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Machining Versus Molding Tolerances in Manufacturing Automotive Sealing Systems

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Abstract

The automotive industry has been at the forefront of converting traditional metal parts to plastics. The latter surely offer greater design freedom, opportunity for consolidation, fewer assembly operations, reduced secondary finishing, weight reduction, lower total system costs, a range of properties tailored to specific applications, the ability to withstand temperatures, immunity to most chemicals and corrosive environments. They offer processing in many colors, electrical non-conductivity (insulation from electrical shocks), good thermal breaks ("warmth-to-the-touch"), and low sound transmission (tendency to muffle noise). Nonetheless, plastics have only tapped an estimated 15% of their tremendous potential to replace metals. This is particularly to increase with newer high-performance plastics, increasing sophistication in alloying and blending technologies, and use of computer-aided design and engineering (CAD/CAE) systems. The latter enable engineers to visualize complex parts and molding tools more effectively and faster than ever before. This article identifies fundamental steps and requirements to conduct an efficient and successful conversion of metallic parts to plastics, reviewing the replacement design process from concept to production; an under-the-hood rear retainer for Ford Motor Company is detailed as a case study.

Keywords: Optimization; Metal to plastic conversion; Weight reduction; Fuel economy; Exhaust emissions (pollutants) reduction; Automotive industry; Composites; Plastics; Sealing systems; Hyper-elasticity; Friction rubbing; Failure prediction; Von mises stress; Contact; Optimal interference; Insertion/assembly forces; Nonlinear finite element analysis (FEA); MARC; Manufacturing/molding tolerances; Least/ maximum material conditions (LMC/MMC); Computer-aided engineering (CAE).

1. Introduction

The world beneath the bonnet, or the hood, of automobiles, is quite harsh. Cycling temperatures and constant vibration indeed create severe stresses on parts. Besides, such parts come in contact with oil, grease, gasoline, transmission and brake fluids, water, ice, road salt, dirt, dust. Wear resistance is critical as well for components attached to automobile engines, or mounted nearby.

Traditionally, using other than metal in engine compartments was unthinkable. But that changed, as many automakers and suppliers continue to adopt plastics like nylon, polyphenylene sulphide and polypropylene, to reduce vehicle weight and improve fuel efficiency (reducing emissions). Other benefits include parts' consolidations, cost savings, durability, corrosion resistance, and sound dampening.

On July 29, 2011, President Obama announced an agreement with 13 large automakers to increase fuel economy to 54.5 miles per gallon (23.17 kilometres per litre) for cars and light-duty trucks by model year 2025. He was joined by Ford, GM, Chrysler, BMW, Honda, Hyundai, Jaguar/Land Rover, Kia, Mazda, Mitsubishi, Nissan, Toyota, and Volvo, which together account for over 90% of vehicles sold in the USA, as well as the United Auto Workers (UAW), and the State of California. The agreement resulted in new CAFE regulations for model year 2017–2025 vehicles. The new administration is reducing this, but not eliminating it. The major increases in stringency and changes in CAFÉ' structure create a need for research that incorporates the demand and supply sides of the new vehicle market in a more detailed manner than was needed with static fuel economy standards.

At this year's SAE Congress in Detroit, lightweight materials were again a hot topic. Automotive engineers continue to scramble to find ways to meet new corporate-average fuel economies. This requires increase travels between fuelling, without sacrificing safety or cost. Consequently, the industry continues to explore new ways to use plastics to replace traditional metal (heavier, machined) components.

Plastics use is expected to increase under-the-hood as automakers particularly rush to build small fuel-efficient engines. General Motors Corp. (GM, Detroit) plans to double global production of 4-cylinder engines by 2020. Within two years, a third of all GM engines assembled in North America will be 4-cylinder - - 21% of which

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turbocharged. Meanwhile, Ford Motor Co. (Dearborn, MI) plans to double production of 4-cylinder domestic engines to more than a million units.

