Politecnico di Torino

Department of Mechanical and Aerospace engineering

Master course in Automotive Engineering

Design criteria for thermo-plastic matrix composites (TPMC) and additive manufacturing of powertrain components

Master's Thesis

Supervisors:

Prof. Cristiana Delprete

Prof. Carlo Rosso

Candidate:

Juan Esteban Vallejo Sosa

Abstract

The design of powertrain system and components is constantly advancing towards a powerplant with higher specific power output while also increasing the overall efficiency, whether in stationary or unsteady regimes of operations. This constant advance is achieved while pursuing the goal of delivering to the final user of the vehicle a reduced fuel consumption as well as to meet ever more challenging emission regulations.

This thesis discusses current internal combustion engine materials and manufacturing processes, both sophisticated and traditional and the main objective is to evaluate the use of composite materials, particularly the thermoplastic matrix composites to generate automotive powertrain components, assessing the possible use of additive manufacturing methods during its production.

The bigger problem of the current manufacturing methods that are employed to produce components in thermoplastic matrix composite materials is the difficulty in escalating the production, due to its construction handmade methods are necessary, making it a slow and expensive process.

The use of additive manufacturing methods for this type of composite materials could have the potential of reducing weight, costs, and production times whereas enhancing efficiency, performance, and durability of the powertrain.

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1 INTRODUCTION.

1.1 Global warming and participation of transport.

Most countries around the world are rapidly urbanizing and transport is regarded as a key force in rapid urban and economic development because the economic position of a country is directly related with the ease with which people, goods, and services can be moved using an efficient transportation system.

Road transportation is the most popular method of transportation among the many modes of transportation, owing mostly to its flexibility, and is becoming increasingly popular as the metropolitan population grows.(Agarwal & Mustafi, 2021)

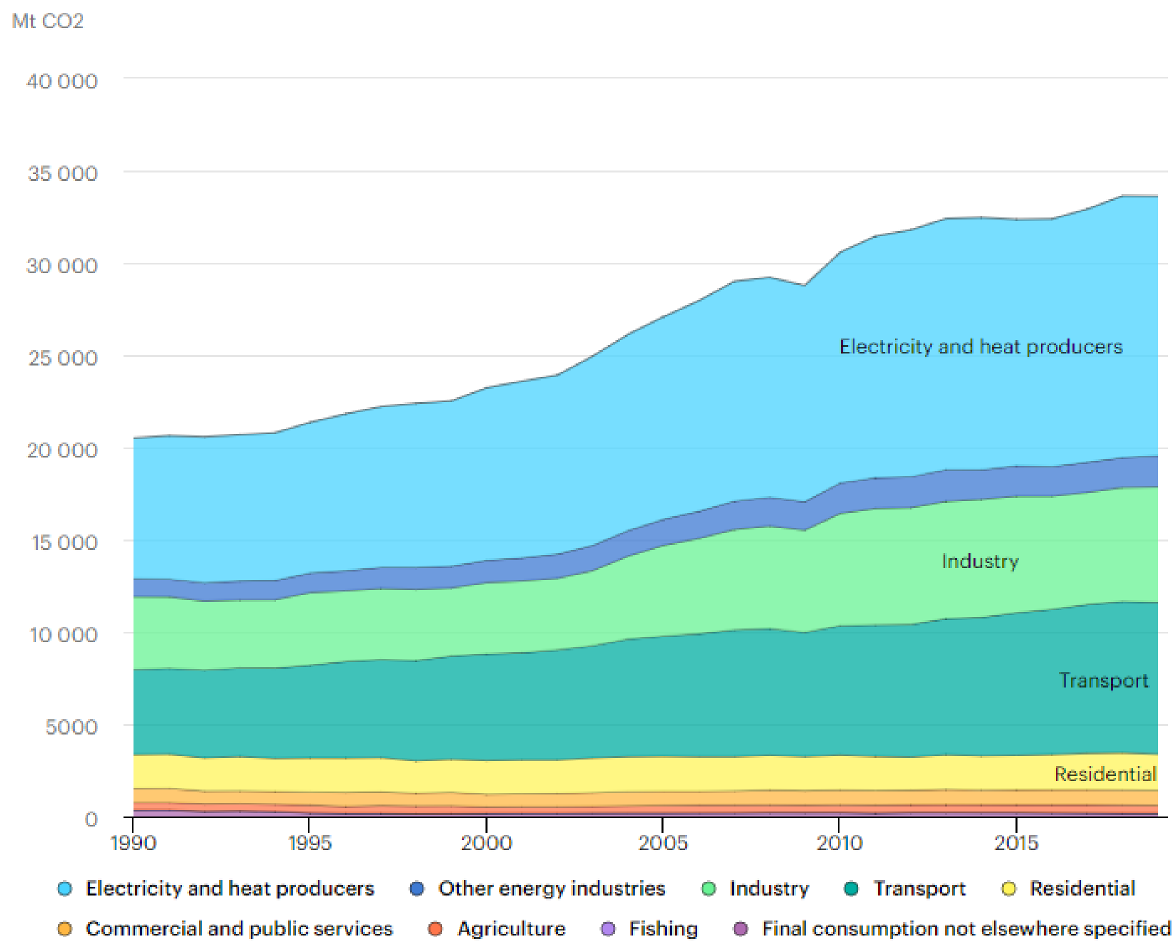


Figure 1. CO2 emissions by sector, World 1990-2019 from (IEA, 2020)

Carbon dioxide (CO_2) is a greenhouse gas that is linked to climate change and contributes largely to global warming. Transport is indeed one of the sectors where efficient policies and social actions are needed to reduce CO_2 emissions and adapt to climatic changes.

As shown in seen in Figure 1 transport sector accounts for 25% of world CO2 emissions (IEA, 2020), those emissions are mainly associated to CO2 produced in the combustion process.

Due to its versatility, the Internal combustion engine (ICE) is one of the most popular technologies of automotive propulsion from light-duty to heavy-duty vehicles.

Even if ICE related emissions are not the only harmful emissions coming from road transport, other combustion derived contaminants like particulate matter, CO, CO2 NOx are a major concern for global warming, air quality and its effects on human health.

Today's efforts are put on developing new materials, new technologies which aimed to reduce the generation of these contaminants and the usage of fossil fuels, while making more efficient the combustion process and reducing the losses associated with the energy transformation from the fuel to mechanical energy used to propel the vehicle.

Transport policymakers have acknowledged the need for CO2 reduction and increased fuel efficiency in the road transport at a series of global conferences, in consequence, they have taken action primarily through supporting innovative vehicle powertrain technologies, the usage of sustainable fuels as biofuels or hydrogen, the improvement of transport infrastructure, as well as making campaigns for consumer information and regulating trough laws (for example, increasing taxes for big CO2-emitting products and processes and vice versa).(UNECE, 2020).

1.2 Vehicle emissions and regulations

According with (World Bank, 2022) GHG emissions from transportation could increase by up to 60% by 2050 if population, economies, and their need for mobility continue to grow.

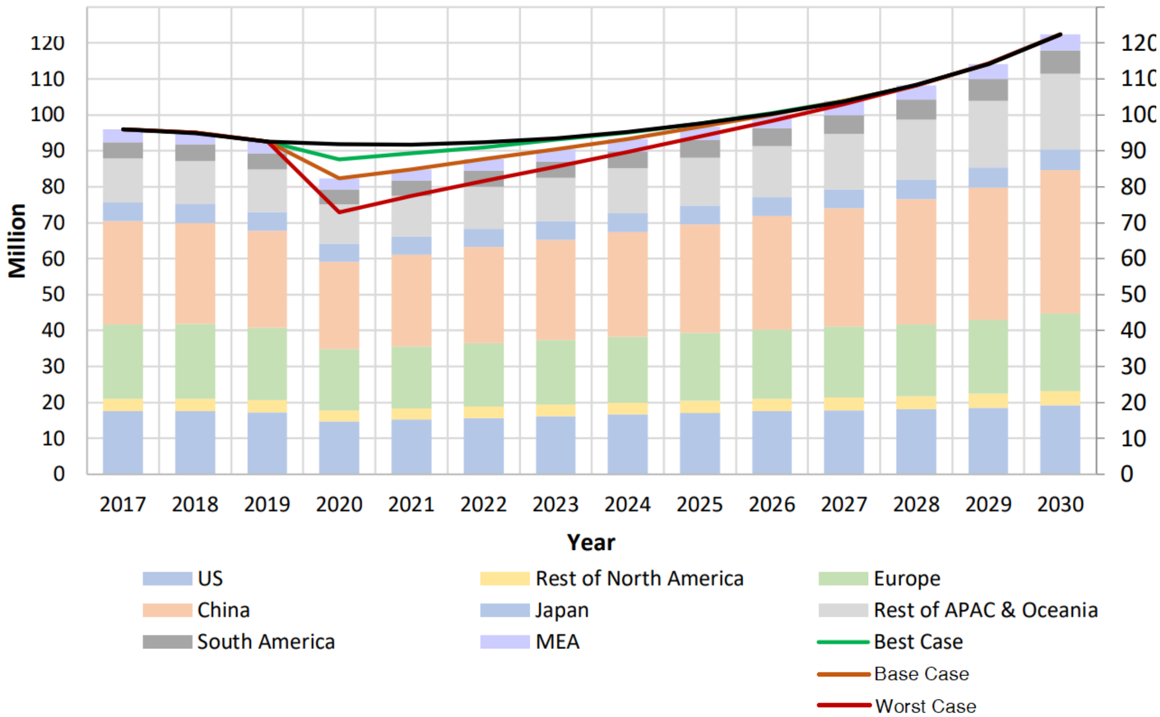


Figure 2 Global & Regional Automotive Sales Volumes Forecasts Under 3 Scenarios 2017-2030 from (Ultima media, 2020)

Increase in the population, economic growth, and growing urbanization have resulted in exponential increase in the automotive population, resulting in proportionately increased emissions and health risks. By 2040, the number of cars on the road worldwide is expected to nearly double, with a projected population of two billion. Another estimate suggests that by 2050, the total number of road vehicles would be between 2 and 3 billion.(Agarwal & Mustafi, 2021).

This trends along with the crescent concern in global warming effects have motivated the creation of stricter regulations and standards around the world, most known standards are the adopted in the bigger economies in the world like EURO (European Union) EPA and CARB (U.S), and others from China, Japan, South Korea, India. Etc.

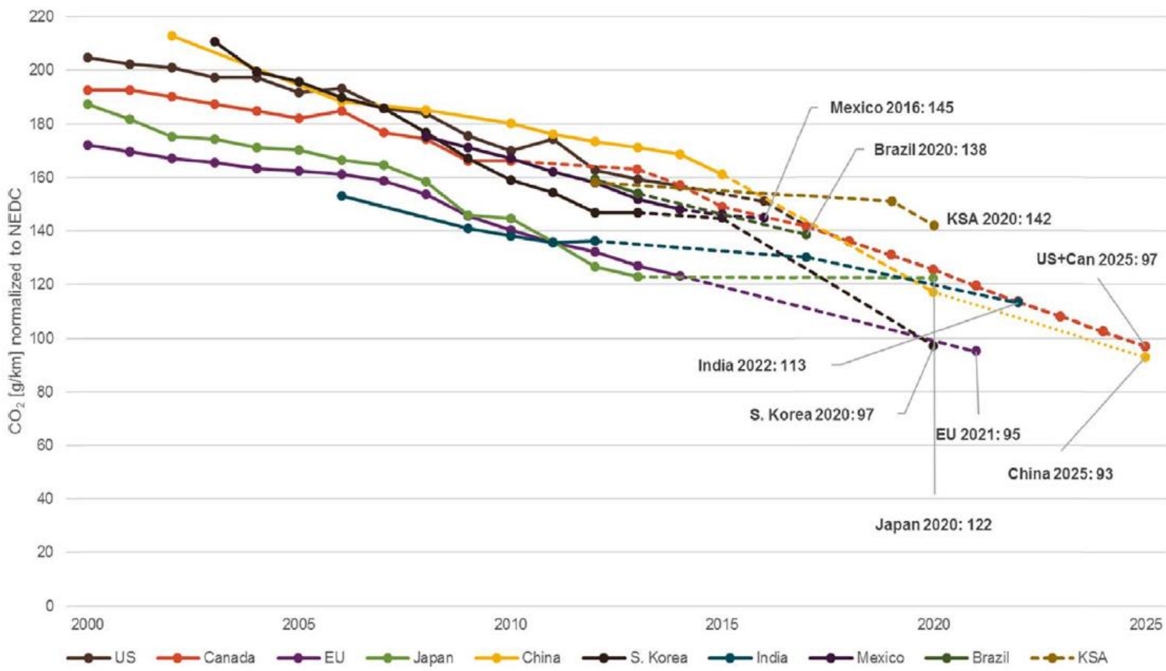


Figure 3 An overview of the various CO2 emission targets in NEDC-equivalents. From (Hooftman et al., 2018)

Figure 3 illustrates the trending of goals of fuel consumption and CO2 emissions regulations of different economies and countries, a clear tendency to reduce the CO2 emission into the atmosphere is shown and further and stricter regulations would limit the powertrain technology in some cases.

Protocols and limitations imposed on new vehicles encourage research and development of new technologies to reduce the consumption / emission of CO2, and other pollutants like PM, NOx, VOCs, CO and other types or unburned hydrocarbons.

In Figure 4 Is shown how some standards around the world have changed over time, setting stricter and challenging limits for automotive emissions.

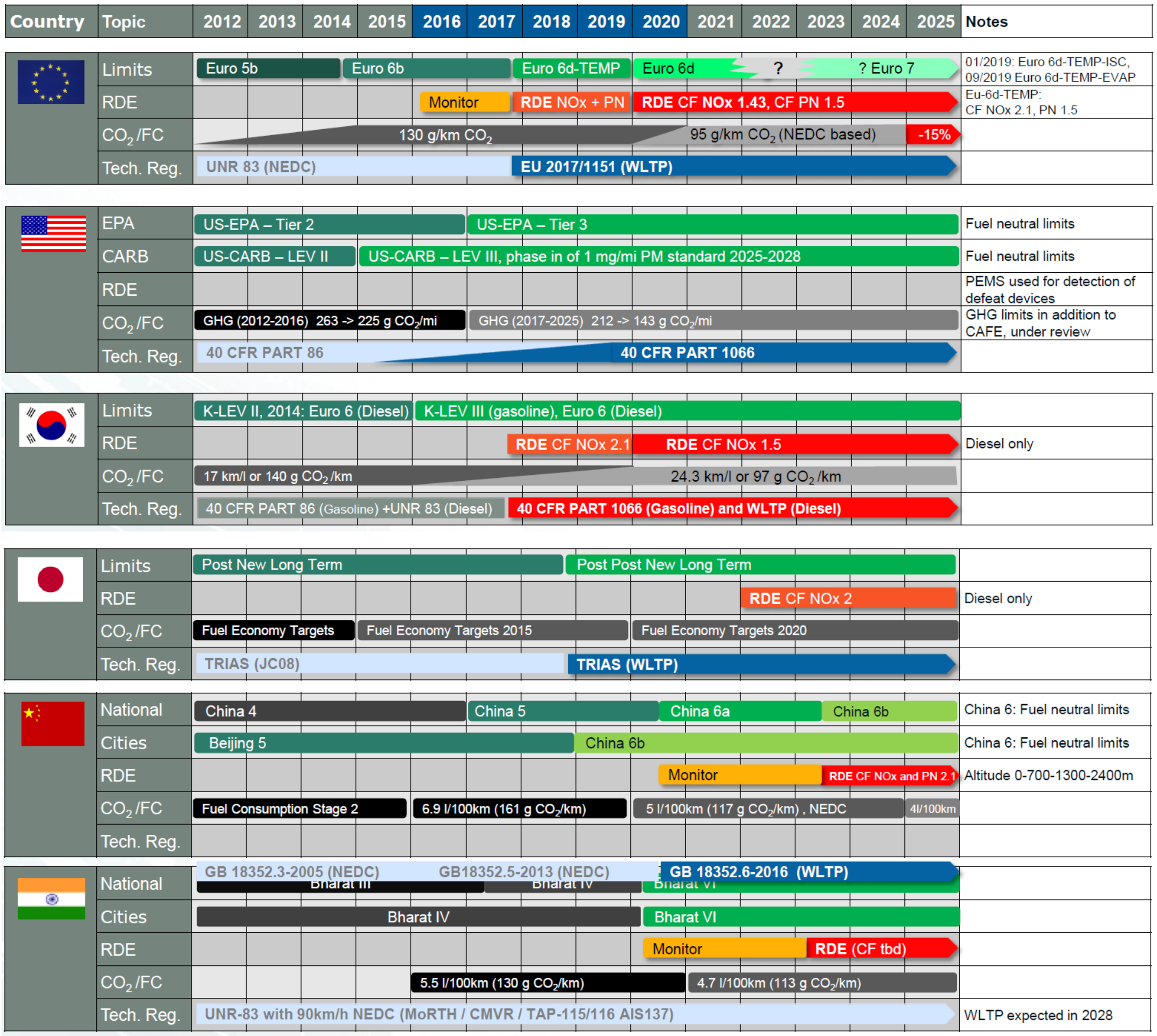


Figure 4. Emission legislation for passenger cars over the time for different standards.(AVL List GmbH, 2018)

The objective of meeting these regulations and standards trigger challenging research projects and further developments that have guided the automotive powertrain technologies to what it is today, and it will continuously advance towards cleaner and more efficient propulsion systems.

