



The Development and Applications of Powder Metallurgy Manufacturing Methods in Automotive Industry

Oğuz ERDEM¹

¹Ahi Evran University, Faculty of Engineering and Architecture, Mechanical Engineering

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Abstract

Over the past decade, automotive industry has developed considerably faster than other sectors in direction of consumers' demands. In order to provide worldwide emission standards, focusing on new technologies and enhancing fuel efficiency is emerged as a new trend among automobile manufacturers. Producing more efficient, lighter and eco-friendly cars without compromising performance and comfort has been the main goal of automotive industry in recent years. The high technology requirements of passenger cars with internal combustion engines as well as in hybrid and electric cars have directed the companies in sector to investigate alternative production methods. When compared with conventional manufacturing processes, powder metallurgy (PM) production methods are increasingly preferred by automobile manufacturers as they allow both profitability and part production in some special applications. In this review paper, it is aimed to give information about the development and application of PM methods in automotive sector.

Key Words

"Powder Metallurgy, Powder Injection Moulding, Metallic Foam, Automotive Industry"

1. INTRODUCTION

Powder Metallurgy (PM) is a technology for producing mechanical parts from metal and other powders. More recently, the vast majority of manufacturing of industrial parts is based on the PM manufacturing methods. Today, the automotive industry accounts for about 70% of the PM market (Turo et al., 2013; Gökçe et al., 2011). PM parts in the automotive sector are in high demand on an international scale due to the cost-benefit and functional flexibility they provide. PM sector, for electrical machinery industry as components; power tools, hydraulic equipment, motors and magnetic components, can supply directly or indirectly. Annual sales for PM parts in the world exceed 30 billion Euros (Turo et al., 2013; Apelian et al., 2015). The PM method's future in the automotive sector is directly related to its more complex and precise part production capability like in the aviation industry (Fan et al., 2010). Today's automotive industry is probably regarded as the sector in which the greatest amount of technology is demanded among all segments of the industry. The automotive industry is constantly in need of exploration of the latest technologies, as well as the weight reduction efforts in vehicles, the discovery of new materials to provide fuel efficiency and the reduction of emission values are becoming more and more important day by day (Sundararajan et al., 2016). Moreover, the trend of increasing performance by decreasing the engine volume known as "Engine Downsizing" is increasingly adopted by automobile manufacturers in the world. In automobiles, the weight reduction sense is often interpreted by automobile designers as the use of low density materials. The use of non-ferrous and powder-reinforced composites in automobiles is now increasingly widespread in the automotive industry through PM methods (Arslan et al., 2015; Akgun & Sahin, 2006). According to the European Aluminium Association (EAA), weight reduction of every 100 kg in cars, provides 0.6 litres of fuel savings every 100 km. 300 kg weight savings can be achieved by using aluminium in a medium sized car with a weight of 1400 kg. This gain value evolves to 20% of the total weight. In this way, the fuel savings of a car over its lifetime can be up to 3000 litres, while emissions to the environment can be reduced by 20% (Toptan et al., 2016). Brake systems are one of the points targeted in automobile weight reduction efforts. In automobiles, gray cast iron is generally used as brake disc material. In recent years, automakers have begun to produce aluminium matrix composite (Al-MC) brake discs, brake drums and other brake equipment with the PM method, which have lighter and superior properties for passenger automobiles (Toptan et al., 2016; Yu et al., 2000; Yu et al., 2005). Many studies have reported that weight gain is between 45% and 61% in the literature (Toptan et al., 2016; Kevorkijan, 2003).

Recently, the PM method is also preferred for the production of metallic foams and intensive work is being done on this area. Because of their low densities and high impact energy absorbing properties, metallic foams are used in the required areas of automobiles. The use of closed-cell aluminium foams is quite increasing nowadays in sections where weight reduction and increased reliability are required in automobiles (Yavuz et al., 2009).

In this study, it is aimed to give information about the development and application of PM methods (such as press-sinter method (PSM), powder injection moulding (PIM), metal injection moulding (MIM), metal foaming and flame spray method (FSM)) in automotive sector. From the past to nowadays examples of PM parts produced in automotive sector are given.

2. PM METHODS USED IN AUTOMOTIVE SECTOR

2.1. Press-sinter Method (PSM)

PSM is based on the principle that metal or alloy powders are mixed with various lubricants in the desired manner and then sintered in a controlled atmosphere. The pressing, also known as compression, compacting or briquetting, can be carried out either cold or hot condition depending on demand (Thümmeler & Oberacker, 2009). When pressure is applied to the powder batch during pressing, the powder particles firstly slide on each other and then is condensed by high pressure transformation (German, 2007). For most applications of PSM, it is desirable that the raw strength value is to be high. If the raw density (green density) value is clarified, it is the first density of the part after pressing and before sintering (Thümmeler & Oberacker, 2009). Figure 1 shows the flow diagram in PSM production of parts (German, 1984).