Far beyond, automakers around the world remain focussed on reducing weights. For instance, Nissan Motor Co. (Tokyo) plans on making its cars 15% lighter by 2022. To do so, the company started making plastic rocker and front covers for diesel engines on its Navara and Pathfinder vehicles. Moulding parts from nylon to replace aluminium, Nissan's engineers were able to reduce weight by 40%. They achieved similar savings by converting electric water valve assembly used on the Armada, Quest, and Titan from steel to plastic.

This manuscript presents a roadmap to help practitioners and management reach further more compact, efficient, and lighter engines for vehicles. Research considers converting a heavily machined aluminium rear retainer to nylon 66 for Ford Motor Co. Cost analysis, materials testing, design parameter definitions, virtual modelling, process simulation, prototyping and testing are discussed in the paper for added guidance towards similar conversion programs.

2. Problem Definition

Plastics under-the-hood started in Europe, with small, fuel-efficient engines. Brian Baleno, global market manager at Solvay Advanced Polymers LLC (Alpharetta, GA), says: "[There is a] higher emphasis in Europe on overall system efficiency and fuel economy gained by using plastic where metals were historically used."

"European automotive engineers have had a long-term, positive experience with thermoplastics," says Marianne Morgan, marketing sector leader for powertrain at BASF Corp. (Florham Park, NJ). "North American manufacturers had some failures with plastics back in the 1980s and 1990s, when their [metal-based] designs were not optimized for plastic materials."

"The use of plastics has significantly increased for under-the-hoods," adds Bill Heatherwick, automotive market segment manager at Branson Ultrasonics Corp. (Danbury, CT). "Ongoing performance improvements of plastics, dimensional stability and heat and chemical resistance, have made increased uses possible. We also have seen perceptions change to accepting plastic as a highly engineered solution. All major resin suppliers have played a key role in educating [engineers]."

Heatherwick adds: "Metal is a known commodity, with reams of performance and testing data to [prove] that it works well," he explains. "Convincing OEMs to take the leap to plastic was the toughest hurdle. As much data now supports plastic solutions to meet test specifications for engine vibration, temperature, and chemical resistance."

For instance, thermoplastics have lower mechanical properties than aluminium and steel: "Properties change with increasing temperatures typically found under-the-hood," says Dave Conley, application development manager at DSM Chemicals Inc. (Augusta, GA). "Changing the design requires a thorough knowledge of applied stresses."

Plastic offers performance characteristics that create greater rigidity as well. That allows engineers to reduce a number of metal parts to a single structural plastic moulding. Snap-fits, bosses, ribs and features like brackets and attachment points, can be moulded in to eliminate assembly steps, reduce weight, and minimize part counts. "Design flexibilities allow engineers to simplify parts and integrate different functions," explains Gianluigi Molteni, formerly a global powertrain segment manager at DuPont Automotive (Troy, MI). "Moulding is also becoming more advanced to allow for further complex designs. That leads to easier packaging and assembly."

Part design freedom allows automotive engineers to create different geometries at times not possible with metal. That is one of the reasons why plastics have become popular for air-intake manifolds. A typical nylon manifold weighs 4 to 6 pounds versus 20 pounds for cast aluminium. But weight savings is only one advantage: "The smooth inside wall of intake channels feature lower drag properties than aluminium," says Morgan. "Plastic can [also] be shaped more easily, which allows more favourable air flow designs."

"Injection-moulded parts offer class-A finishes in internal air-fuel tracts to assist in air flow and engine efficiency," adds Dan Schewe, regional sales manager at Forward Technology Inc. (Cokato, MN). "Cast parts are typically rough and require substantial cleaning and machining. Plastics allow the part designer to use just the right amount of material needed to accommodate the requirements of the application. The wall thickness on an intake manifold is sized not only for normal air flow but also for having sufficient strength for vibration and possible engine back-fires."

3. Literature Review

A comprehensive literature search used keywords like "convert", "plastic", and "automotive" at nearby university libraries, from 1884 to date (2017). One hundred and sixty seven (167) papers were compiled but only 79 somewhat related to this presentation. Many articles talked about recycling plastics (among other residues) at the end of vehicle lives. Other articles presented new resins from renewable sources or recycled residues and products, and even off retiring vehicles. Articles relevant to this presentation are listed per publication year and alphabetical order at the end of this manuscript.