1.3 Lowering weight related to lowering fuel consumption and emissions

Is well know that technology advances are mainly led by advances in technology of materials, and that final limitations in technological and engineering advances are mainly given by materials and their ease to be shaped in usable products.

In the transportation sector, vehicle weight reduction is a very well-known approach for lowering fuel consumption. The inertial forces that the engine must overcome are reduced as the vehicle's mass is reduced, and thus the power needed to move the vehicle is consequently diminishes.(Bandivadekar, 2008)

Electric vehicles, vehicles with new combustion and fuel technologies, have been developed to improve the energy efficiency of automobiles and trucks. Another key breakthrough is the increased usage of lightweight materials, which can enhance passenger vehicle fuel efficiency by 6–8 percent for every 10% weight reduction while simultaneously making electric and alternative vehicles more competitive (Elmarakbi & Azoti, 2015). As a result, the next generation of automobiles must be lighter, cleaner, and more fuel-efficient.

According with (Joost, 2012), by replacing cast iron and traditional steel components with lightweight materials like high-strength steel, magnesium alloys, aluminium alloys, carbon fibre, and polymer composites, the total weight of vehicle's body and chassis can be reduced by up to 50%. However, there would be significant issues with the safety trade-off. Improved performance, manufacturability, cost, and modelling are all parameters to consider before the replacement of the component's material.

The amount of inertial resistance encountered when accelerating a vehicle with an internal combustion engine is determined not only by the vehicle's weight, but also by the rotational masses present in the vehicle drivetrain. These accelerated and decelerated rotational masses include big part of powertrain components from the crank system to the wheels and tires of the vehicle.(Ubysz, 2010)

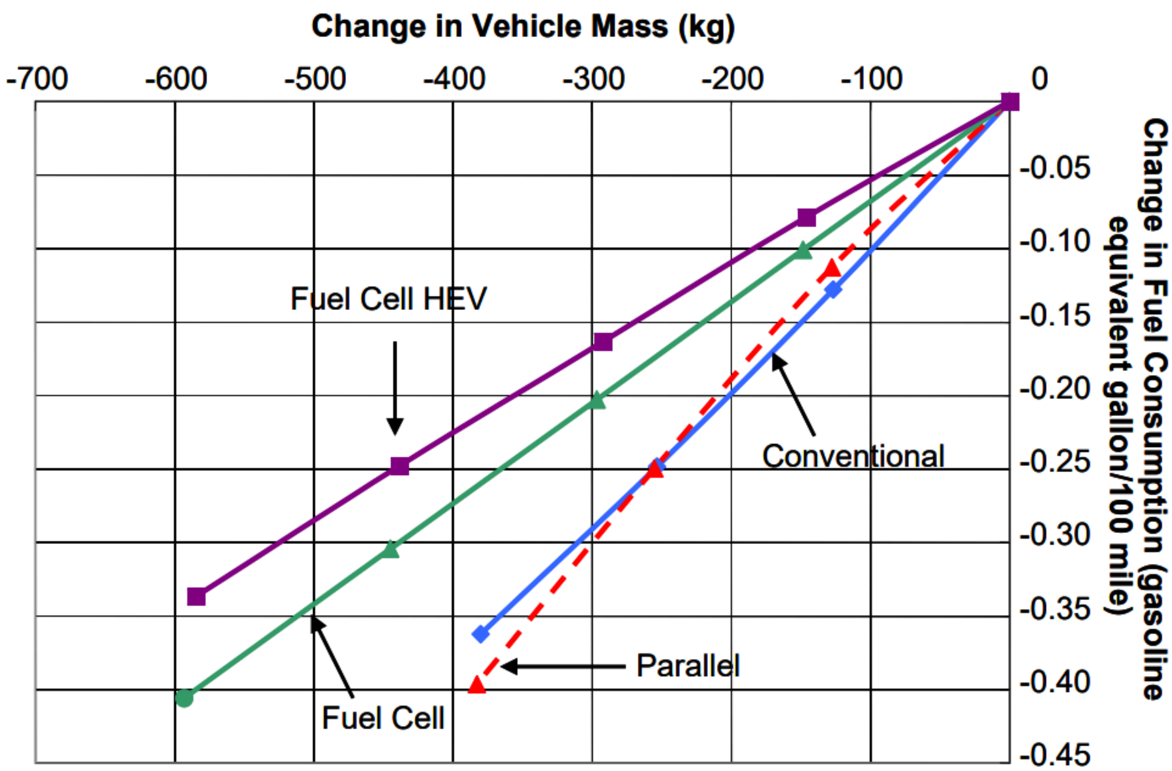


Figure 5 Change in Fuel Consumption Gasoline Equivalent due to Mass Reduction for the Compact Vehicle – Combined Cycle. From (Pagerit et al., 2006)

Reducing the mass in powertrain components can derive in lower vibrations, higher specific power output and better performance and specifically the reduction of rotating masses contributes to the reduction of rotational inertia, allowing for a wider range of operating speeds and thus more power.

As a result, less energy is invested in speeding up these masses and more is inverted in vehicle propulsion, ergo, better fuel efficiency.Figure 5

2 LITERATURE

2.1 Materials commonly used in powertrain development

Engineering materials employed for vehicle powertrain has changed over the past of time, mainly driven by the demand of lighter and stronger materials, advances in manufacturing technology and the crescent concern in safety within the vehicle and environmental impacts of automotive transport.

2.1.1 Steel and cast iron.

Steel has been a pillar of the automobile industry since its origin, and despite ongoing competition from lightweight alternatives such as aluminium and carbon fiber-reinforced polymers (CFRPs), it is still the most widely employed material for car manufacturing today with a mean of 900 kg used in each vehicle.(World Steel Asociation, 2020)

- Nearly 25% of vehicle curb mass is steel used in the body structure, doors, trunk, and panels to have a good energy absorption in case of crashes.
- Around 20% of the weight accounts for the steel used in the drivetrain (most of it been cast iron and carbon steel) for structural powertrain components like engine block and for wear resistant components as gears and bearings.
- The suspension components represent around the 10% of vehicle curb weight where high strength rolled is usually used.
- The remaining part of vehicle weight where steel and cast iron are employed are wheels, fuel tank, steering system, braking system, tires, etc.

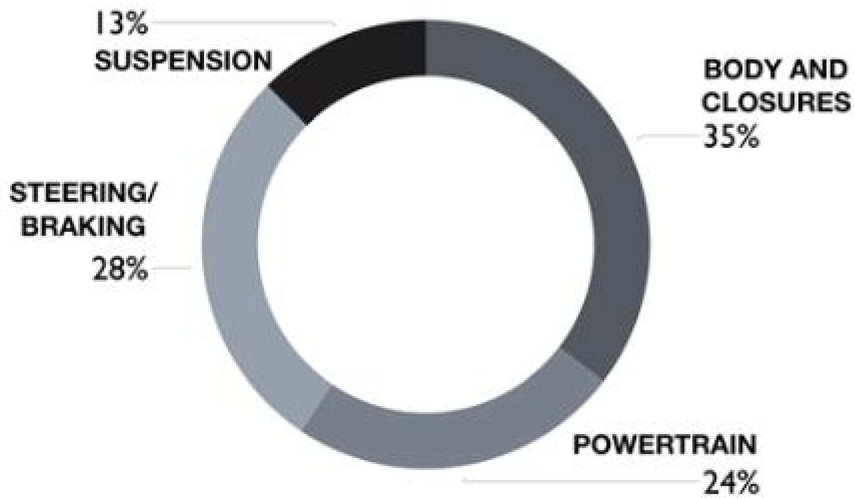


Figure 6 Breakdown of average vehicle steel content. Source: World Steel Association

Steel sheet metal, forged steel parts, and cast-iron account for over 70% of an average car's weight, indicating that ferrous metals, primarily steel, continue to dominate the automotive market. Due to their high density of 7.8 g/cm3, ferrous alloys are not often regarded as lightweight materials. However, efforts are being made to alter the qualities that make them useful in reducing the weight of transport vehicles. Applying high-strength steels results in thinner sheets, resulting in a vehicle weight reduction, while increasing strength alone results in a design weight reduction without modifying the specific density of materials. Parallel to this, there are ongoing efforts to reduce the density of ferrous alloys, especially steel.(Sullivan et al., 2015)

Steels for the automobile sector are classed as classic mild steel, conventional high-strength low alloy (HSLA) steel, and advanced high-strength steel (AHSS) (Kuziak et al., 2008), based on the strength criterion. There is no consistent worldwide vocabulary for classifying high-strength steels due to constant development. The complex multiphase microstructures of AHSS steels, which contains bainite, martensite, and residual austenite, enable them to acquire exceptional mechanical characteristics Figure 7. The ultimate tensile strength (UTS) of the AHSS is typically between 450 and 800 MPa. Steels having a UTS more than 1000 MPs are called ultra-high-strength steels.(Czerwinski, 2021)

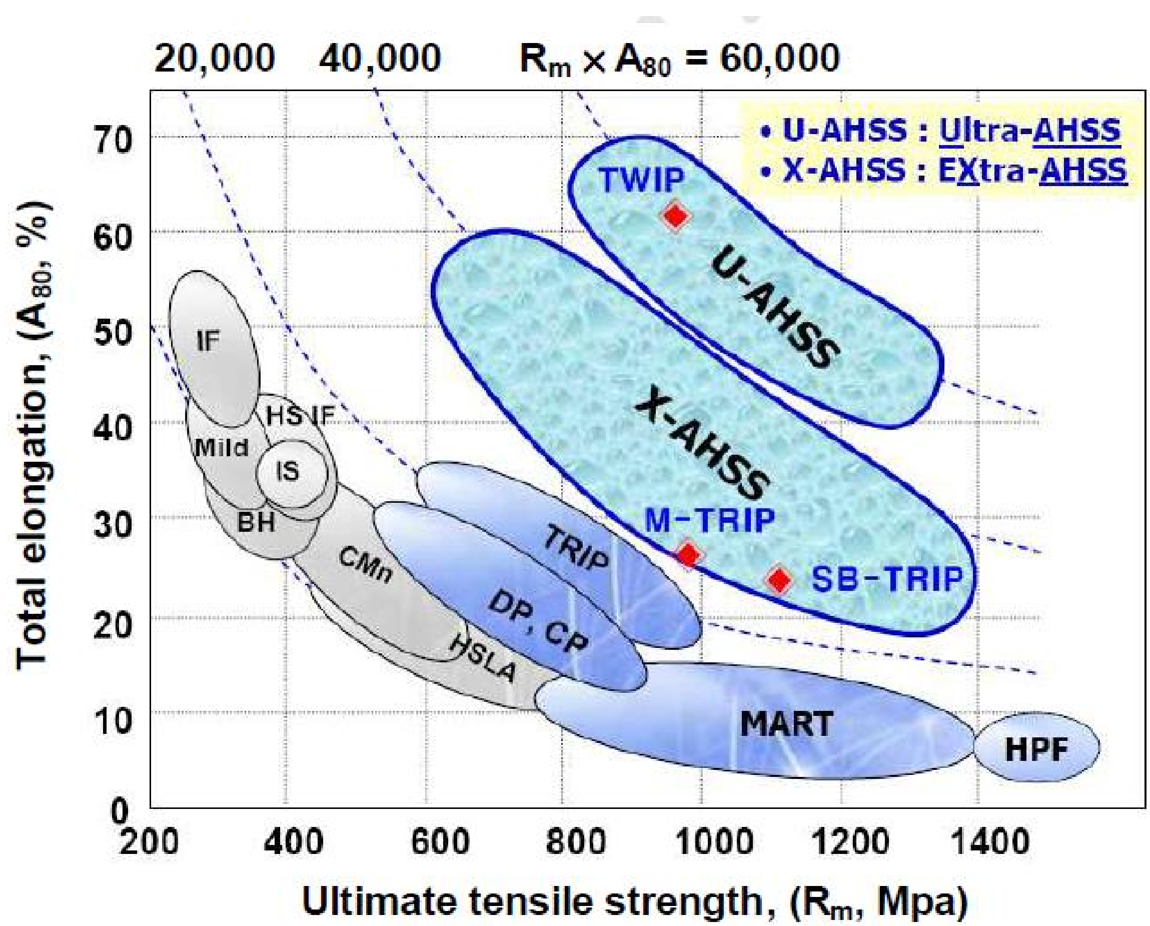


Figure 7 Total elongation vs Ultimate tensile strength (Rm) for various generations of high strength steels. From (Tisza & Czinege, 2018)

High strength steels, and innovative alloys are used to further reduce the overall weight of powertrain and vehicles and along with innovative design paradigms lightweight oriented have also allow to minimize the materials and optimize the utilization of material strength using numerical methods used to model complex geometries of lighter structures.

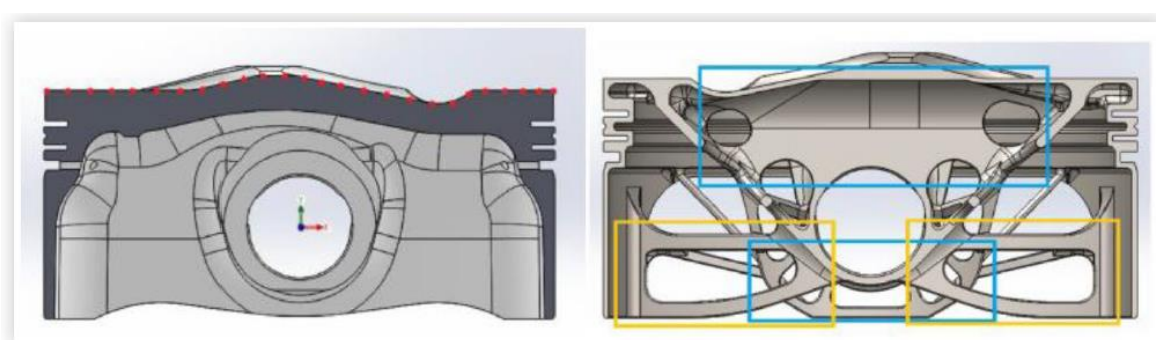


Figure 8 Piston Before (left) and after (right) topology optimization. From (Barbieri et al., 2018; Gray & Depcik, 2020)

Size, shape, and topology of components are all factors in structure design optimization, which aims to distribute materials within a component to reduce its use while also improving strength and stiffness, crashworthiness, structural and vibration performance. As (Czerwinski, 2021) stands, topology optimization (Figure 8) is a very useful design technique for developing conceptual architectures and is a tremendously powerful instrument that can be utilized for mass reduction.

2.1.2 Aluminium

Aluminium is a fast-growing competitor to steel in the automotive industry (Figure 9), with its use as an automotive body material increasing dramatically over the last decades. It is a material that is lighter than steel and with higher specific mechanical properties. The material's small weight has made it attractive among auto engineers looking to reduce vehicle mass for better fuel economy and emissions.(Czerwinski, 2021)

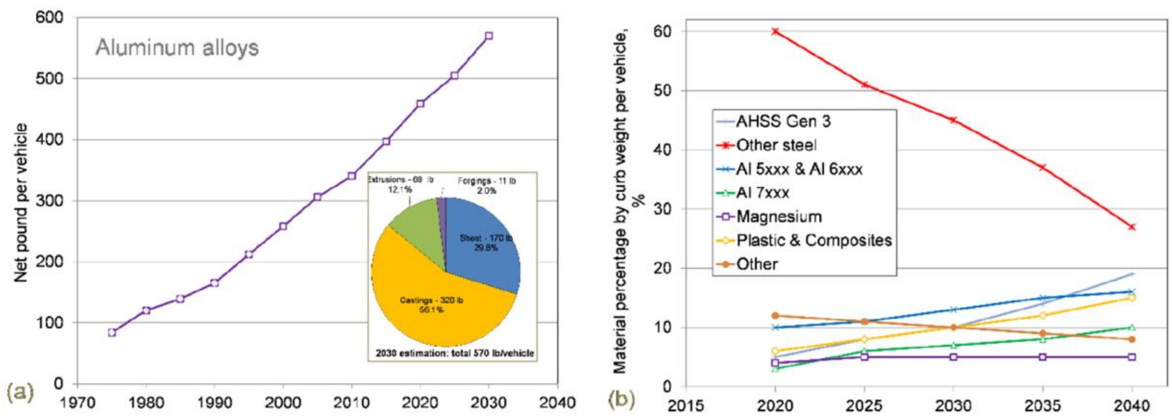


*Figure 9 Present and predicted contribution of automotive materials: **(a)** Automotive aluminium content from 70s to predicted in 2030. **(b)** Material percentage of curb weight per vehicle used in vehicle structure. From* (Czerwinski, 2021)

Aluminium integrates very well into a circular economy since it can easily recover and reused in new goods. According to (The Aluminum Asociation, 2020), aluminium is the fastest growing automotive element and its consumption in the automotive sector has increased from 154 kg per car in 2010 to 208 kg per vehicle in 2020 in the US. It is predicted to increase by 12% from 2020 levels to 233 kg per car by 2026. According to European statistics, the quantity of aluminium per car has climbed from 50 kg in 1990 to 151 kg now, with a projected increase to 196 kg per vehicle by 2025.(Czerwinski, 2021)

Even if aluminium is becoming more popular, the engine, gearbox, wheels, heat exchangers, chassis, and suspension are one of the few components where aluminium is currently used. At present, the primary impediment to expanded aluminium use is perceived to be cost.

From the manufacturing point of view, aluminium is malleable, recyclable, easier to machining material, and has a lower melting point in consequence requires less energy to be conformed or cast into final components.