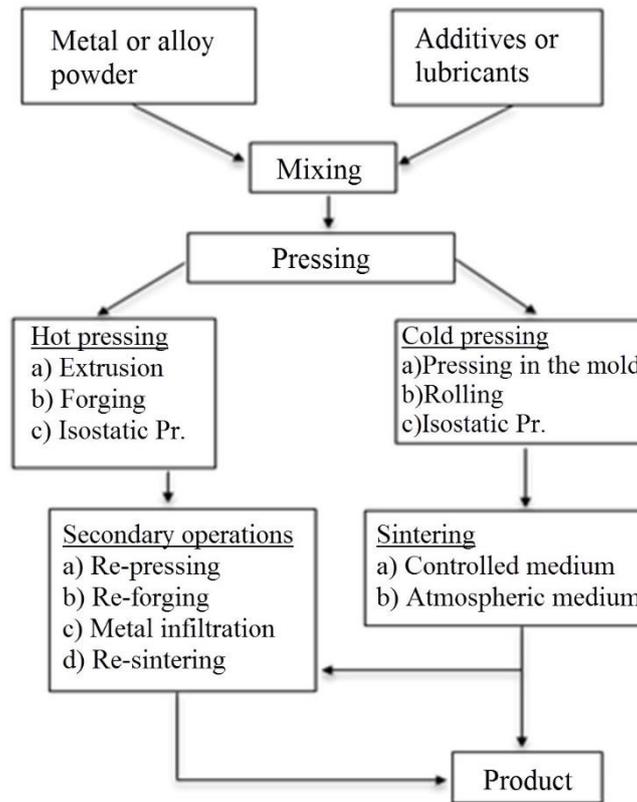


Figure 1. Flow diagram for parts production with PSM

The mixing process is carried out under controlled atmospheric conditions so that the powders are not contaminated and their properties are not changed. During mixing, lubricating agents such as stearic acid, calcium stearate, zinc stearate and lithium stearate are generally added in amounts of 0.5 to 3% to prevent friction of the powder particles which may form between each other and on the mould surfaces. In some special cases, it may also be preferred in inert gas environments to avoid oxidation during the mixing process. On the other hand, mixing is carried out by specially designed mixers (two-dimensional or three-dimensional). In automotive parts produced by PSM, pressing in the mould is generally preferred. According to the part to be produced, this process usually can be carried out in one-way or two-way moulds in cold form. Pressing pressure can vary from 0 to 800 MPa. Sintering process is generally carried out in controlled atmospheres at a temperature below 1/3 of the melting temperature of the raw material of the product to be produced (powder) and at a specified time (sintering time) (Thümmeler & Oberacker, 2009).

2.2. Powder Injection Moulding (PIM) and Metal Injection Moulding (MIM)

PIM is a manufacturing method which is combining plastic injection and powder metallurgy (German, 1990). It is a moulding technology by mixing very fine-grained metal or ceramic powders with thermoplastic binders and moulding this mixture in plastic injection machines. If the powder used in the method is metal powder, it is expressed as MIM. PIM is an advanced powder processing technology developed to produce small, complex shape, precise size, precise tolerance, smooth surface, difficult to machining and excessively process able parts at reasonable cost (Karataş & Sarıtaş, 1998). PIM has four main steps; mixing, injection moulding, debinding and sintering (Upadhyaya, 2002). Mixture consisting of powder and binder is called feedstock. In order to prepare feedstock, the metal or ceramic powders are homogeneously mixed with thermoplastic binder or wax-based polymeric materials and lubricants. The initial properties of the feedstock are directly influenced by the properties of the final product after sintering. Therefore, the feedstock composition is very critical. The desired flow type is provided by the rheology study before the moulding process in the injection moulding machine. Thus, problems that may occur during moulding are avoided. Powder and binder are mixed at optimum rates and then, the feedstock is granulated. The granule feedstock is moulded into the desired shape by controlling the injection pressure, the cylinder temperature and the flow rate in the injection moulding machine. These three parameters (injection pressure, the cylinder temperature and the flow rate) are very important during moulding cycle. Injection pressure and ironing pressure are critical both in mould filling and in the preservation of the parts shape. Cylinder temperature is quite important for the feedstock not to be spoiled and also flow ability of the feedstock (German, 1990; Karataş, 1997; Erdem, 2010; Ergüney, 2005). The moulding cycle starts with closing and locking the moulds. The granules placed in the feeding hopper are melted by the heaters in the cylinder block and pushed to the mould with the help of a helical screw in the cylinder block. The feedstock transferred to the mould is kept under pressure for a while so its solidification is ensured. The injection part of the machine is withdrawn and the mould is opened to remove the part. This cycle should be completed as soon as possible at minimum cost. The task of the helical screw is to homogenize and convey the feedstock to the mould. The next stage; is to remove the binders from raw parts under controlled conditions. The debinding process is carried out in two ways: thermally (thermal decomposition) or solvent (solvent decomposition). Then the desired condensation and strength increase is achieved by the sintering process. At the end of the sintering process, a relatively low-porosity part is produced which is very close to full

density. Full dense parts produced by PIM shows close mechanical properties when compared to forged and cast parts (Karataş, 1997; Erdem, 2010). Figure 2 shows the flow diagram of PIM (German, 1990; Erdem, 2010).