As early as October 13, 1975, Dunning of the Allied Chemical Corporation, Fibers Division, now, Honeywell (Charlotte, NC), presented a new thermoplastics process, developed in that decade, referred to as plastics stamping. The idea was simple: The use of sheet metal processes and equipment to convert plastic sheets into parts of the right performance at the right price. Dunning reviewed STX stampable sheets, part conversion processes, and potential uses of the stamped sheets in automobiles.

Desai [1], was closest to this contribution suggesting, to optimize prototype to production cycle, assessing service conditions for a given part in a broader sense. This should include loads and restraints, but also extreme temperatures, chemical environment, humidity, and assembly methods. Desai confirms that metallic part conversion to plastic should have a balanced compromise between functionality and moulding. And tooling should have unique features for a specific high performance engineering polymers (HPEP).

As recently as February 9, 2016, Ramesh Akshay and Ajay Virmalwar of India's Tata Technologies Ltd, presented at the International Mobility Conference, [2], conversion of brackets from sheet metal to plastics, with added benefits in manufacturing. An optimum process based on topology optimization and CAE mould filling analyses was used. A set of case study brackets holding electrical modules in premium cars was selected. These were to mount on the BIW (body-in-white) of a car traditionally made up of sheet metal. A few proposals were created with different thermoplastic materials, and verified for durability and NVH (noise vibration and harshness) load cases. Measurable outputs included strength, stiffness, percentage weight reduction, and cost.

Reviewed articles, reported in the reference section, did not present the four ingredients to product development, to use in converting metal parts to plastics: 1. Material characterizations, 2. Design parameter definitions, 3. Modelling, CAD/CAE, and 4. Validation testing. Scientific articles do not get into details of how to convert metallic parts to plastics; things learned at companies are not exposed in the public domain for secrecy. The task becomes further more challenging when dealing with sealing systems involving hyper- and visco-elastic flexible gasket components, as illustrated in this paper.

4. Rear Retainer Case Study

Converting metal parts to plastics requires understanding mechanical, chemical, and rheological characteristics of resins. Besides, strength and modulus, creep, fatigue, and degradation in working environments are crucial. Thermo- mechanical compatibility with metallic components, like inserts at bolt holes, is also necessary.

Design of rear retainer (Figure 1) calls for material conditions: Interference between rubber and plastic ensures sealability in time, but over-compressing a gasket generates high reaction of rubber on plastic housings and promotes visco-elasticity. Important are design parameters, aged rubber characteristics, plastics to failure under true stress-strain conditions. Flow simulation ensures that no stress concentration superposes weak material areas. Friction testing permits to quantify assembly force requirements.

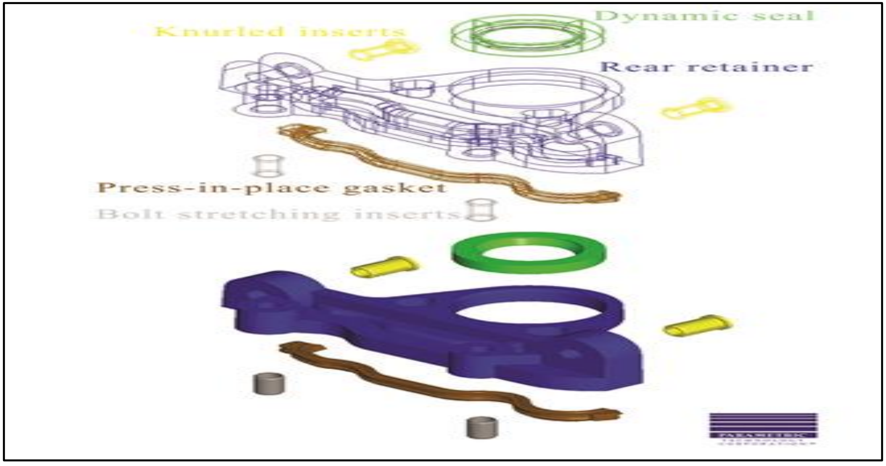
4.1. Computer-Aided Design

Ford Motor Company sought an arbiter for disagreements between plastic and rubber part suppliers over moulding tolerance of rear retainer: Series of laboratory trials and computer analyses were thus set.