The most popular manufacturing method for aluminium components is casting; When compared with alternative production technologies as chill casting or sandcasting, high pressure die casting provides considerable time reduction for manufacturing cycle of individual parts while also allowing a wider range of shapes, lower cost and high accuracy and consistency of the parts.

2.1.3 Plastics

Plastics are a category of functional polymeric compounds with a set of desirable properties. They are strong, long-lasting, and light. They can be transparent, translucent, or opaque; soft, flexible, or hard; and in virtually any shape, size, or colour.

They can withstand chemicals, and corrosion. They are good thermal and electrical insulators and can also be made electrically and thermally conductive. Plastics are particularly cost-effective in a wide number of commercial applications, including a wide range of usage in the automotive industry, due to their adaptability.

Plastics, like aluminium, have benefited from the never-ending quest for greater fuel economy in today's vehicles. As vehicles are getting lighter every time, different and more adapted materials are required to supply some applications.

Prior to the 1970s, plastics were primarily considered non-engineering materials and have been used in applications such as hoses, gaskets, belts, sealing, carpet, adhesives, tyres, and so on as part of an engineering solution.(Sehanobish, 2009)

Plastics have now permeated engineering applications in the automotive industry, rapidly replacing traditional materials in only the last 30 years. Because of their low strength-to-density ratio, plastics are a relatively weak choice for engineering applications where high strength is required like high stressed pieces and structural components.

Polymeric materials have become one of the most popular materials for non-structural applications as interior and trimming, covers and places were not aggressive conditions have to be withstood. (Figure 10)

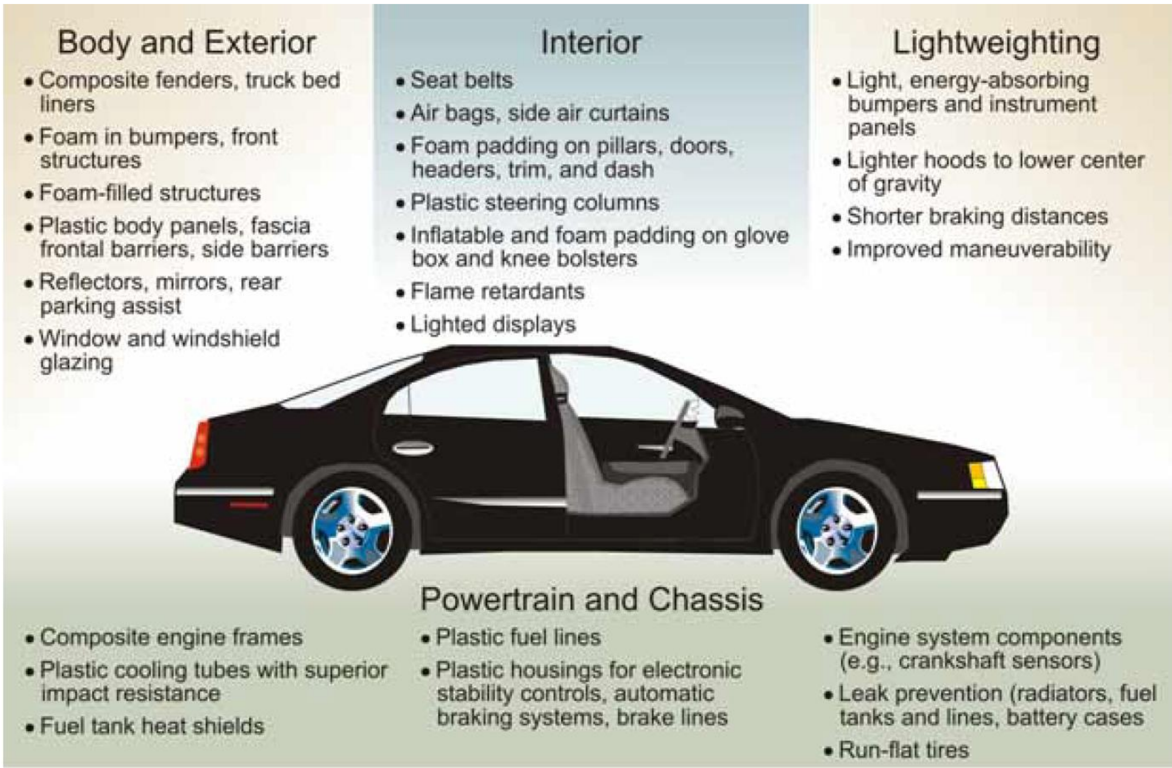


Figure 10 Overview of use of plastic in vehicles. From (Fisher et al., 2007)

The use of thermoplastic and thermoset polymers has risen from approximately 30 Kg in 1970 to over 150 Kilograms in the present time, and in today car they make up for 15% of vehicle weight and 50% of volume.

Technological developments in polymers, manufacturing cost and simplicity, along with the recyclability of most of thermoplastics are some of the reasons for the constant increasing of plastics application in the automotive industry.

2.2 Composite materials.

Composites are not a new or recent idea, in fact nature itself have shown us an innumerable number of examples like Wood which is composed by cellulose Fibres in a lignin matrix (Krishan K. Chawla, 2020) or bone, which consist in collagen Fibres inserted in a mineral matrix. (Weiner & Wagner, 1998)

Composites have been widely used as engineering materials in diverse cases like glass Fibre with resin, asphalt mixed with sand, black carbon in rubber composites among others examples, in particular applications for a long time, but the beginning of the 1960s is a reasonable assumption for the emergence composite materials as a discipline, these been mostly influenced by the increase of the demand of lighter and stronger components in aerospace, energy, transport and construction sectors.(Krishan K. Chawla, 2020)

In early years, usage of composite materials in automotive sector to reduce weight has been limited above all by its high production cost derived from the complex manufacturing process, which in some cases is performed partially or completely by hand. Recently, with the advancement in manufacturing technologies and therefore lowering manufacturing costs, the use of composites has been spreading allowing the inclusion of these in a wider range of vehicles.

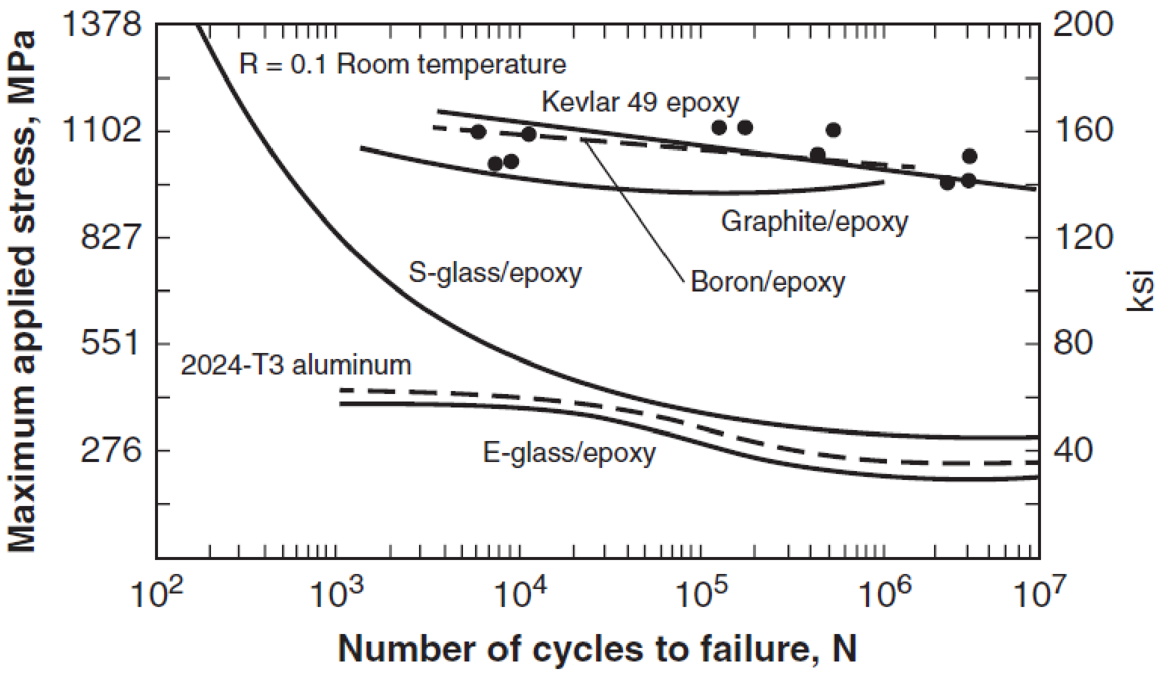


Figure 11 Number of cycles to failure as a function of maximum stress for aluminum and unidirectional polymer matrix composites subjected to tension–tension fatigue with a stress ratio R = 0.1 from (Zweben, 2015)

Considering the low thermal expansion in comparison with common alloys, the very good resistance to fatigue shown in Figure 11 and high mechanical characteristics and their light weight the potential of composites to replace some other engineering materials is very high. (Figure 12)

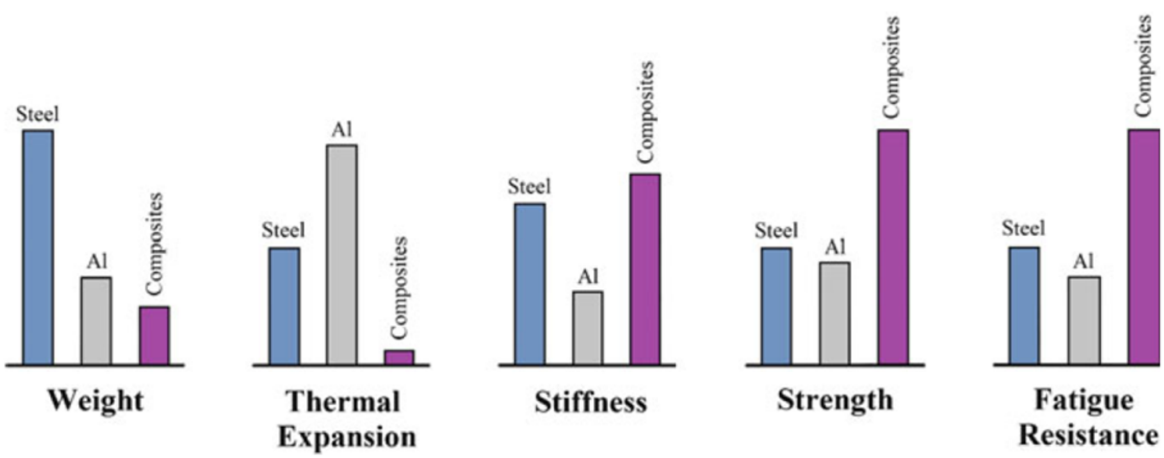


Figure 12. Qualitative comparison of properties of composite materials, steel, and aluminium. from (Krishan K. Chawla, 2020)

A composite material is defined as the result of the merge of two dissimilar materials with different properties and chemical composition to acquire improved properties compared with the properties of a single material. In a composite material, constituents form an interface and are both clearly distinct between distinguishing composite materials from solid solutions and alloys.

Usually engineered composites are created to replace materials where the application requires a particular mix of properties taking advantage of each of the constituent materials. Some popular reasons to use composites materials are to reduce weight, to increase mechanical properties, to have a better chemical resistance, to reduce cost of materials and in some cases to ease the manufacturing process.

Materials conforming a composite are catalogued as matrix and reinforcement. The Matrix function is to protect, hold in place, and transfer the loads to the reinforcement, in consequence the matrix's mechanical properties are usually reduced compared with the ones of the reinforcement. The properties of the matrix as chemical resistance, temperature range, abrasion resistance, heat and electric conductivity limit the conditions of service of the composite, all of them determine the external characteristics of the finished material. (Barbero, 2010)

The most common matrix material are polymers mainly due to their ease of manufacturing, allowing them to conform complex parts while keeping reduced tooling costs.

The component that is used as reinforcement is placed with the scope of provide to the overall material better mechanical properties and it can be placed inside the matrix in different shapes and arrangements to better accomplish the desired properties of the material and the design requirements of every application.

Reinforcement can be in the form of whiskers, flakes, particles, fibres, and some more complex structural shapes. One of the most common reinforcement types are fibres, due to the increased mechanical properties and low density associated to the fibrous form of the material.

Figure 13 shows how composite materials can be categorized based on the material used as matrix or reinforcement and its shape and disposition within it.

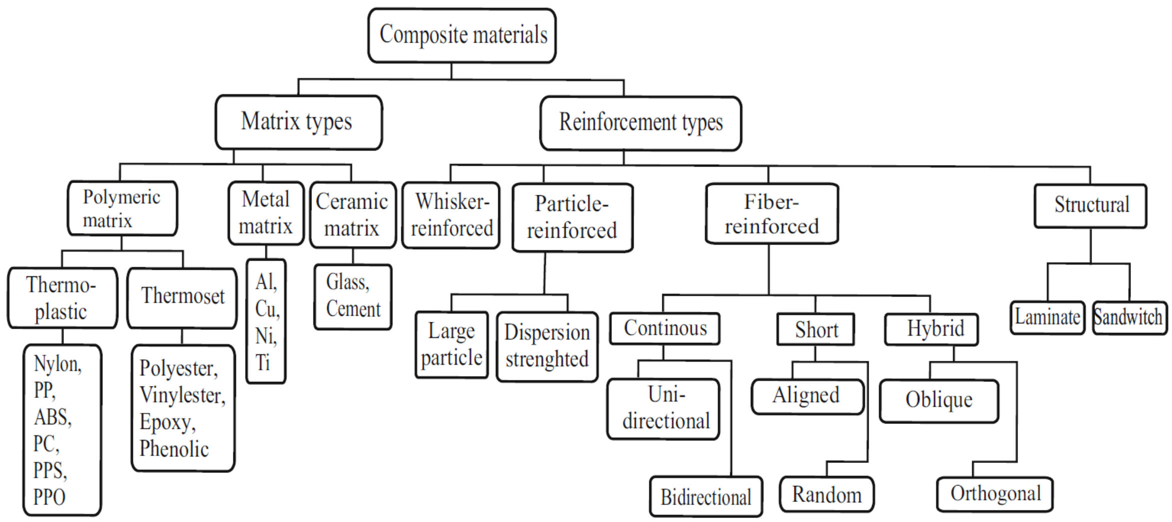


Figure 13. Composites classification based on type of material used as constituents. (from (Priyanka et al., 2017)*)*

Among popular materials used as fibre reinforcement of composites are aramid fibres, carbon fibres, alumina, and glass fibres which are commonly silica based (~50–60 % SiO2) and some other oxides of boron, calcium, aluminium, iron or sodium (Krishan K. Chawla, 2020)), etc. Some of which endow the engineered composite with high strength and high stiffness simultaneously.

Carbon fibre reinforced composites (CFRCs) materials are one of the most known and popular composite material, long continuous fibres oriented in multiple directions are used as the structural part of the material while thermoset or thermoplastic polymers are commonly used as the matrix.

2.2.1 Metal Matrix composites

Metal matrix composites (MMCs) are often an alternative option to reach high strength in some powertrain components while keeping a lower weight, thus reducing masses and in some cases also enhancing the thermal properties and wear resistance of the components.

Because of its low density, outstanding strength and ductility, and excellent thermal conductivity and corrosion resistance, discontinuously reinforced aluminium matrix has been proven to have a high potential for automotive applications. (Mussatto et al., 2021) To enhance the aluminium's low resistance to seizure and galling, it is reinforced with hard ceramic particles, short fibers, or whiskers which also can act as solid lubricants.

Table 1 Powertrain components made of Metal matrix composites and their main characteristics.