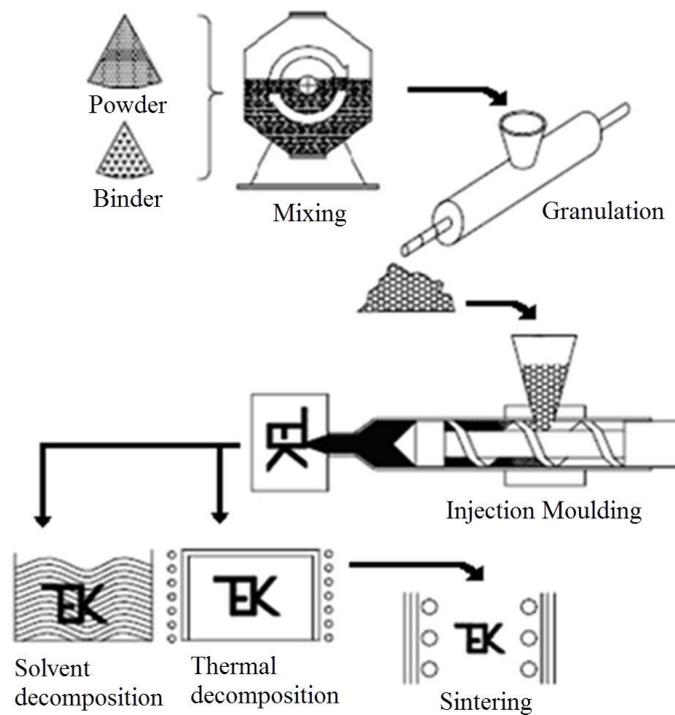


Figure 2. Flow diagram of PIM

2.3. Metal Foaming

There are two methods currently used for foaming the metal. The first is the melting method and the second is the PM method (Yavuz et al., 2009; Simone & Gibson, 1998; Banhart, 2000). Three types of foam can be produced by melting: a) injecting gas into the melt from the outside, b) adding the foaming agents to generate a gas in the molten metal, c) foaming agents previously added to the melt, which then generate foam in certain medium (Yavuz et al., 2009; Yang & Nakae, 2000).

Metallic foam production by melting process takes place mainly in three stages. In the first step, the foaming metal or alloy is melted. In the second step, gas or a foaming agent is added to generate a porous structure. In the third step, the molten metal is solidified by cooling (Yavuz et al., 2009; Baumgarter et al., 2000). In the production of foam made by forming gas bubbles in the molten metal, the gas bubbles which tend to swell rapidly to the surface are due to the high lifting force of the liquid and where metallic foams are formed. Extremely high viscosity causes bubbles to be suppressed, while extremely low viscosity causes rapid bubbling of the bubbles (Yavuz et al., 2009; Gergely et al., 2000). Therefore, the control of the viscosity of the molten metal during foaming is very critical.

Zirconium hydride (ZrH_2) or titanium di-hydride (TiH_2) is generally used as the foaming agent in the production of metallic foams. Other chemical compounds such as calcium carbonate ($CaCO_3$), calcium hydride (CaH_2), calcium-magnesium carbonate (C_2CaMgO_6), calcium sulphate ($CaSO_4$), ferrous sulphate (FeO_4S), lead carbonate ($PbCO_3$), lead oxide (PbO) and sodium nitrite ($NaNO_2$) can be used as foaming agents under certain temperature and pressure conditions. Whether a metal will foam or not and whether it will be in the desired density depends on the decomposition rate of the gas released when the foaming agent is decomposed. The foaming agent material may be in the form of particles, granules or powder such that it can be easily dispersed in the base metal (Yavuz et al., 2009; Banhart, 2001).

The PM method is one of the most commonly used methods for the production of metal foaming and recently it is being extensively studied in this field. With the aid of the PM method, it is possible to produce sandwich foams, spherical foams and foam in profiles besides the known simple foam productions (Yavuz et al., 2009; Stöbener et al., 2003). In addition, particle reinforced foam production is also preferred in order to increase the mechanical properties of the foam material.

In the PM method for metal foaming, metal powders (generally Al powder) are mixed with the foaming agent (usually TiH_2 or ZrH_2) and pressed. As the temperature increases during the foaming process, the foaming agent in the structure dissociates and H_2 gas is released. The decomposition is visible at about 400 °C for TiH_2 . This temperature is well below the melting point of aluminium (Yavuz et al., 2009; Matijasevic, 2006). During the decomposition process, expansion occurs at high temperature, in other words, foaming (Figure 3) occurs (Yavuz et al., 2009; Esmaelzadeh & Simci, 2007; Türker, 2009). It has been proven by studies that the surface tension of the foam and the viscosity of the liquid metal change in the case of adding ceramic particles into

the melt. It is therefore known that the stability of the foam in the melt can be improved depending on these properties (surface tension and viscosity). For this reason, SiC, Al₂O₃ and various boron containing particles are added to Al-based materials predominantly. Recently, it has been discovered that powder-reinforced metallic foams (PMF) provide excellent energy damping (Yavuz et al.). Thus, PMF is rather preferred in automobile pillar's and chassis's because of the damping property's.