Fig-1. Rear retainer moulded out of Nylon 66

Rear retainer and associated components were parametrically built in Pro|Engineer™ (cf: http://www.ptc.com); e.g. Figure 2.

Fig-2. CAD of rear retainer in wireframes and solids



Fully nonlinear analyses of rear retainer assembly used MARC™ (cf: http://www.mscsoftware.com) but only on the section failing, for reduce costs.

4.2 Materials Characterization

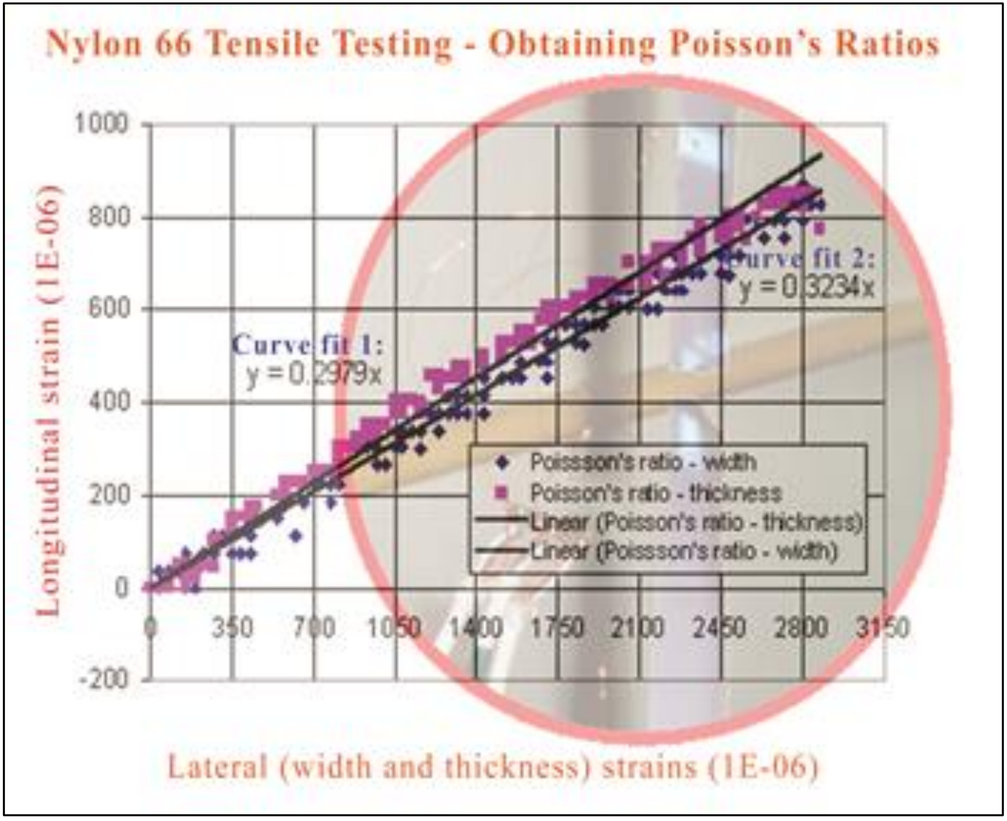
Analysing the rear retainer case study requires data on plastics and rubbers, and metal making for rubber "carriers"; other inserts can be assumed non-deforming.

4.2.1 Characterizing Nylon 66 for Rear Retainer

Certainly, suppliers provide data on plastics, but amounts and orientations of reinforcements remain geometry and process-dependent. Plaques were thus made for "dog-bone" machining then pulling while miniature disks were punched from parts prototyped for compression testing.