Component	**Materials**	**advantages**	**disadvantages (limitations)**	**Manufacturing method used**	**Technological maturity**	**suitable for AM?**
Piston (Figure 16)	"Aluminium alloy matrix reinforced with ceramic particles and fibers." (Stojanovic & Glisovic, 2016) "Silicon carbide (SiC) is commonly used as reinforcement"	Reduction in the coefficient of thermal expansion (CTE). Improved resistance to thermal fatigue and reduced wear. Allow operation range with higher temperature due to it enhanced heat transfer.	Not stated	"Squeeze casting technique"	"Serial production of these pistons has begun in Japan in 1983"(Stojanovic & Glisovic, 2016)	Yes / Selective laser melting / Powder metallurgy
Piston pin	(Steel and Al-alloy) steel sleeve and pressed-in aluminum core.	Up to 30% weight reduction, particularly in large pins. It allows significant overall mass reduction of the entire engine due to the mass savings of counterweights and balance shafts.	In low operating temperatures the aluminium core shrinks more than the steel sleeve, but the interference fit must be maintained between the core and the sleeve. To meet the necessary minimum overlaps very tight component	Press-in fit "Exemplary representation of the production of a composite pin" Figure 14	"The idea of a piston pin as composite is not new. Already at the beginning of the 20th century the first patents were applied." (Maurizi & Lochmann, 2015)	No

			tolerances must be guaranteed. There are connection risks such as adhesive wear and material changes due to high joining temperatures			
Cylinder Block	hypereutectic aluminum-silicon composite (Al– Si)	Improved warm qualities reduced weight enhanced wear resistance	slightly higher cost	stir and squeeze casting	"They have been utilized by a few distinctive car makers, including General Engines, Porsche, Audi, Mercedes Benz, Volkswagen, and BMW."(Srivyas & Charoo, 2019)	Yes/ powder metallurgy, Friction powder sintering, spark plasma sintering
Liners (Figure 15)	Aluminium amalgams fortified with graphite	reduced wear due to grease keeps the presence of limit oil.	Not stated	stir and squeeze casting	Used in Toyota Celica 2000	Yes/ powder metallurgy, Friction powder sintering, spark plasma sintering
Rotor of the axial flux electric motor on EV	Aluminium MMC with ceramic reinforcement	Not only save weight; the component's lower mass and reduction in force implies that engineers may be able to eliminate the number of fixing bolts	More complex manufacturing methods	Machining	Functional prototype	Complex but feasible

		required, reducing the bill of materials and assembly time. Minimise parasitic mass, improving the power-to-inertia ratio and therefore efficiency and responsiveness. Better thermal resistance. (Srivyas & Charoo, 2019)				

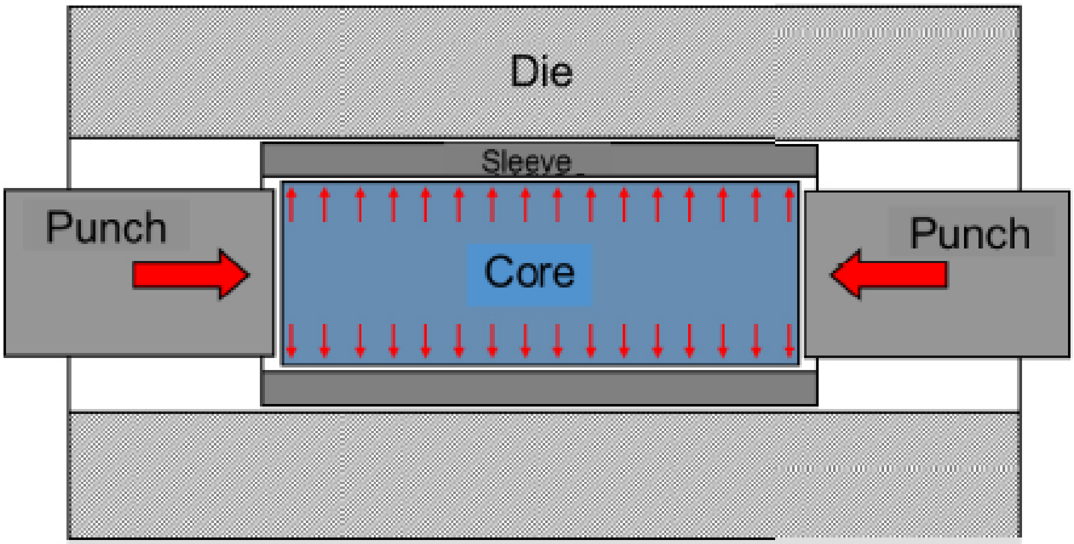


Figure 14 Squeeze casting technique for manufacturing of the piston pin. from

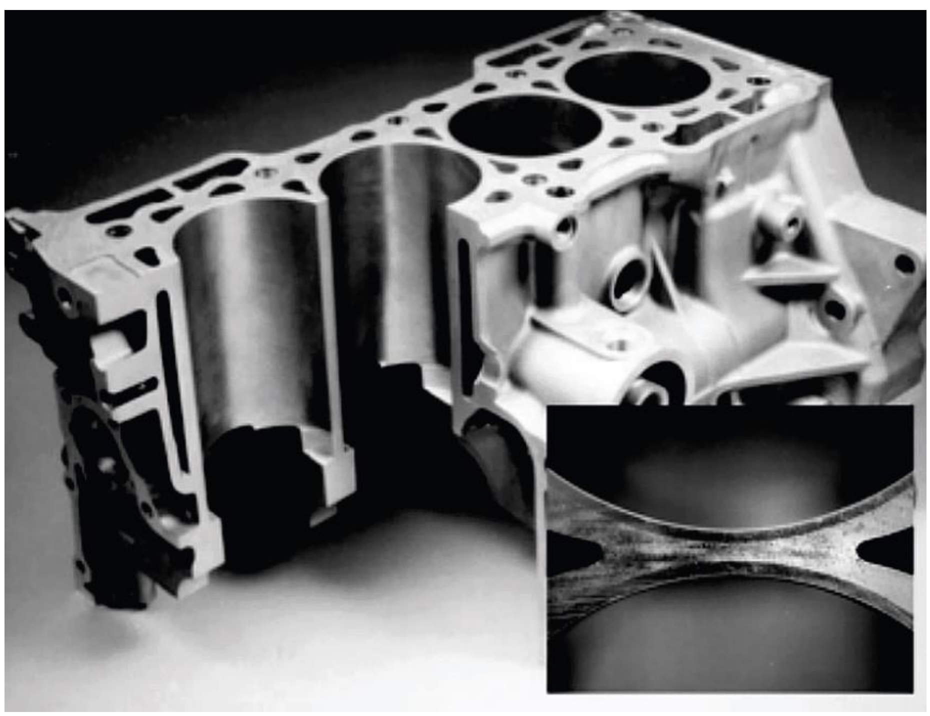


Figure 15 Honda prelude's engine Liner made of Aluminium MMC. from

The main objective is to produce inexpensive aluminium MMCs reinforced with SiC and Al_2O_3 that may be used to replace other structural vehicle components and decrease weight and boost engine efficiency but in some high-performance applications, some powertrain engine components like pistons, connecting rods (Stojanovic & Glisovic, 2016), cylinders or another components as vehicle braking systems (rotors), suspension systems, and chassis (Prasad & Asthana, 2004) can benefit from aluminium MMC with SiC reinforcement.

Recently developed aluminium MMCs can offer a greater specific stiffness, as well better wear and fatigue resistance.(Czerwinski, 2021).

Figure 16. Pistons made of aluminium MMC from (Stojanović & Ivanović, 2015)

Adopting aluminium MMC with ceramic reinforcement for rotor design In the place of steel for the axial flux electric motor used in EV saves 45% - 73% weight, increases the rotor's power-to-inertia ratio and motor power density by 225% - 300% (Czerwinski, 2021). Consequently, this allows the optimization of EVs motor's efficiency as function of speed and torque which largely determines the vehicle's energy consumption.

Table 1 shows some known applications for MMCs in the powertrain components of vehicles.

2.2.2 Polymer matrix composites and thier properties.

Regardless of whether the matrix materials can be polymers, metals, or ceramics; polymer matrices are the most frequently used because they allow for the manufacture of complicated pieces with minimal tooling and capital investment. (Barbero, 2010)

The high specific mechanical properties of polymer matrix composites are one of the big reasons to its crescent use in engineering applications; been fibre reinforced the most common type of filling or reinforcement; for instance, according to (Kaw, 2006) in a weight for weight comparison, graphite/epoxy composites are roughly five times stronger than steel.

Continuous fibre reinforcement composites present anisotropic mechanical properties, giving the material some advantages and disadvantages at the same time. Matrix type, fibre type, interface, volume fraction of components, manufacturing technique along with fibre orientation all of them influence the direction of the different mechanical properties of the finished part.

In specific applications anisotropic properties are an advantage due to the possible design of the component and material according with the force distribution within the part, reducing the amount of material used and improving the mechanical resistance of the material in the desired orientation and disposition.

Matrix dominated properties like corrosion resistance, flammability, thermal resistance, and manufacturing methods limit or define the type of polymer used to engineer the composite material; in fact, low operating temperatures, high expansion due to moisture and thermal effect, and low elastic properties in certain directions are indeed the major disadvantages of PMCs.

Table 2 Typical Mechanical properties of Graphite/epoxy composites and monolithic materials. From (Kaw, 2006)

Property	Units	Graphite/ epoxy	Glass/ epoxy	Steel	Aluminum
Specific gravity	—	1.6	1.8	7.8	2.6
Young's modulus	GPa	181.0	38.6	206.8	68.95
Ultimate tensile strength	MPa	150.0	1062	648.1	275.8
Coefficient of thermal expansion	μm/m/°C	0.02	8.6	11.7	23

The two primary types of polymers used to create advanced composites are thermosets and thermoplastics. Today, thermoset resins predominate, with thermoplastics playing a much smaller part in the production of advanced composites.

Production of a cured or finished part from thermoset resins requires the addition of a hardener or curing element, the impregnation of the reinforcing material, and a final curing step. Except for finishing, the part cannot be altered or reshaped after curing. Epoxies are currently the most widely used thermoset matrix for polymer matrix composites.

The properties of polymer matrix composites, particularly their strengths, are strongly temperature dependent. This also applies to epoxy formulations, even if they can have distinct cure and glass transition temperatures, polymers with good and elevated temperature properties such as polyimides, can in some cases compete with titanium mechanical properties.

Some aircraft gas turbine engine components that are made of polyimide matrices and can withstand service temperatures of up to 290°C. Again, the effect of temperature on composite properties must be considered on an individual basis. (Zweben, 2015)

Thermoplastic polymers are subdivided into three main classes, crystalline, amorphous, and liquid crystal, examples of crystalline are nylon, polyethylene sulphide, acetal, polypropylene, polyether sulphone and polyether ether ketone (PEEK). Amorphous thermoplastic polymers examples are polyetherimide, poly sulphone, acrylonitrile-butadiene-styrene (ABS), polystyrene and polycarbonate.

Amorphous thermoplastics have usually low solvent resistance, while crystalline materials tend to perform better in this aspect.(Zweben, 2015)

A crescent number of applications in thermoplastic matrix composites is due to the adaptability of it to different manufacturing methods, the possibility of been long and short fibre reinforced and since thermoplastic materials are known by been a cheap and highly recycled material.

2.2.3 Manufacturing methods

Manufacturing methods for different types of composites materials varies with matrix and reinforcement material, with different geometries and disposition of reinforcement as well with the requested work conditions and characteristics of the final product. In Figure 17 is evidenced the manufacturing technologies used in the production of metal matrix composites while in Table 3 the typical processes of manufacturing for polymer matrix composites are indicated based in the type of polymer matrix type and reinforcement disposition and geometry.

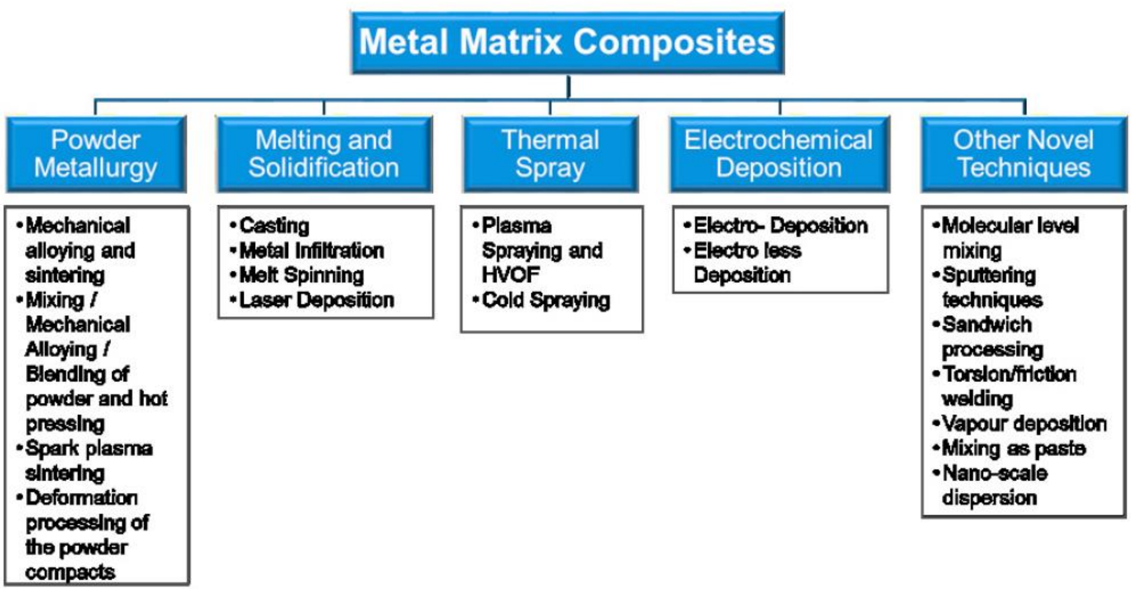


Figure 17 Metal Matrix composites manufacturing methods. From (Behera et al., 2019)

According to (Behera et al., 2019) among the documented manufacturing methods, casting and powder metallurgy are the most used methods to manufacture MMCs components.

Table 3 Most common polymer matrix composite manufacturing techniques. From (Cardarelli, 2018)

Polymer matrix	Reinforcement type	Techniques
Thermosetting polymers (e.g., epoxy)	Fibers, laminate, felts	Hand lay-up, spraying
	Monofilaments	Filament winding
	Fibers	Pultrusion
	Laminates	Autoclaving
	Reinforcement porous preform	Resin molding, impregnation
Thermoplastics	Laminate	Stacking
		Diaphragm forming
	Ribbon	Tape laying
	Fiber	
	Cut fibers, particulates	Injection molding

Even if some problems like segregation are common, metal casting have traditionally dominated the means of obtaining metal matrix composites parts.

Bearing in mind the critical issues of MMCs processing, is observed that conventional manufacturing techniques do not achieve a controlled dispersion of reinforcement, hence the full benefits of using metal matrix composites. In consequence, can be stated that for processing metal matrix composites, additive manufacturing methods have been identified as superior alternatives. Particularly the selective laser melting route has been determined to be the most promising option.

Polymer matrix composites have several substantial manufacturing advantages over monolithic materials and ceramics. for example, may be formed into large, complex geometry that would be hard or impossible to achieve with conventional materials.

As reported by (Zweben, 2015) ,the ability to produce complicated forms allows for part consolidation, reducing machining, assembly, and fastening costs. Some technologies enable the creation of parts to their ultimate shape or close to the final form resulting in cost reductions in production. The simplicity with which smooth shapes can be created is a key feature in the usage of this kind of composites in aerospace, turbine blades, and many other applications where fluid-dynamics are critical.

Some of the most common procedures for manufacturing polymer matrix composites (Figure 18) include filament winding (used mainly in pipes), autoclave forming (mostly used to make complicated forms and flat panels for structures where minimal void content and excellent quality are needed), and resin transfer moulding (employed method when small quantity of parts is required). (Kaw, 2006)

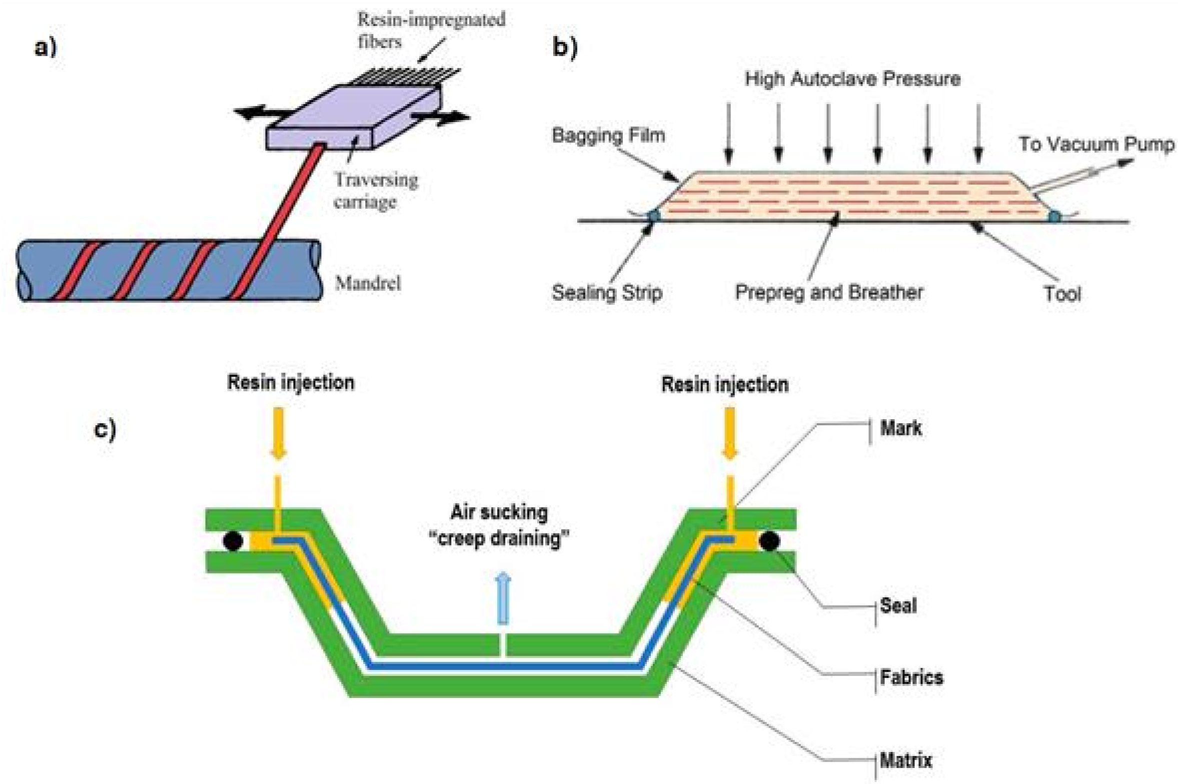


Figure 18 Three of the most common procedures for manufacturing polymer matrix composites a) filament winding. b) Autoclave-based processing. c) Resin transfer molding. From (Krishan K. Chawla, 2020) & (*Resin Transfer Moulding*, 2020)

Even if polymer matrix composites have been largely used during a long time, limitations related with the scalability of production have limited the spread along different industries. The next generation of composite design and manufacture has new perspectives because of the recent developments in additive manufacturing (AM).

2.3 Additive manufacturing

One of the technological advances of the transition from the analogue to the digital era is the mechanical design and the manufacturing of every kind of components in a very diverse range of industries.