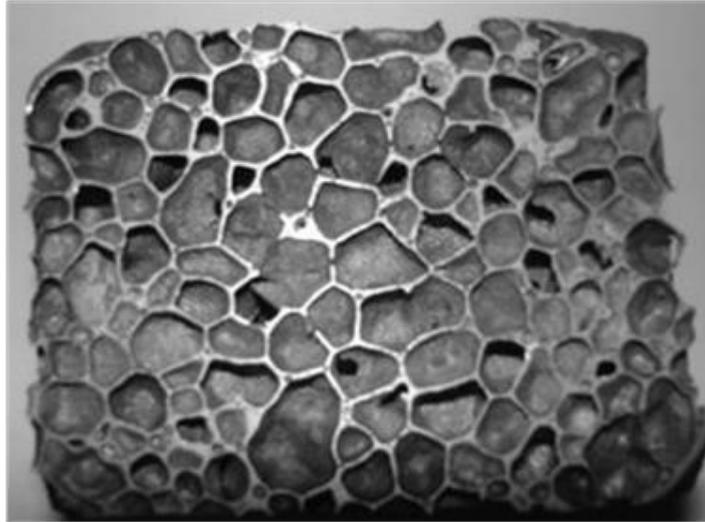


Figure 3. Aluminium based foam material

2.4. Flame spray method (FSM)

In FSM, the coating materials in powder or wire form are sprayed onto the surface of the workpiece in the presence of combustible, combustible and carrier gases from a spray gun. In the method, the powdered metal alloys in the mixture are sprayed onto the surface to be coated with the oxy-acetylene flame center by vacuuming with oxygen. It is called cold system because the surface temperature of the part during the coating process is set not to exceed 200 °C. The flame temperature is around 330 °C. Adhesion is mechanical and the thickness of the coating varies between 0.05 and 2.5 mm depending on the shape of the workpiece. Adhesion resistance is around 600-1000 PSI and the average surface roughness varies between 10-20 µm depending on the coating parameters (Figure 4) (Halamoğlu, 2003; Öner & Can, 2007).



Figure 4. FSM application

3. AUTOMOBILE COMPONENTS MANUFACTURED BY USING PM METHODS

Today, parts manufactured by PM methods are used in transmission, engine, chassis and other components of family cars, buses, trucks, light commercial vehicles and many other transport vehicles. Potential locations for PM applications in an automobile are shown in Figure 5.

The rotor and gears of the oil pump, produced with PSM and widely used in most vehicles, as well as various bearings are shown in Figure 6a and various transmission parts produced by PSM: clutch engaging hub, gear shift yokes and gears are shown in Figure 6b. Automobile gearboxes can be manual (manual shifting), semi-automatic (double clutch dsg gearbox or CVT gearbox etc.) and automatic (torque converter). The main purpose of the gears in each gearbox is to provide torque transmission reliably and silently. Extremely high geometric precision is expected in gears in gearbox applications. Therefore, the number of components produced by the PM in the synchronization module of the manual gearboxes is already quite large (Figure 7). All major components of both semi-automatic and automatic transmissions: hubs, clutch plates, clutch plate bearings, synchromesh parts and many other components have recently been manufactured by PM methods (Chang & Zhao, 2013).