Load cells measured forces and strain gauges in axial and two lateral (width and thickness) directions (e.g; Figure 3); these are used to post-process "true" stresses and strains.

Fig-3. Characterizing plastic under quasi-static tension



4.2.2. Characterizing viton™ for Dynamic Seal

Rubber undergoes four basic deformation modes: uniaxial, equi-biaxial, planar, and volumetric, tensile or compressive. As rubber is known to be nearly incompressible, only four tests – feasible in the laboratory - are necessary: UT, UC, PT, and Volumetric Compression or VC. Still, ET can replace UC with relatively compressible rubbers (or in "open" designs).

Dynamic seal rubber constants: Various models (Mooney, Rivlin, Signorini, third and fourth orders, Yeoh) were fit to test data, Ogden's proved most appropriate. Neo-Hooken proved a poor fit; other polynomial models were better. Still, one term Ogden was sufficient to represent the rubber for dynamic seal in rear retainer (convergence was reach at two terms (cf: Table 1).

Table-1. Ogden model constants

Terms	α_i	μ_i	D_i
1	0.135296E+01	0.159808E+01	0.216214E+07
2	0.115387E+01 -0.549584E-04	0.182442E+01 -0.124897E+02	0.210584E+07
3	0.115387E+010 -0.549584E-04	0.182442E+010 -0.124897E+02	0.210584E+07

4.3. Definition of Design Parameters

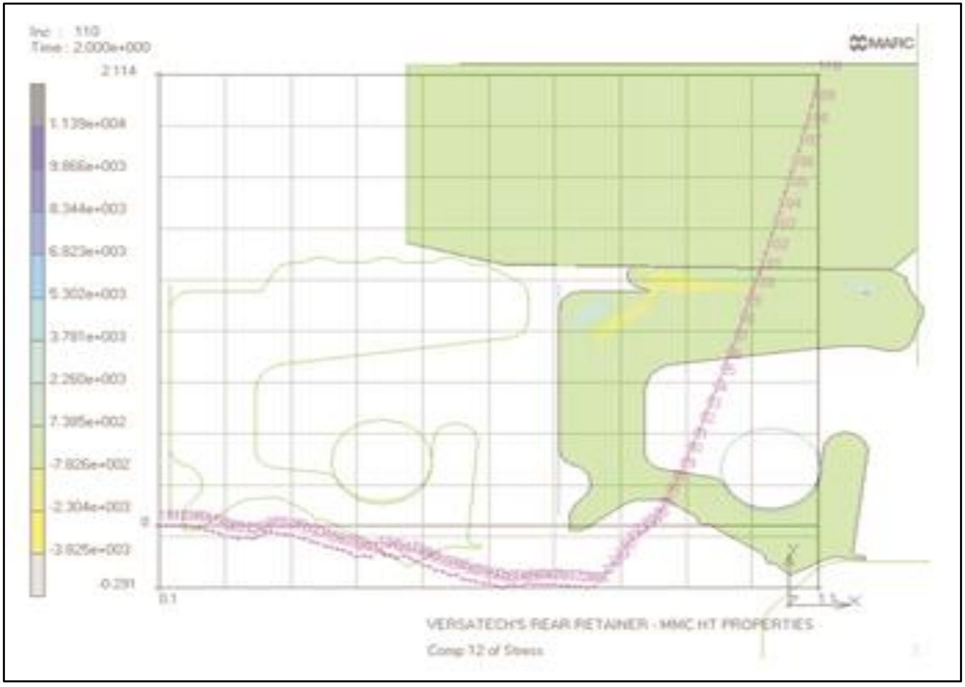
A "minimum pressure to seal" was established at "time zero" by progressively compressing and pressurizing a ring gasket, and substantiated with visco-elasticity (relaxation of rubber and creep of plastic). Strain gauges on plastic tensile coupons established the onset of cracking through local axial strain and cross-sectional contraction in width and thickness.

