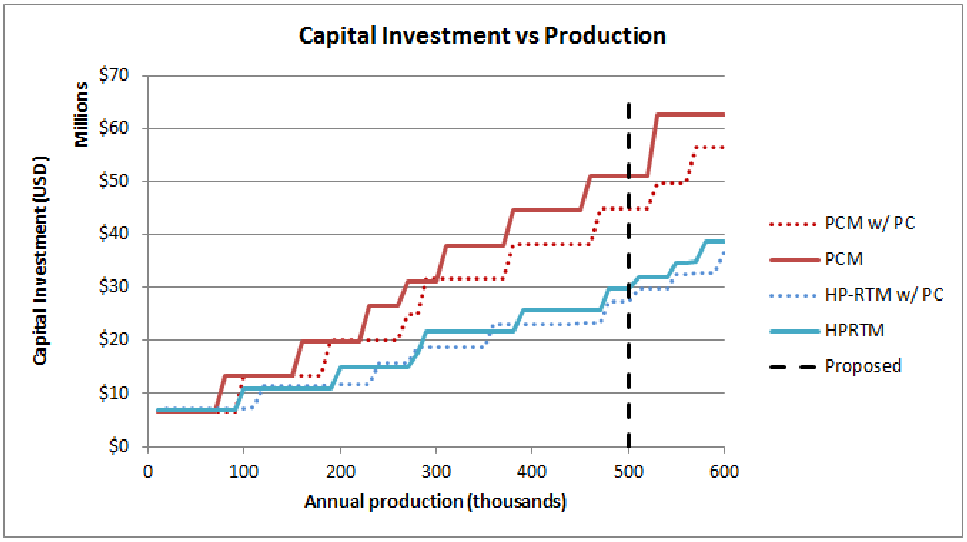


Figure 6 Total capital investment vs annual production volume for HP-RTM and PCM production scenarios

The effect of demolding early is more prominent with prepreg compression molding due to the long initial dwell time in the compression press. By reducing the tool cure time until just after the gel point, the remainder of the curing can be conducted in bulk in an oven. The added cost and process steps of the oven are offset by the sharp reduction in the number of production lines required to meet the annual production volume. The same effect on the HP-RTM process is noted, but at a much reduced level of impact. This is understood since the critical path for this process is related to the fiber preforming operations, so a reduction in cure time does not help as significantly if the same cycle time reduction in preforming cannot also be achieved.

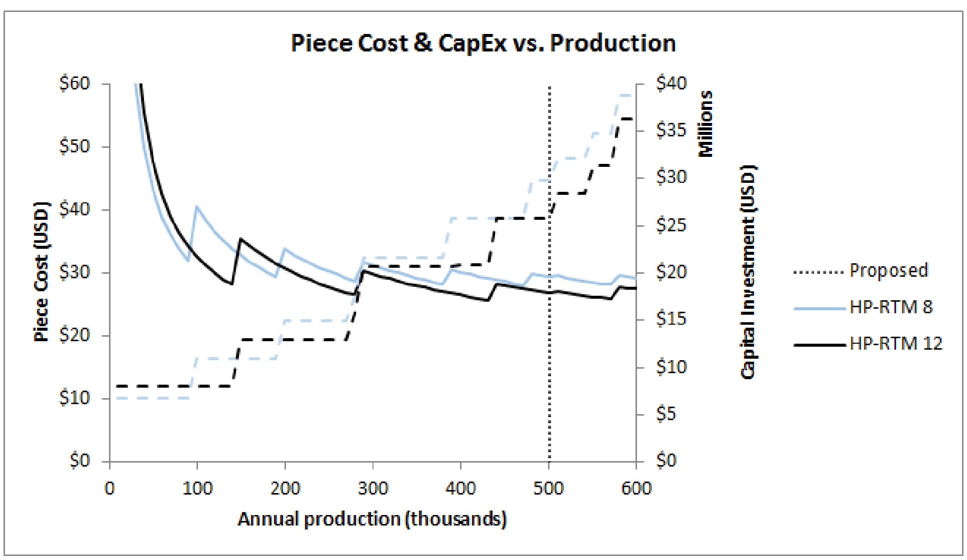


Figure 7 Effect of gang molding on HP-RTM piece cost and capital investment per annual production volume

Figure 7 shows the leaf spring cost as a function of the annual production volume and demonstrates HP-RTM is a cost effective technology at larger build rates. The graph shows the influence of the number of mold cavities. A tool set with 12 cavities is more expensive than 8 and requires a higher capacity press increasing the total costs. However, the annual production capacity is also higher, shifting the point at which additional lines are required, and lowering the total cost in this production volume range.

The previously mentioned thermal latency is one of the key enabling technologies that allows the HP-RTM process technology to supersede prepreg compression molding. For example, in a 12 cavity mold almost 22 kg of resin is required to be injected. At a rate of 120 g/s, the resin would need to remain viscous for the 3 minute injection window at the mold temperature. While the mold temperature could be decreased to extend the working time of the resin, this would negatively impact the overall cycle time. Thus, Hexion's long-latency epoxy enables the cost-efficient processing of composite leaf springs.

Summary and Next Steps

Epoxy composite leaf springs are a mature technology. Newer processing methods such as high pressure resin transfer molding can dramatically reduce cycle time and consequently the production piece cost. Epoxy systems tailored for HP-RTM are thereby needed to enable this application development.

Thick-sectioned glass reinforced epoxy laminates were fabricated to validate the performance and cost models for this technology. Hexion's TRAC 06150 epoxy system is shown to be suitable for epoxy composite leaf springs, the key feature being a long thermal latency. This epoxy exhibits excellent static and dynamic performance in a range of operating conditions. The resultant is a cost of $25-30 per piece at a HP-RTM production volume of 500k parts per year.

References

1. Reichwein, HG, Langemeier, P, Hasson, T, Schendzielorz, M (2010) Light, Strong and Economical – Epoxy Fiber-Reinforced Structures for Automotive Mass Production, SAE Automotive Conference, 2010.
2. Henkel Press release - BENTELER-SGL mass-produces composite leaf springs for the new Volvo XC90 using Loctite Matrix resin from Henkel, 2014.
3. Schürmann, H (2007) Konstruieren mit Faser-Verbund-Werkstoffen. Springer, Berlin Heidelberg, 2007.
4. ter Heide, S, Moser, L, Tournillon, V, Hasson, T (2016) Epoxy Matrix Technologies for Mass Production of Composite Leaf Springs, SAE Automotive Conference, 2016.
5. Baskaran, M et al. (2014) Manufacturing Cost Comparison of RTM, HP-RTM and CRTM for an automotive roof. European Conference on Composite Materials, ECCM-16, Seville, Spain, 22-26 June 2014.
6. Karlsson, M (2013) The development of a technical cost model for composites. MSc Thesis, KTH Royal Institute of Technology in Sweden.
7. Masi, BA (1986) Fabrication Methods and Costs for Thermoset and Thermoplastic Composite Processing for Aerospace Applications. MSc Thesis, Massachusetts Institute of Technology.