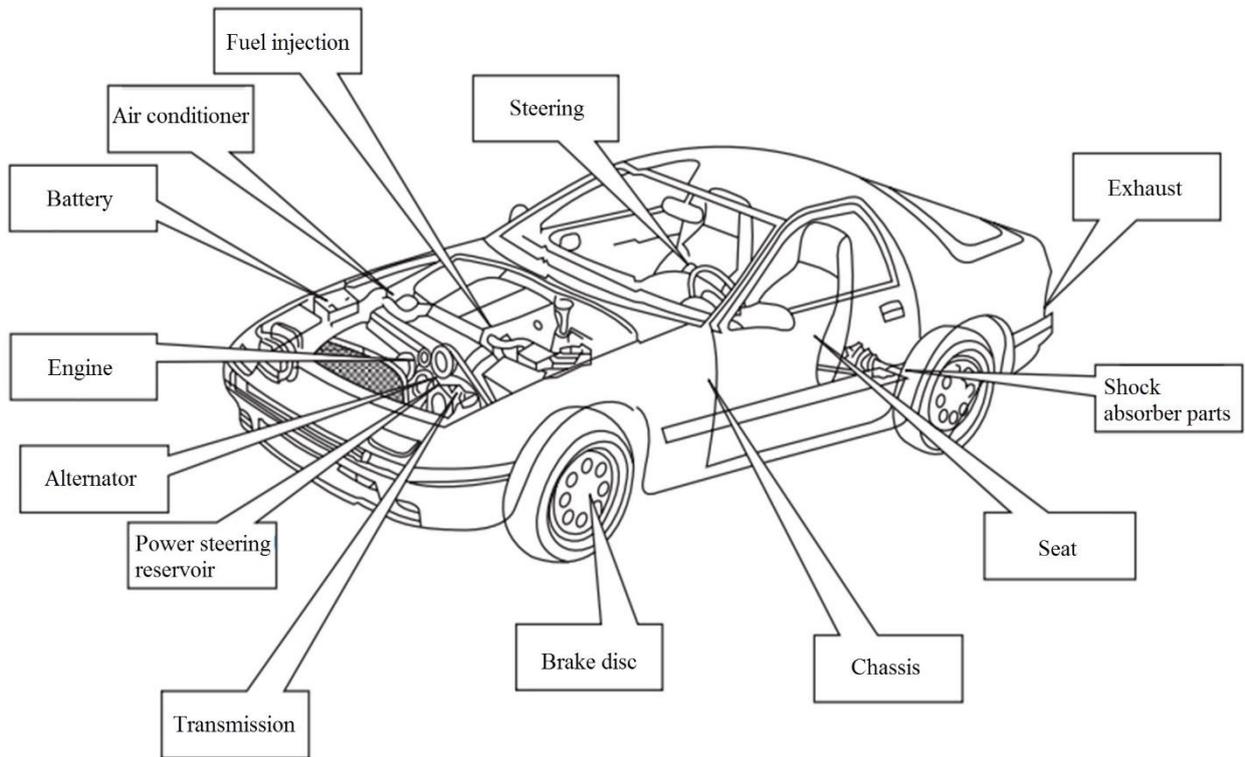


Figure 5. Potential areas for PM applications in an automobile

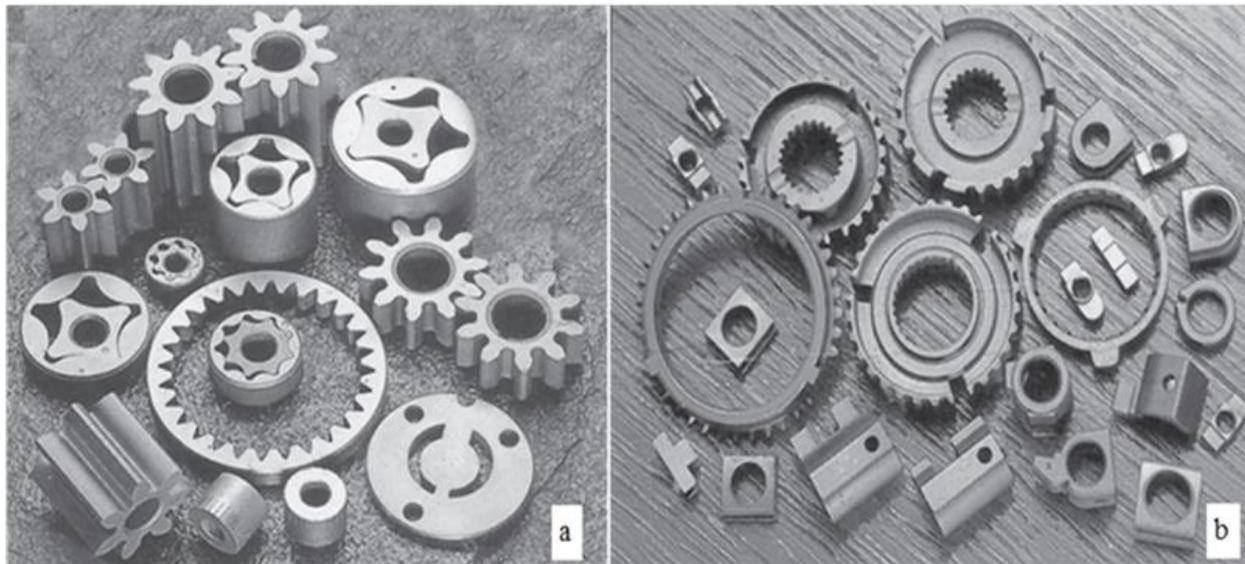


Figure 6. Automobile parts manufactured by PSM: a) oil pump parts, b) transmission parts