Additive manufacturing is a novel way of industrial manufacturing where a computer-controlled process generates three dimensional objects through the deposition of layers of material in precise and sometimes complex geometries.

As is implied by its name, additive manufacturing consists in the commanded and timed addition of material to create a complete part, on the contrary, in traditional manufacturing methods is often necessary removing material through machining methods or giving a desired shape to the raw material.

Additive manufacturing (AM) techniques open a wide portfolio of applications like architecture, design, art, automotive, aerospace and in other large engineering disciplines.

Figure 19. A large number of factors like environment, measurement, operator training, and process parameters that influence the AM process deriving in a direct influence in the final component quality, performance and characteristics.

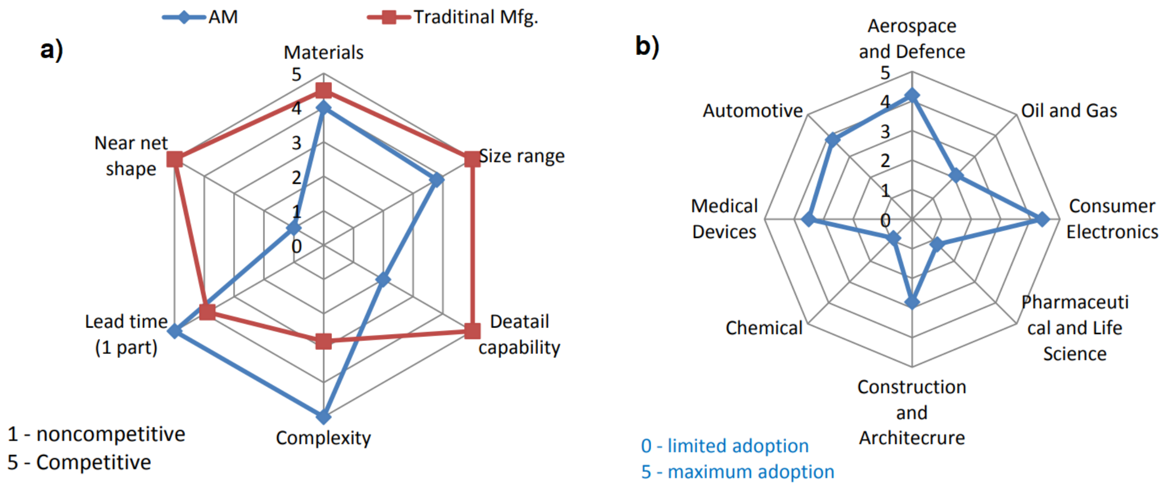


Figure 19 Additive manufacturing. a) Competitiveness against traditional methods. b) Forecast of adoption rate across industries 2015 - 2025. From (Durakovic, 2018)

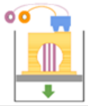
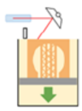
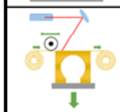
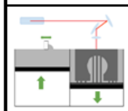
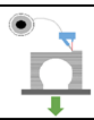
The optimization of the manufacturing process requires a comprehensive knowledge of the effects of the key process variables but also the interactions among them, in consequence some tools as numerical simulations and finite element analysis facilitate the evaluation and the definition of the most suitable parameters, materials and conditions in additive manufacturing of every specific part.

Research and development, rapid prototyping, iterative design etc, are some industries and sectors that have been positively impact with the development and fast adoption of this newly manufacturing method.

AM supports new design paradigms as artificial intelligence for generative design and topology optimization. The versatility of the process enables the possibility of making very complex structures, derived from this novel design techniques, as a result, designers spend less time perfecting designs and more time engineering.

Table 4 evidence some known methods of AM along with the indication of the geometry of the feedstock raw material, the way in which the layers are bonding among them.

Table 4 Summary of AM methods and compatible materials. From (Razavykia, Brusa, et al., 2020)

Process		Acronyms	Feedstock	Material	Bonding and join
	Extrusion (or fused filament fabrication or fused deposition modeling)	FFF, FDM	Filament, rod, pellets	Polymer	Fused with heat
	Photopolymerization (or stereolithography)	SLA	Liquid	Photopolymer, metal, ceramics, composite	Cured with laser, projector, UV light
	Material Jetting (or Binder Jetting)	MJ (BJ)	Powder, liquid	Ceramic, wax, polymer, metal, sand	Cured with UV light, heat
	Laminated Object Manufacturing (or Sheet Lamination)	LOM	Sheet	Paper, metal, polymer	Joined with agent, heat and pressure
	Selective Laser Melting	SLM	Powder	Metal	Fused with laser and electron beam
	Directed Energy Deposition	DED, EBM	Wire, powder	Metal	Fused with laser and electron beam

2.3.1 Composite materials and additive manufacturing

One of the biggest disadvantages present in the manufacturing process of thermoplastic matrix composite materials is the high cost of raw materials and infrastructure (winding machine or pultrusion lines). This makes it much more viable for high production numbers and in which a constant profile can be made and subsequently cut.

However, there is a growing interest and development in production methods associated with additive manufacturing. 3D printing allows the manufacture of parts with complex geometries and shorter production numbers in a precise and reproducible way without the need to manufacture other tools such as moulds or the use of expensive machines.

Printed components can be light, resistant and precise while reducing material waste in their manufacture, making 3d printing technology an environmentally friendly manufacturing method.

Fused deposition modelling (FDM) which is one of the most widely used 3d printing method is based on heating and melting reinforced or unreinforced thermoplastics, taking it above its glass transition temperature and, subsequently, extruding the molten material through a heated nozzle onto the printing surface, generating layers that join one on top of the other to form a final part.

Since no pressure is applied during the material deposition process, some pores, empty spaces, or interstices form between layers and between threads are generated, this reduces the stiffness and strength of the material compared to other components made using a conventional manufacturing method.

There is also a risk that when printing parts with pronounced curvatures and using a continuous fibre as reinforcement, the fibre may twist or break during the extrusion or deposition process.

In the additive manufacturing of this type of materials there are a large number of factors that influence the properties and quality of the final component, some of them are temperature, material selection, geometric complexity of the piece, filling density, layer and or thread thickness, printing speed, and as in hand-lay-up method in composites manufacturing, the final properties of the component strongly depend on the orientation of the fibres, whether they are short or continuous.

https://all3dp.com/1/carbon-Fibre-3d-printing-a-guide-for-decision-makers/

2.4 Powertrain components

2.4.1 Design requirements for powertrain components

Piston

Connecting rod

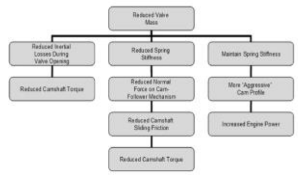
Crankshaft

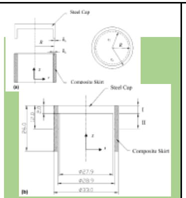
Valvetrain

Engine

2.4.2 Components previously designed for composite materials

Component	Materials	advantages	disadvantages (limitations)	Manufacturing method used	Technological maturity	suitable for AM?
piston pin	steel and CF/PEI-AS4,	- Increased torque on crankshaft due to the affected alternating forces increasing the overall efficiency of the engine. - High thermal durability (170 °C) and superior mechanical properties.(Razavykia, Delprete, et al., 2020)	"The shear stress around the pin holes suggests considering a different distribution of the Fibres or the usage of another composite with a better shear strength at this zone."(Razavykia, Delprete, et al., 2020)	Not specified	Simulation applying commercial engine data and geometries concluding that the material meets the requirements for the application.	Yes / depending on Fibre orientation needed
connrod	Unidirectional carbon Fibre reinforced Polyetherimide (CF/PEI) thermoplastic composite	- “Lighter than actual connecting rods.” - “Better distribution of the stress caused by the assembly preload, through the material”. - “The torque with composite material components demonstrated a higher peak value due to the lower inertial force." - Lower oscillation with respect to the steel components which is also a consequence of the lower inertial force.(Razavykia, Delprete, et al., 2020)	Requires acurate design and manufacturing, generating higher production cost than conventional connecting rods.	Not specified	- Simulation applying commercial engine data and geometries concluding that the material meets the requirements for the application. - Carbon Fibre reinforced connecting rods are already used but due to its high cost is not a spread and common solution for road car's engine.(Razavykia, Delprete, et al., 2020)	Yes

Intake valves	 PETI-RFI Mat carbon Fibre unidirectional reinforcement	 Fig. 1 Effects of reduced valve mass on engine performance. Increased fuel economy Increased power output and h power density, Reduced Noise and increase confort. Increased performance	- Required the addition of the stainless steel valve cap to address the valve face degradation increasing the weight of the valve and affecting the flexural stiffness which under high RPM can give concern about seating and sealing control of the valve. -High projected production costs	Resin transfer molding RTM was the scalable option by the time of the research	Product development, manufacturing parameters defined, cost assesment for mass production.	Yes / There would be some limitations related to the manufacturing method, further test required to asses the effect of the manufacturng method in component properties

Valve lifter	 Surface harde steel for the fa carbon/pheno composite for	 Reduced weight by 65% "Inertia loads can cause unde behaviors of the valve train ar diminishing them is helpful in improving the engine perform	A more complex manufacturing method and expensive materials may increase its production cost	carbon/phenolic fabric prepreg is roll-wrapped manually over a mandrel, then vacuum bagged and cured in an autoclave, then Composite skirt and the steel cap already manufactured are press-fitted as the final process	Prototype hybrid valve lifters were design and manufactured a series of durability tests were conducted on the laboratory bench	Yes / Surface and mechanical properties may differ from the assesed model
Engine Cover	thermoplastic composite 1.48g/cm3 density material	"can achieve similar structural requirements (NVH) as the metal cam covers while providing substantial cost saving and weight reduction."	Not adressed	Not specified	"the experimental parts were prototyped and tested in a Ford F150 vehicle for NVH performance."	Yes

Gearbox housing	  which was to molded with short-Fibre-re plastic.	ng weight downto e long range (electric le)	 "injection molding ribs on the organo sheeting were used to ensure stiffness targets were achieved"	extrusion-coated	Thermoplastic composite gearbox housing for electric vehicles was developed and manufactured after a reengineering process using topology optimization	Yes / Multiple additive manufacturing technolgies would be necessary to acquiere a similar result.

3 CASE OF STUDY

The camshaft is a very critical component of the 4-stroke internal combustion engine, that is because its main function is to produce and keep synchronized the exchange gases process within the engine by the opening and closing the in-cylinder valves.

The camshaft is driven by the crankshaft by gears, chain-sprocket, or a synchronous belt in order to keep constant the ratio and the position of the engine main shaft and the camshaft. The engine camshaft is rotating at half the speed of the crank and the set of cams which open the valves either directly or through pushrods.(Figure 20).

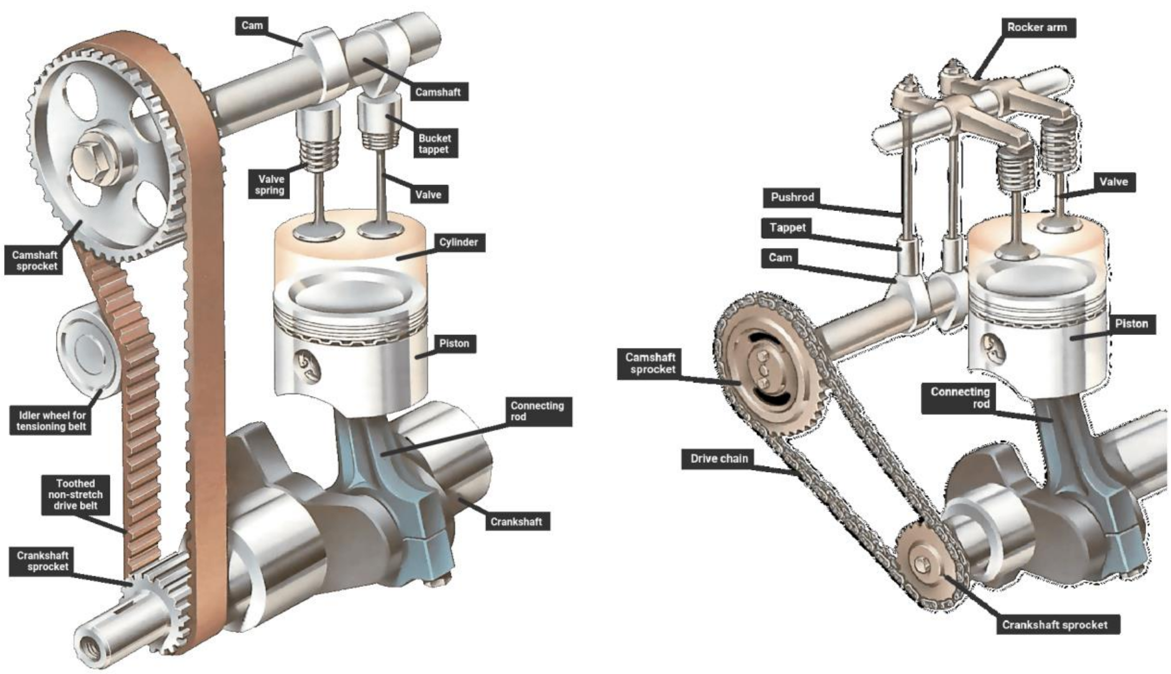


Figure 20 Two different arrange of engine valvetrain. Single over head camshaft (left) & Over head valve or pushrod engine (right) from pngegg.com

The objective is to determine the stress distribution and the maximum displacement on the cam shaft for the static case through finite element analysis.

A comparative study is held between two camshafts , one of them as the original equipment manufacturer option (made in cast carbon steel) (tableff) and in the case it would be made form a short carbon fibre reinforced thermoplastic (tablegg).

The camshaft geometry is from a widely used engine in 1990's which main characteristics are shown in tabled

3.1 State of the art

There are multiple studies where the 3D modelling, modal analysis and statical analysis has been performed (Gupta, 2022), (Saraswat et al., 2017), (Patil et al., 2013), (Ansari, 2017), (Benade & Bhapkar, 2021) in order to evaluate both a set of different materials and different geometries while looking for a improved material or shape to enhance the performance and the efficiency of the automotive engine.

Even if diverse finite element analysis has been performed before in order to understand the static, dynamic and fatigue behaviour of the component, no proposal could be found of a thermoplastic matrix composite camshaft.

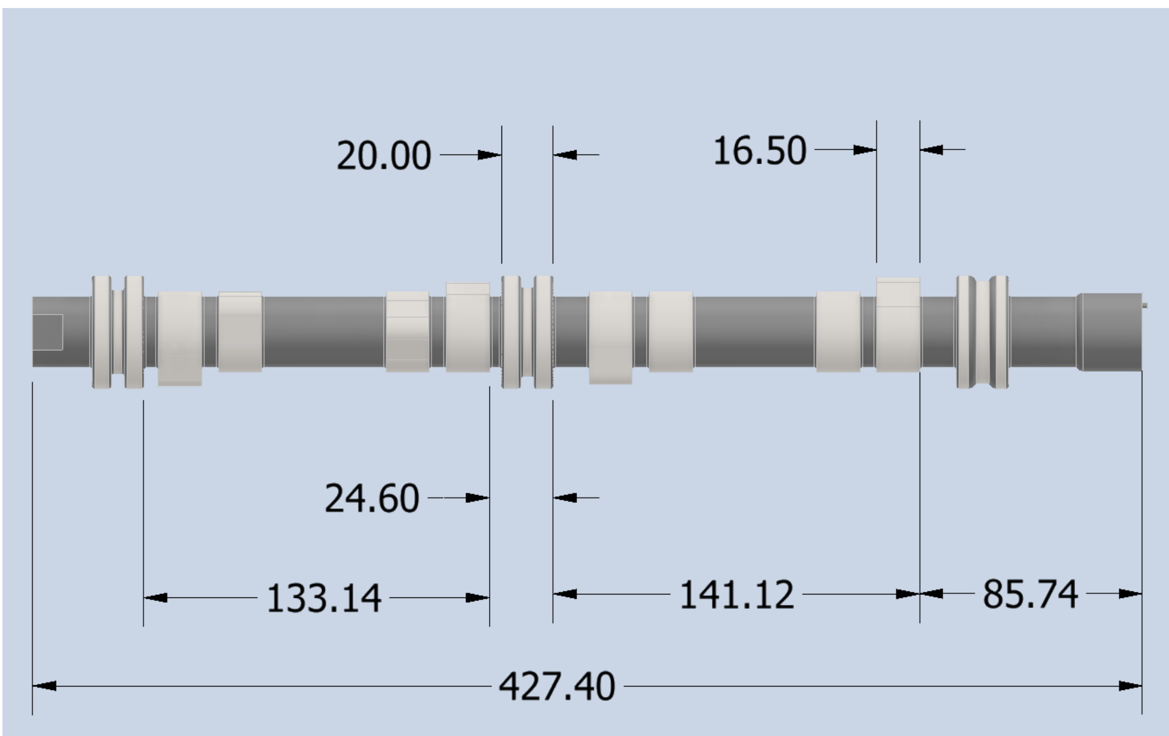
3.2 Design requirements

From the material point of view

Introduce the case

Describe the engine

Reference	B3 series
Type	Spark ignition
Aspiration	Naturally aspirated
Valvetrain	SOHC
No Valves	8 valves, 2 per cylinder
Cylinders	4 in line
Displacement	1323 cm^3
Bore	71 mm
Stroke	83.6 mm
Rated power	Up to 54kW / 72HP at 5500 RPM
Rated torque	Up to 105Nm at 3500 RPM
Compression ratio	9.7:1
Used in	Kia Pride, Ford Festiva, Mazda (121, 323 LX)