4.4. Computer-Aided Engineering

Modelling accounted for contacts seal to bore of rear retainer, and seal to the various rigid bodies (circular spring, insertion and retention plates, and shaft). To expedite the modelling, only the weakest section failing when testing prototypes, was analyzed. Friction, measured in the laboratory was coded through a subroutine in FEA.

Several history-cases set the spring in the seal, and inserted this in the plastic housing and shaft assembly. X, y, z axes defined axial, radial, and hoop directions. Model validation compared predicted retainer's reaction to insertion of seal to data recorded in the laboratory. Post-processing monitored deformation of seal during assembly. A taper (non-existent when machining aluminium parts) was used by the plastic moulder to ease, release of part from mould and seal insertion, besides lubrication.

Fig-4. Correlating FEA insertion forces to testing



Radial stress contours, when inserting the dynamic seal in the plastic housing, indicate the level of sealing. Sadly sealing lines on the dynamic seal did not compress equally, as only the plastic housing was addressed in this study.

Finally, a maximum interference between the dynamic seal and inner bore of plastic retainer was defined through FEA and materials testing in the laboratory (Figure 4). The data was passed to the plastic moulder to gauge manufacturing tolerances of the new plastic rear retainer, and ensure its compatibility with the existing dynamic seal design and dimensions.

5. Future Directions

Converting metallic parts to plastics in automobile should but expand and accelerate. Auto suppliers and material formulators continue to find new uses for plastics under-the-hood, including cases that were unimaginable just a few years ago. For example, Mann + Hummel GmbH (Ludwigsburg, Germany) recently started to mass-produce a plastic oil pan. The all-plastic component cuts weight by 60 % compared to a traditional all-aluminium part, or 30 % compared to hybrid aluminium and plastic subassemblies. "Further benefits with regard to cost, weight, installation space and assembly can be achieved by integrating additional components," says Dr. Dieter Seipler, the company's CEO. "For instance, with plastic, additional functions can be integrated to the same extent as in air-intake systems".

"Integration of such components as oil tubes, pick-up pipes, strainers, separate oil reservoirs and baffles may be considered," adds Dr. Seipler. "Installation of a complete oil module consisting of oil filter and oil cooler also offers considerable potential, both from technical and economic points of view." "Plastic oil pans can be moulded into difficult shapes to optimize scarce space in the engine compartment," says Richard Schultz, Project Consultant at Ducker Worldwide (Troy, MI). "As a result, you can create a more intricate part." In the past, oil pans were either steel or aluminium. In the future, plastic may dominate. That's what happened with fuel tanks. "They were all made out of steel 20 years ago," says Schultz. "Today, 81 % of fuel tanks are plastic."

During the past two decades, intake manifolds have also slowly been evolving from metal-to-plastic designs. "Back in the mid-1980s, 80 % of intake manifolds were aluminium," Schultz recalls. "Today, aluminium accounts for 58 % of the market, and that will eventually drop to 50 % as plastic continues to make inroads." Although there's more plastic in engine compartments today, Schultz believes steel will continue to play an important role.

“New high-strength steels can save 15 % to 20 % weight over mild steel, because parts can be made thinner,” he points out. “That makes it competitive with plastic and other lightweight materials.”

Still, many engine components, such as exhaust manifolds and turbochargers, cannot be made out of plastic and require the physical properties of metal. “By definition, plastics will always strain under load and creep when stressed,” says Holt. “These properties can be ameliorated, but never fully eliminated. However, who would have guessed 40 years ago that plastic intake manifolds would become commonplace in today’s market? Many [assembly] advances have allowed the use of plastics to not only survive the production line, but facing long-term environmental under-the-hood stresses.”

“[Ongoing] efforts to improve quality and engine performance will lead to continued advancements in plastic materials,” predicts Branson Ultrasonics’ Heatherwick. “There are several new applications currently in development that will take the use of plastics in powertrain to the next generation.” Due to confidentiality agreements, he can’t reveal any details. But, several resin suppliers provide a glimpse of how plastic will be used under-the-hood of future vehicles. DuPont’s Molteni claims there is a lot of R&D work currently being done on resonators and exhaust systems.

Acknowledgment

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