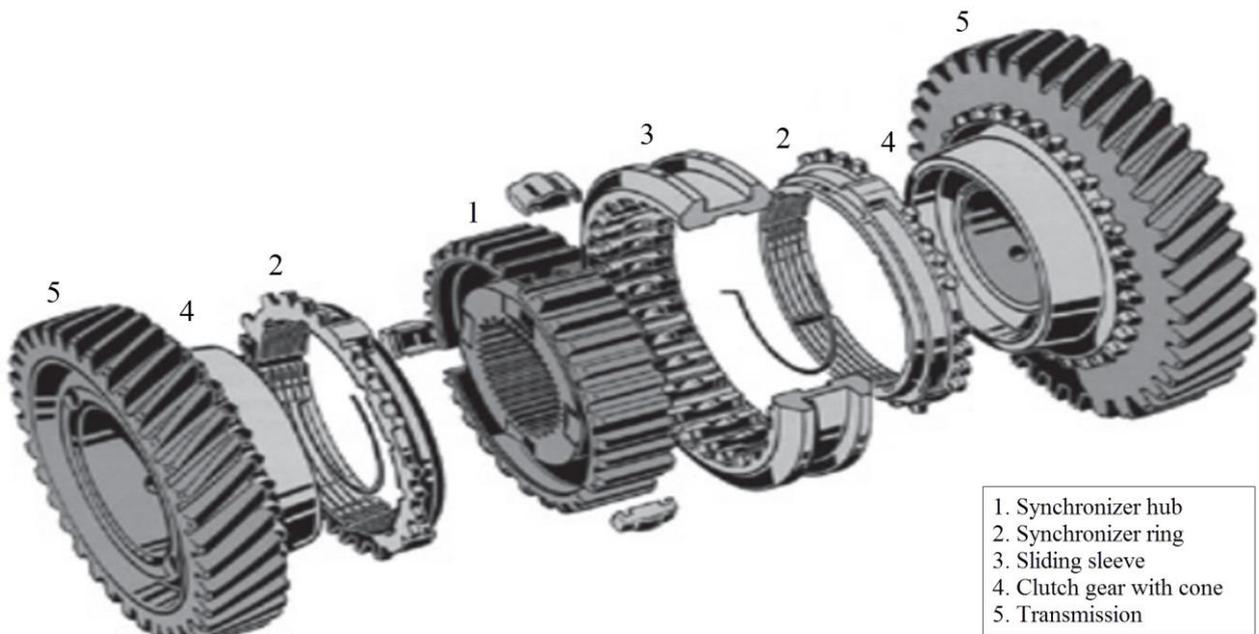


Figure 7. Synchronization module parts manufactured by PSM in gear boxes

With lower fuel consumption, more performance, more environmentally friendly automobile demands, has been led to significant changes in automobile engines. The engines are divided into categories according to the type of fuel used: petrol, diesel, hybrid or fuel cell. The schematic representation of the piston motor is shown in the Figure 8. PM methods have played an important role in the development of new engines by replacing existing engine components with better ones and increasing design possibilities (Chang & Zhao, 2013).

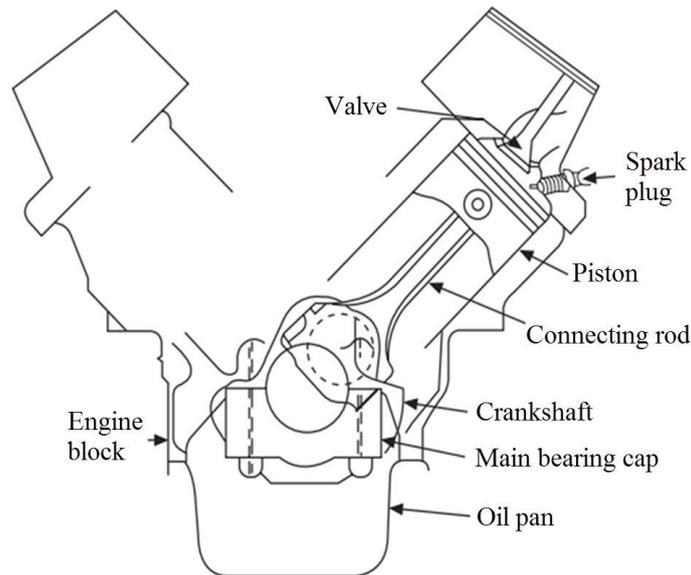


Figure 8. Schematic representation of the piston motor

The camshaft can be produced more economically thanks to the PM methods when traditionally produced from solid bars in difficult conditions by the forging method. While the camshafts are traditionally produced from solid bars under difficult conditions by forging method, owing to PM methods, they can be produced more economically. Now, it is possible to manufacture composite cams and camshafts. If clarification is required, before pressing, composite materials are obtained with reinforcements added in powder mixtures and then compression is carried out. In other words, PM allows the production of composite cams and intermediate rings as shown in Figure 9. So, it contributes to production of lighter engines and therefore provides fuel economy. The composite cams and camshafts manufactured by PSM have a high dimensional accuracy, high abrasion resistance and lighter weight (Chang & Zhao, 2013).

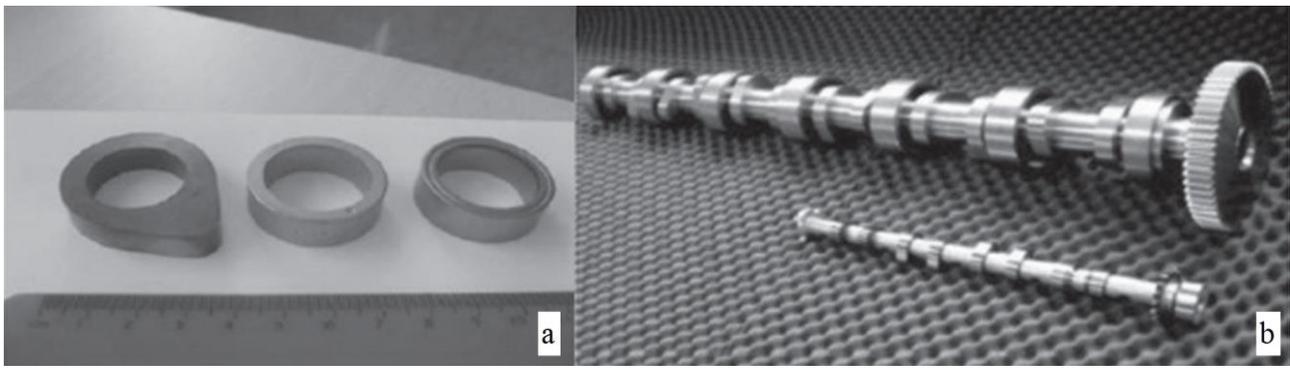


Figure 9. Composite motor components produced by PSM: a) cam and intermediate rings, b) camshaft

In the study of Arslan et al. (2015), composite cam production and characterization has been carried out using SiC added 7075 Al-alloy PM technique (production with PSM). In the work supported by ESTAŞ Eksantrik San. Inc., Pb and Mg powders are used to facilitate the sintering process. Zinc stearate is preferred as lubricant in the study. The homogeneously mixed powders were poured into the metal cam mould, and then the cold pre-forming is carried out by applying a pressure of 300 MPa. Sintering was carried out to pre-formed cams in a tube furnace at 600 °C in a dry N₂ gas medium. Metallographic examination (scanning electron microscopy analysis and EDS analysis) was performed on the produced cams at the end of the study. Hardness, wear and bending tests have been performed. As a result, it was determined that hardness, bending strength and wear resistance increased as the reinforcement volume ratio increased (Figure 10) (Arslan et al., 2015).