Heat resistance,

3.2.1 Forces acting over the camshaft

Parameter	Value	Dimension
Engine speed	5500	RPM

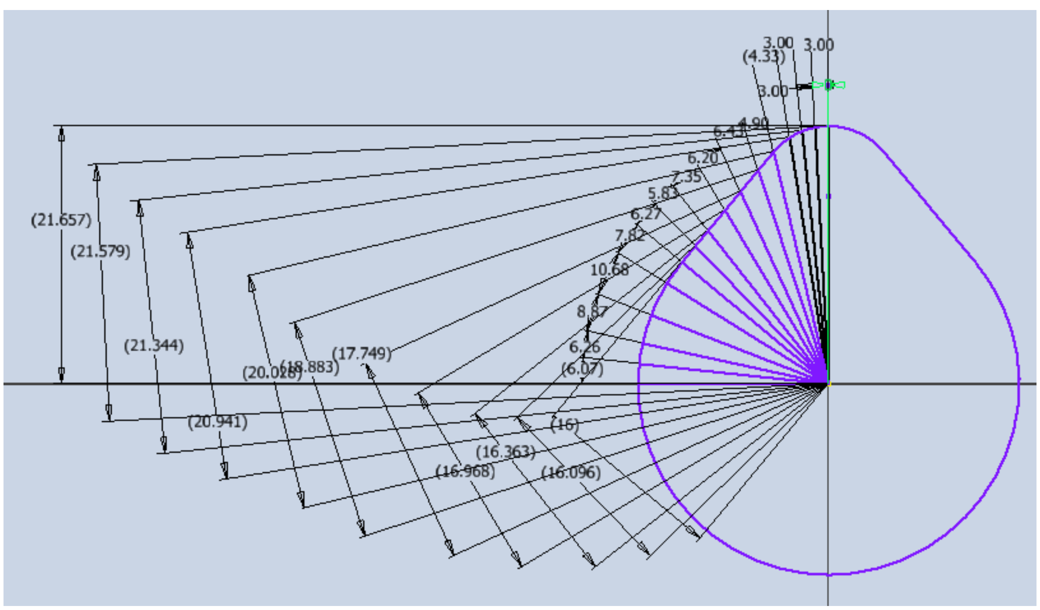
Engine power	54	kW
Valves stem diameter	7	mm
Intake valve head diameter	32	mm
Exhaust valve head diameter	28	mm
Intake valve height	105.3	mm
Exhaust valve height	104.1	mm
Intake valve mass	50	g
Exhaust valve mass	46	g
Rocker arm mass	51	g
Valve retainers (keepers) mass	1.01	g
Valve spring retainer mass	8.2	g
Maximum intake pressure	0.4	Bar

The parameters to calculate the dynamic parameters of the valvetrain are listed in the table above

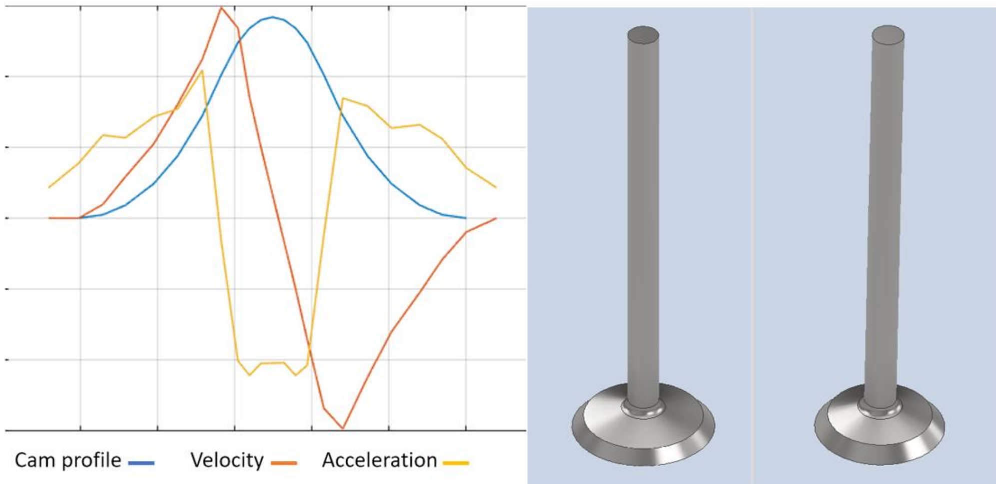
The maximum force is transmitted by the rocker-arm to the camshaft when the spring starts to push the valve to return from its fully opened to fully closed position.

This maximum force has to be generated by the valve spring is computedat rated power engine speed. It is determined by the computed acceleration of the valve times the alternating masses of the valve group.

Alternating mass consists of the sum of the valve mass which was inferred from geometry, keepers mass and spring retainers mass, and ½ of the rocker arm mass.



Starting from the CAD the cam geometry, the height profile, the vertical velocity, and acceleration of the valve group can be derived.



a) b) c)

The maximum negative acceleration along with the resultant alternating mass are combined to obtain the force acting over the cam lobe.

Equations and Maximum force value

Minimum force that the spring has to withstand and guarantee is the force generated over the back of the intake valve when intake pressure is maximum and the valve has to remaing closed.

This pressure times the back area of the valve is giving the preload that the springs must have to guarantee the correct working of the engine gas exchange process.

Equations and minimum force

The constant torque applied over the camshaft is derived from the percentage of friction losses, the fraction of this losses that is going to the valvetrain system and the rotation speed of the camshaft.

According with(calabretta e cacciatore) and (wong et tung) around 10% to 15% of engine friction losses is associated with the valvetrain components.

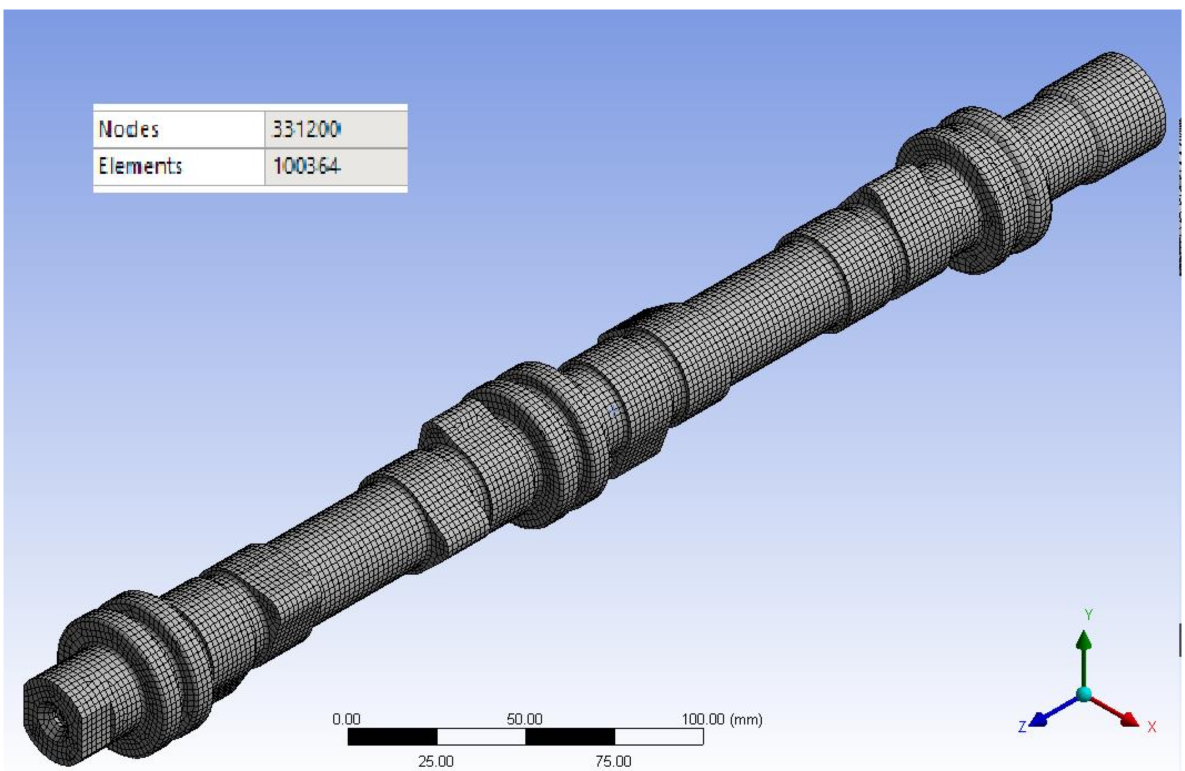
According to

And

$$\text{Torque (Nm)} = \frac{60 \times \text{Power (W)}}{2\pi \times \text{Speed (Rpm)}}$$

3.3 Geometry, meshing, and simulation set up

Original camshaft 3D geometry was obtained in a large collaborative database of CAD drawings named grabcad, the adaptation of the model to an usable format and solid geometry was performed with inventor 2022 software, and finally, the FEA analysis was completely done in Ansys Workbench static structural module.



Mesh metrics

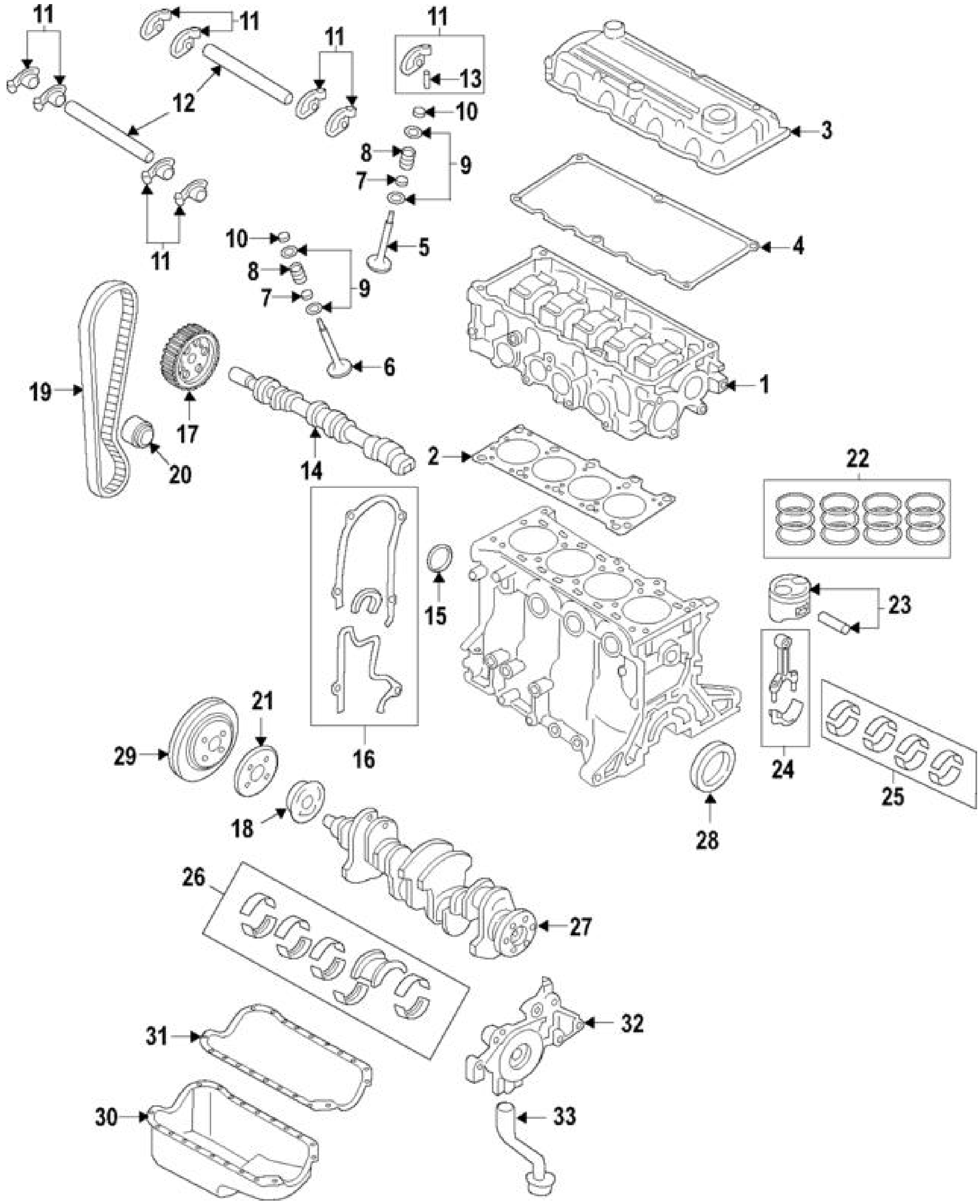
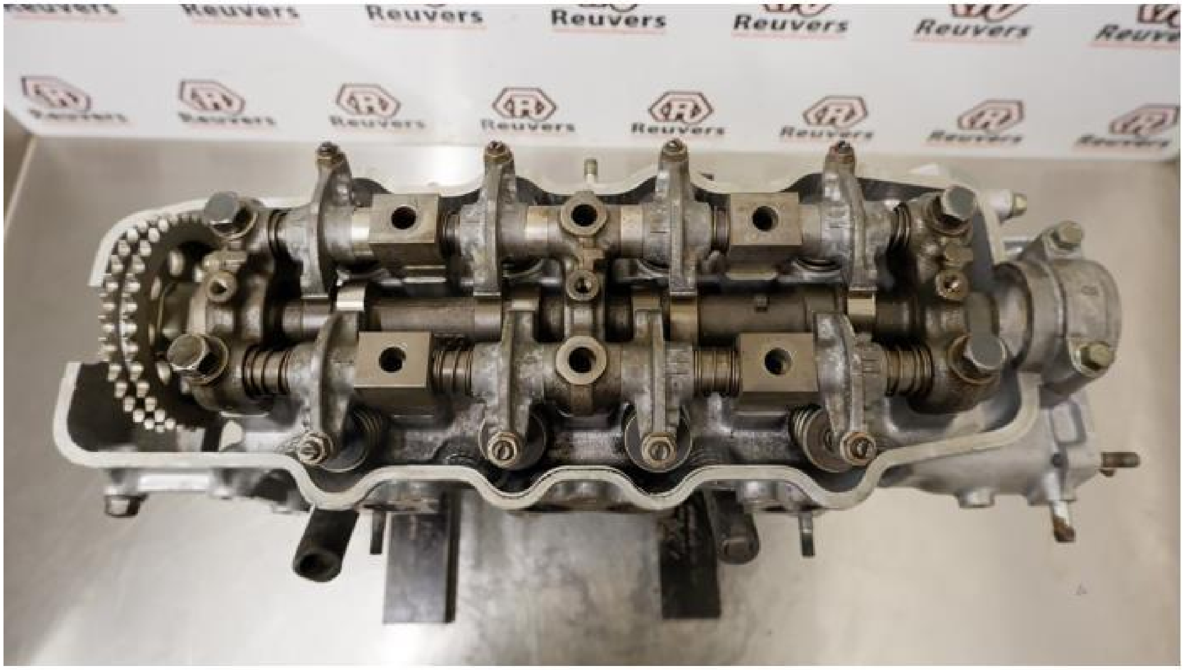
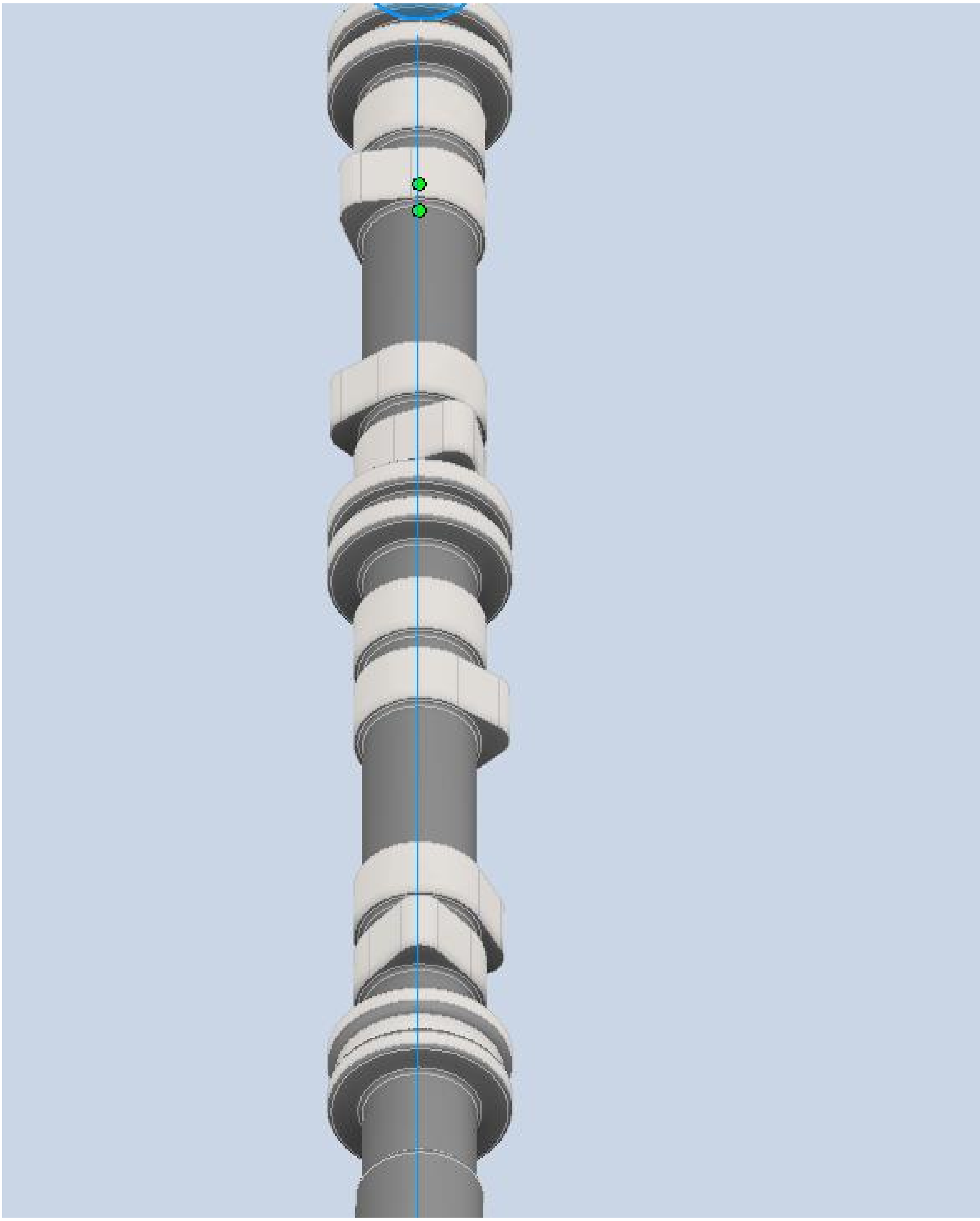