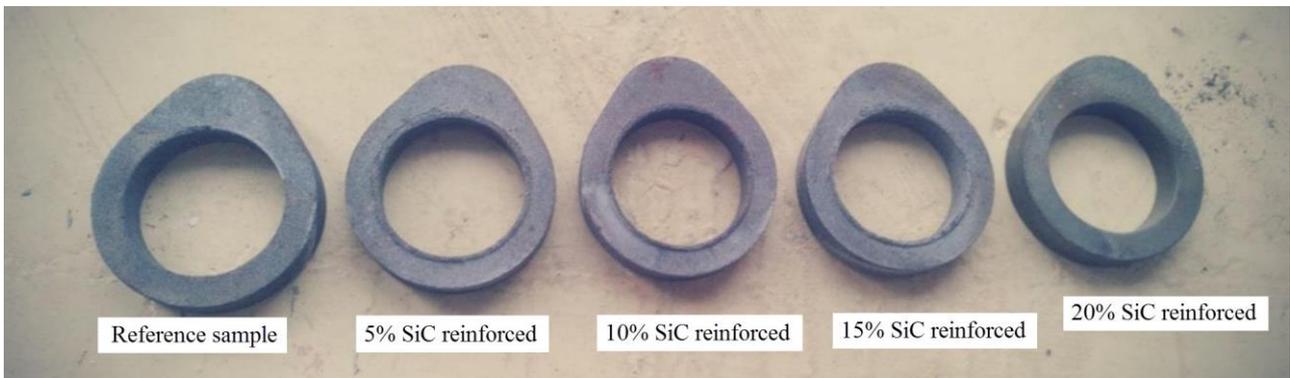


Figure 10. SiC reinforced Al-7075 matrix composite cams manufactured by PSM

The other components of the engine are: the connecting rod (Figure 11) (Fujiki, 2001) the camshaft and crankshaft gears, the timing gears, the G rotor and gear type oil pumps, the water pump impellers, the distribution pulleys (Figure 12a), the fuel pump parts (Figure 12b), the flange distributor gears, swing arm supports and attachments, engine ears, valve weights, valve housing inserts, valve lift guides, stainless steel gas flap attachments, turbochargers and fuel injector parts can also be produced by PM methods (Chang & Zhao, 2013). Over the past two decades, aluminium matrix composites (Al-MC) have been extensively explored in the automotive industry due to their lightness, high strength, high modulus of elasticity and superior abrasion resistance. One of the potential applications of Al-MC's is; Al-SiC composite brake discs (Figure 13) (Toptan et al., 2016).



Figure 11. PSM-produced rod: a) production of GKN company, b) production of Toyota engine

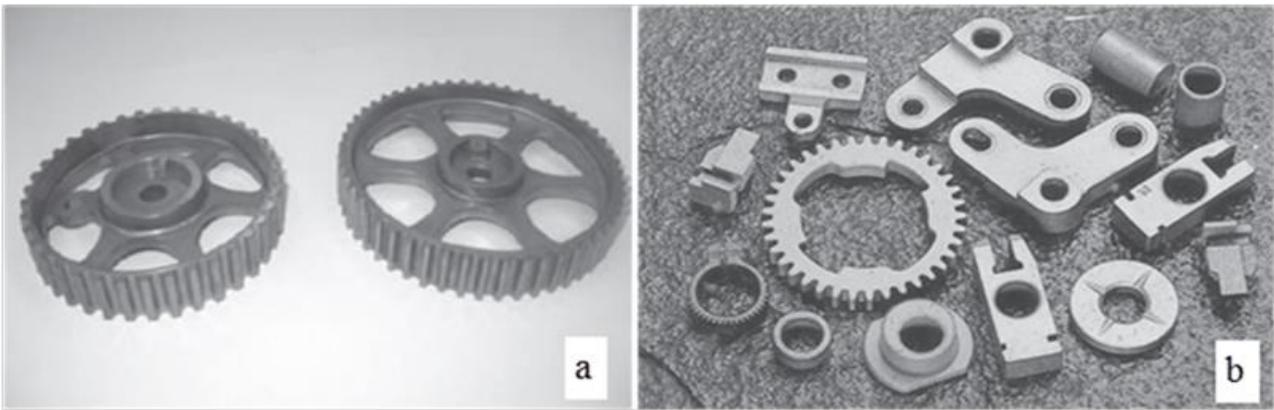


Figure 12. Parts manufactured by PSM: a) distribution pulleys, b) fuel pump parts