Figure 21 https://www.mazdaswag.com/oem-parts/mazda-timing-belt-b66012205c



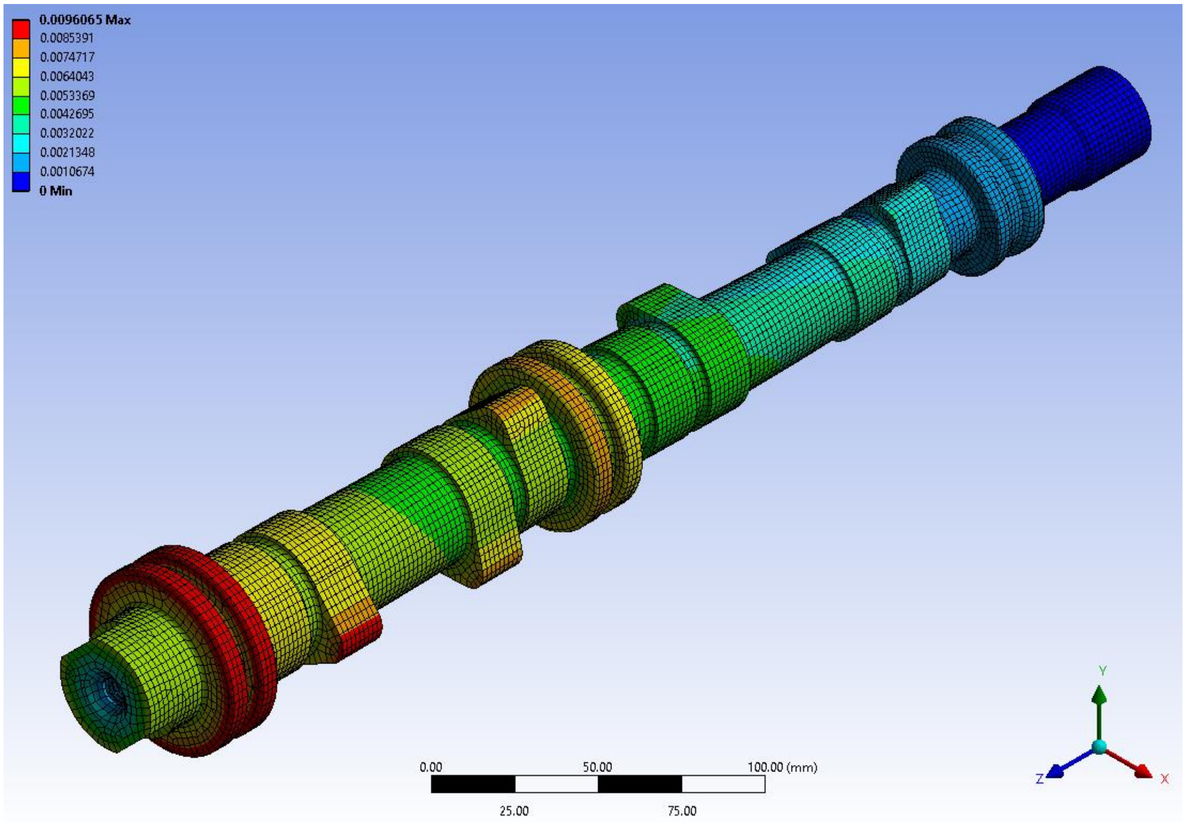
https://www.proxyparts.com/car-parts-stock/information/engine-code/b3/part/cylinder-head/partid/11851653/

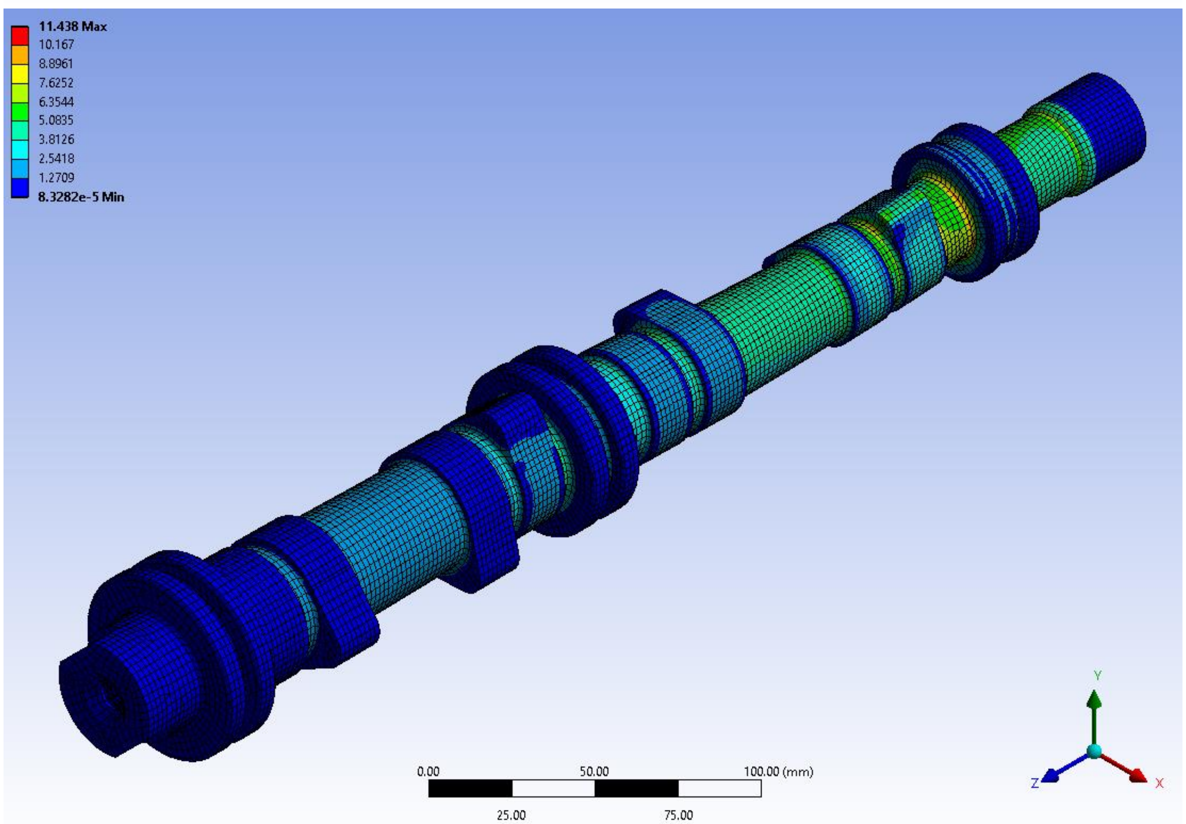


3.4 Finite elements analysis

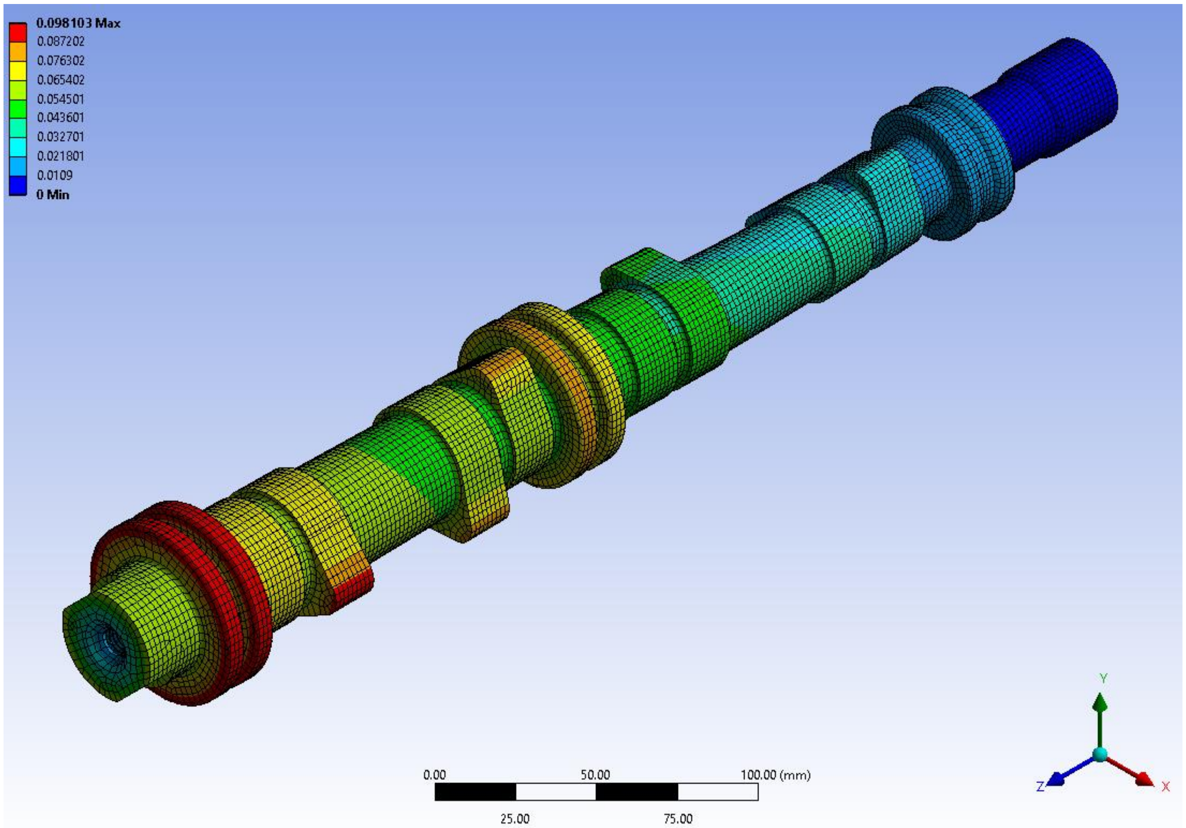
3.5 Results

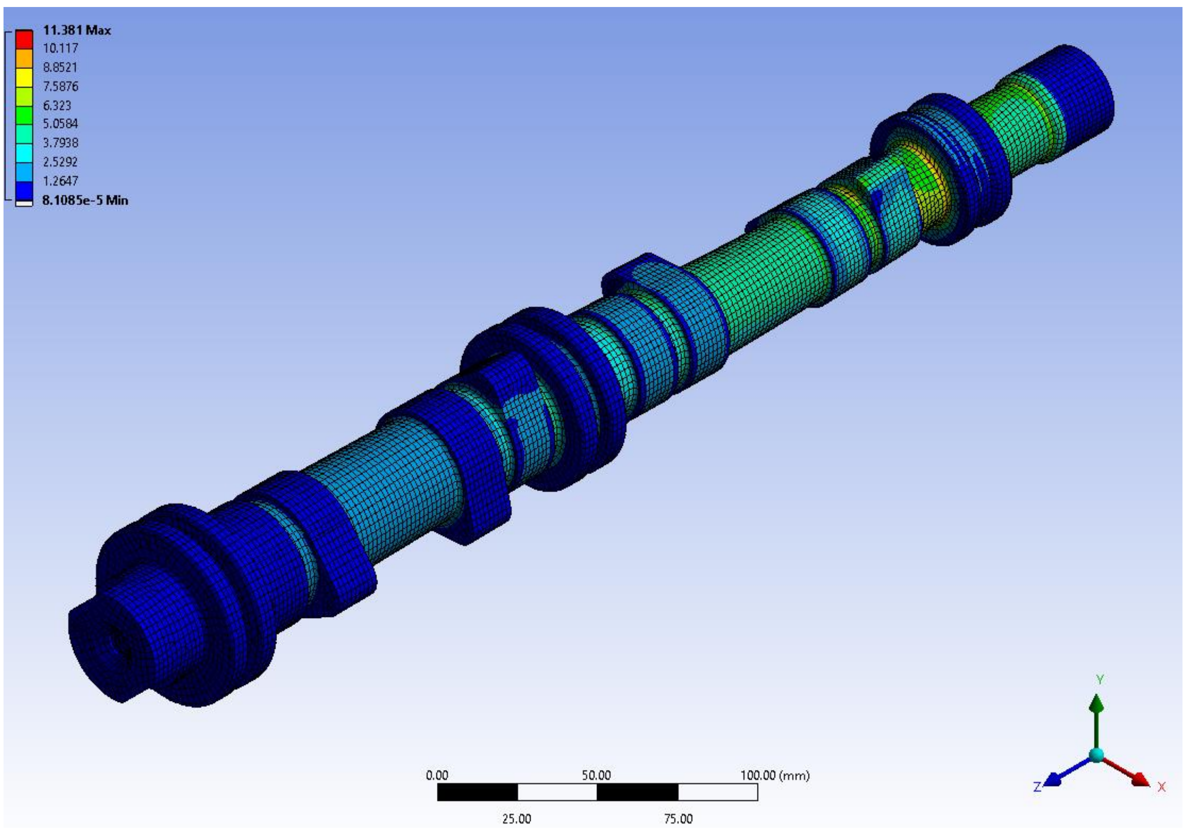
Total deformation and maximum equivalen von misses stres of steel camshaft


0.0096065 Max
0.0085391
0.0074717
0.0064043
0.0053369
0.0042695
0.0032022
0.0021348
0.0010674
0 Min
0.00
50.00
100.00 (mm)
25.00
75.00
Y
Z
X


11.438 Max
10.167
8.8961
7.6252
6.3544
5.0835
3.8126
2.5418
1.2709
8.3282e-5 Min
0.00
50.00
100.00 (mm)
25.00
75.00
Y
Z
X

Total deformation and Equivalent von misses stress short carbon fiber reinforced PEEK

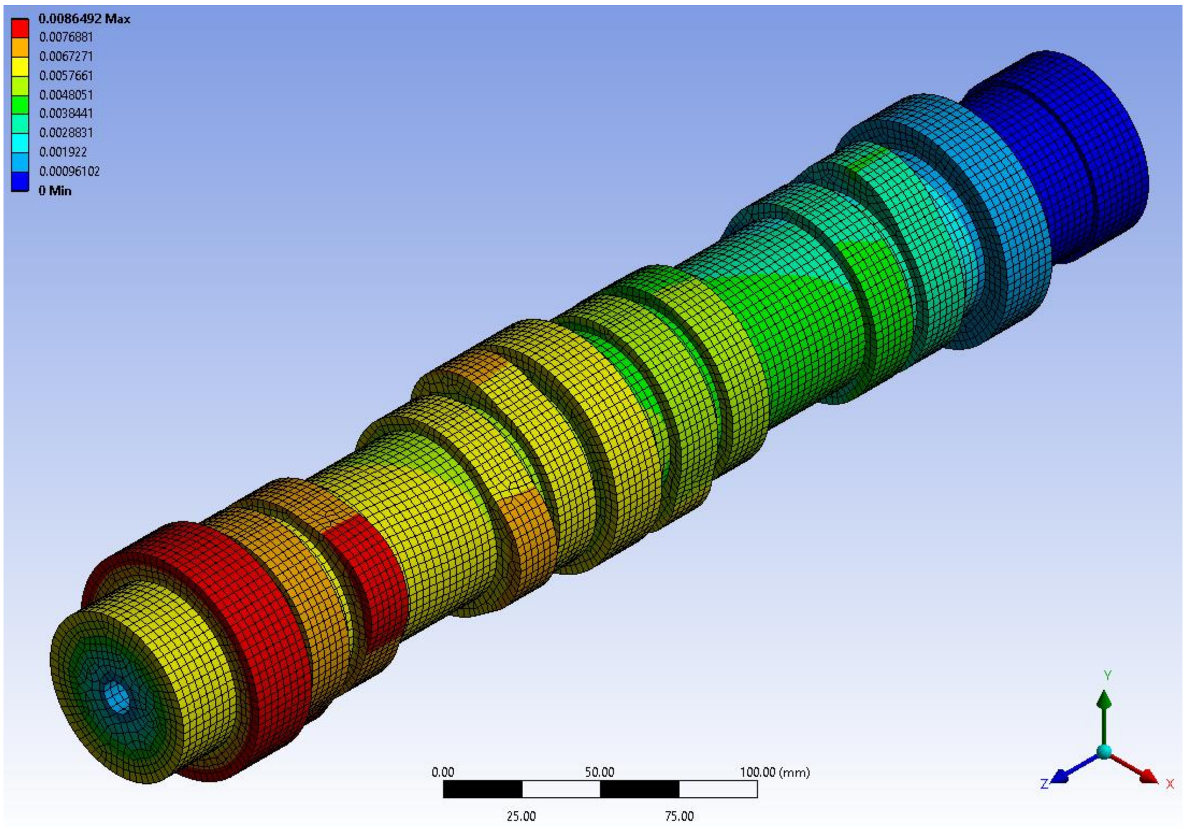


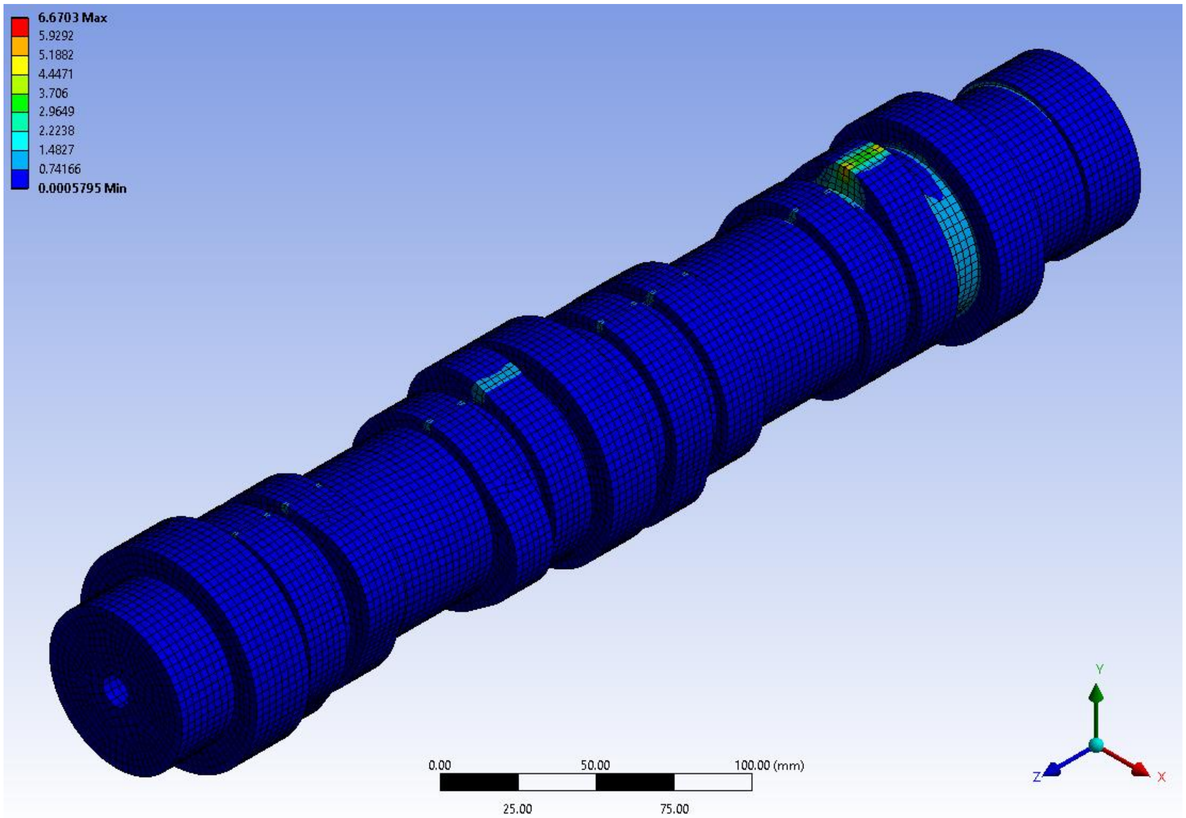


4 DISCUSSION

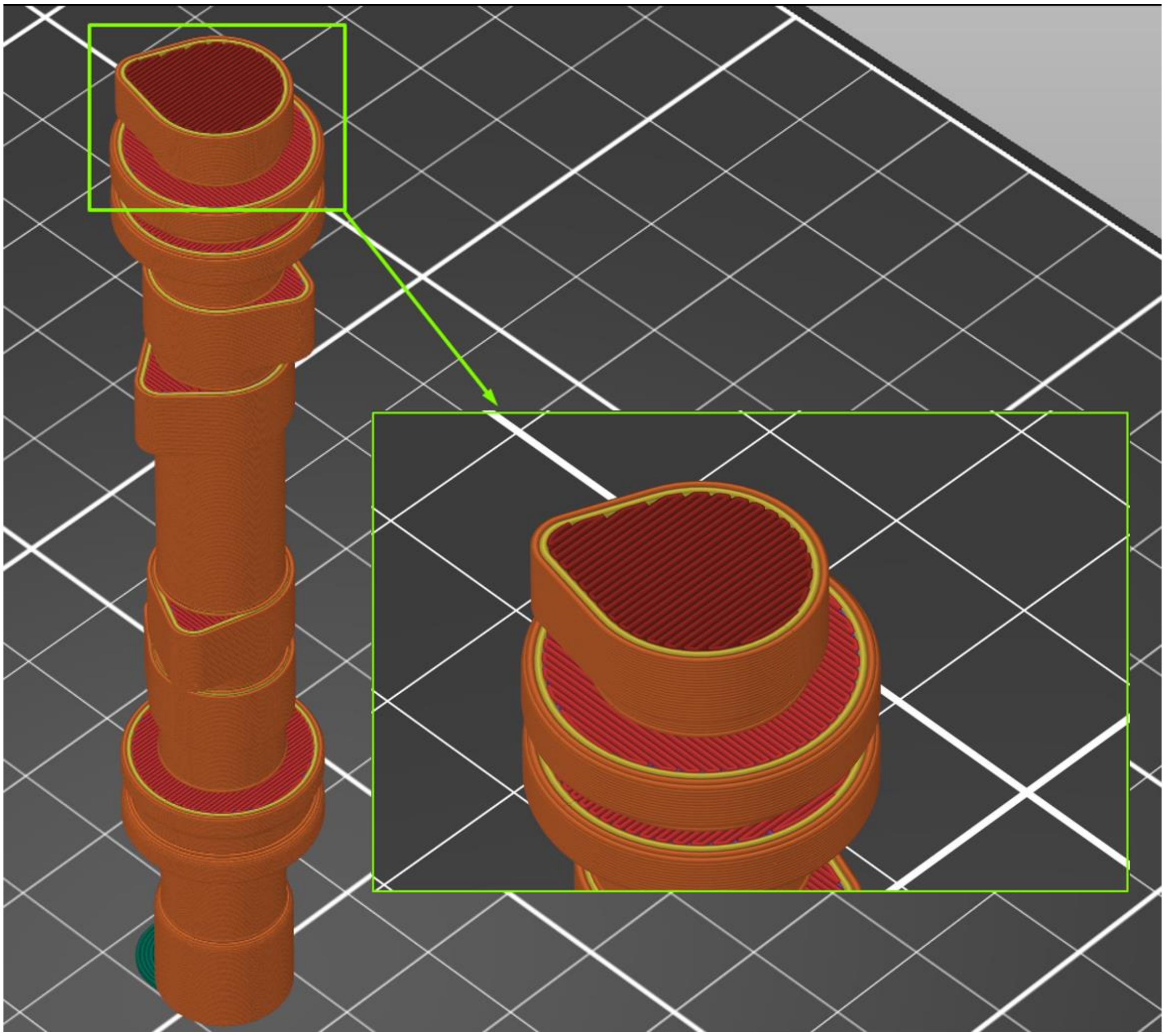
A proposed geometry to be manufactured in PEEK reinforced with short carbon fibres of the camshaft to withstand the same forces and moments but keeping max deformation lower than the OEM component

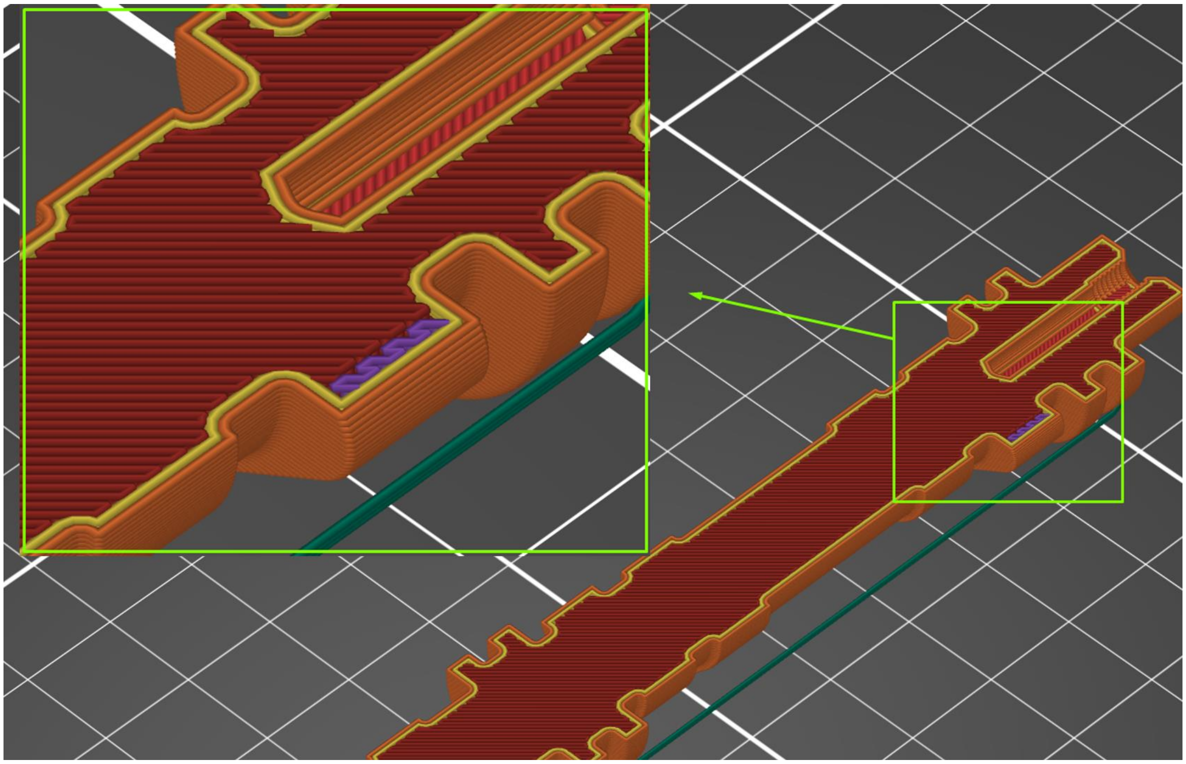
This is the result

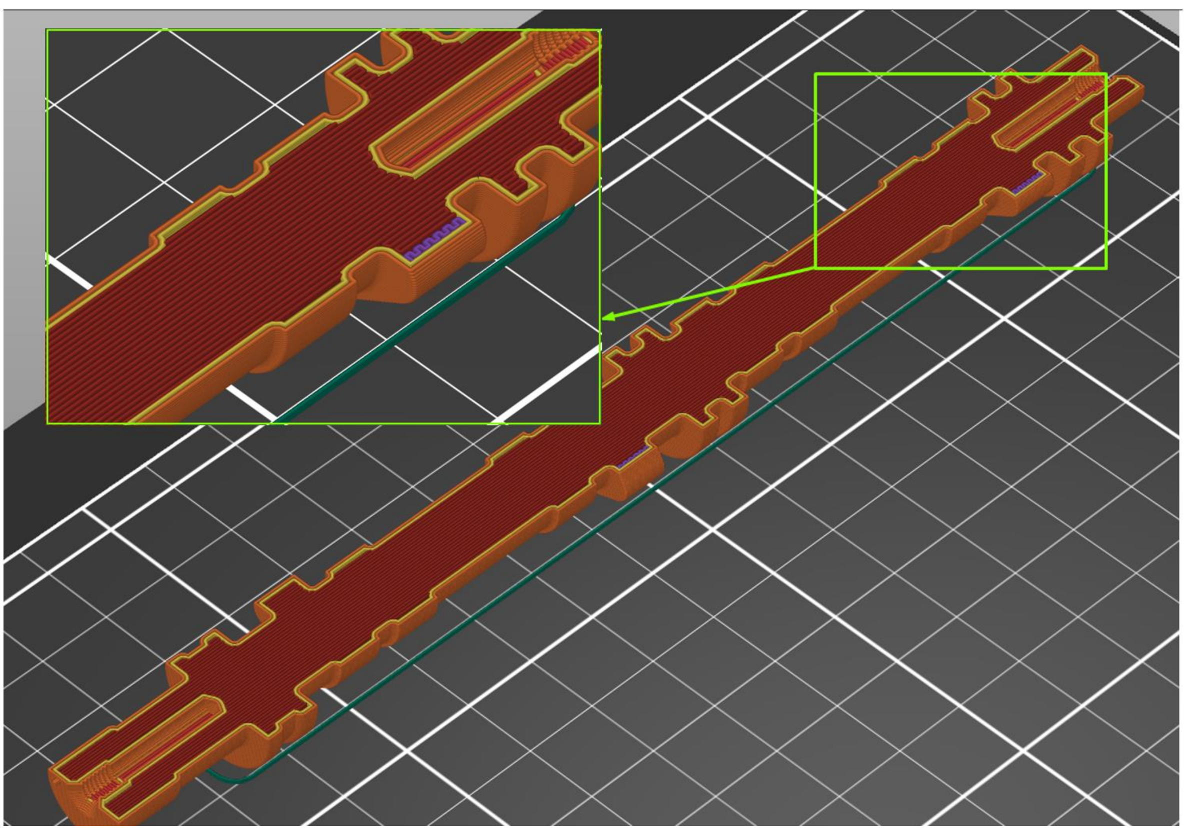




6.6703 Max
5.9292
5.1882
4.4471
3.706
2.9649
2.2238
1.4827
0.74166
0.0005795 Min
0.00
50.00
100.00 (mm)
25.00
75.00
Y
Z
X







Recycling of composite materials

5 CONCLUSION

Nowadays, composites are a great but expensive option to design powertrain components. Conventional methods of PMCs manufacturing have proven to be widely accepted in the high-performance vehicle industry; however, given the non-scalability of production, their use has not spread to the rest of the industry.

Qualified workers for manual processes and longer production times are the main reasons why the manufacturing costs of composite materials using conventional methods are higher.

It is known that the different additive manufacturing methods can be pretty valuable for manufacturing these components because they offer the possibility of more efficient use of raw materials, achieving high resistance while reducing the weight of the element.

The high efficiency in the use of materials is due to the exploitation of the material properties, aligning the most robust directional properties of the material with the direction in which the maximum stresses occur within the component. However, the gained advantage of alignment is much more profitable when composites with anisotropic properties (continuous fibers reinforcement) are employed.

The manufacture of composites with continuous fiber reinforcement is performed by adding single lines (AM) or single layers (conventional methods); this aspect limits the properties of the final piece in the perpendicular vector to the yarn or layer because there is no reinforcement to withstand loads in that direction.

A consequence derived from this limitation is that for some components where there is a great variety, change and combination of stresses within the piece, it can be complex to acquire the alignment of the fibers and the main stresses to optimize the amount of material.

Composite materials with a more regular distribution of their mechanical properties at the macro level (isotropic) are obtained through the use of reinforcement with particles, short fibers, whiskers or randomly distributed reinforcement.

These compounds with isotropic properties are widely used in the manufacture of powertrain components, as evidenced by MMCs and some PMCs. However, their use is not usually motivated by their mechanical resistance, but rather by other properties such as their coefficient of thermal expansion or their capacity for expansion. conduct heat or for its improved resistance to fatigue or wear.

In the case of the camshaft analyzed, in order to obtain a relevant advantage from the use of thermoplastic matrix composite materials, it would be more convenient to use fabrics with multidimensional fibers in the conformation of the shaft axis, since the forces are combined (shear, flexion and torsion) and are in frequent change associated with the rotation of the tree.

The use of dispersed fibers and AM methods such as selective sintering or selective laser melting make it possible to manufacture the evaluated component, however, as the properties of the compound are reduced compared to that reinforced with continuous fibers, the camshaft acquires reduced properties with respect to to that with continuous fibers, consequently, the final component obtained will have a greater weight to still meet the design requirements.

Better results on performance can be achieved when reduced weight in some other quantity of components as piston, piston pin, connecting rod, crankshaft, valves, valves lifter, power consumed from the crankshaft to the distribution system is about $&%$&, reducing the rotation inertia of the canshaft wont reduce so much this losses.

Some other materiasl as metal matrix composites can do for a better solution due to its wear resistance it means not multiple material camshaft (follower and cam on steel)

Mre can be achieved from the engine if camshaft is replaced with other type of technology like cammless from koenisegg or electromechanically actuated valves

A redesign of the camshaft has to be performed due to the different properties of the proposed material for the camshaft, is valuable to take in account that when CFRC are used in this type of application, the surface of the cams has to be done in a material with a higher hardness and resistance to wear, this, due to the high and concentrate friction forces applied by the spring through the rocker and the cam followers.

A reduction of mass and moment of inertia of the camshaft is reached through the use of an alternative material. This, even if the reduction of engine losses and masses is not so big is showing the potential of weight reduction technology development that can be further applied to ICE

Further developments on materials engineering and additive manufacturing will enhance the potential of the ICE and powertrain to be improved everyday.

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