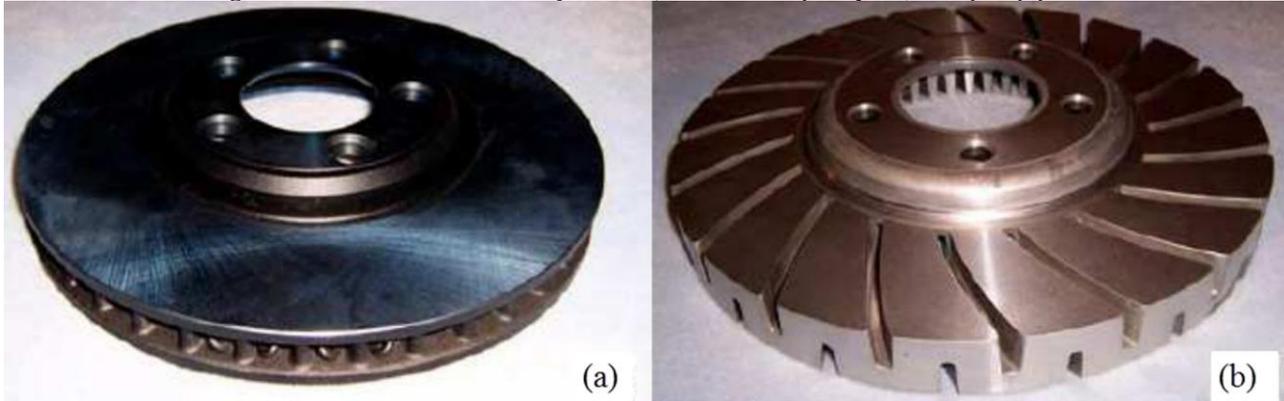


Figure 13. Brake disk: a) Brake disk (weight: 8.44 kg), manufactured from gray cast iron used in the sedan automobile, b) brake disc made of Al-SiC composite material (weight: 3.32 kg) specially designed for the same automobile

Brake pads can also be produced by PM. In the study of Ertan et al. (2010), the materials forming the brake pads (BM1: copper powder, aramid, rock wool, BM2: graphite powder, coke, ZnS, BM3: ZrSiO₄, Fe₂O₃, cashew powder) were mixed in a laboratory type rotary electric mixer for 5 minutes until they became homogeneous. After mixing, the mixture materials (BM1, BM2, BM3) were poured under equal weight to the 8 mould cavity found in the presses. Then brake pads are moulded at a pressure of 7.5 MPa and at a temperature of 150 °C for 5 minutes. The upper and lower surfaces of the pad-shaped powder mixture are cleaned in the grinding machine and brought to the desired size and then given to the sintering furnace (Figure 14). Later produced brake pads were subjected to friction tests. In addition to experimental studies, PSM-produced brake pad from metallic powders is also widely used in practice (Figure 15).

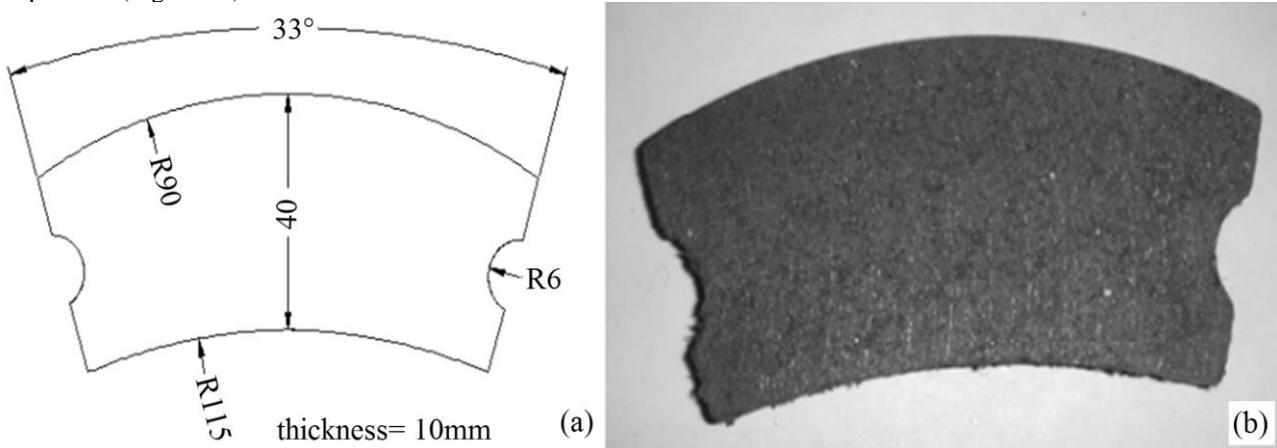


Figure 14. The brake pad manufactured by PSM: a) technical drawing, b) photo image

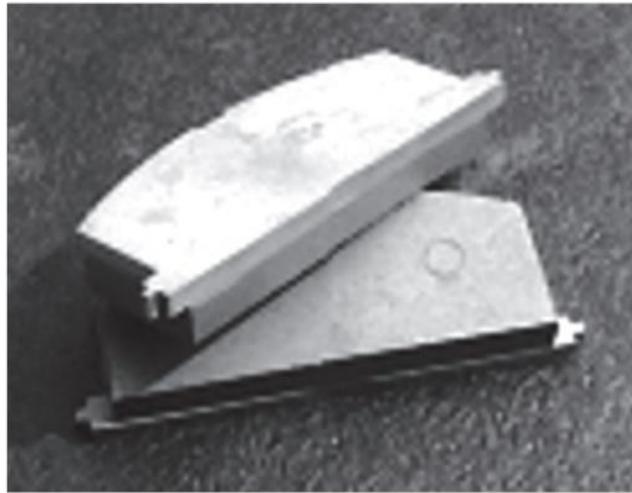


Figure 15. Metallic brake pad (PMAI)

PIM and MIM applications in the automotive industry are increasing day by day due to increasing demand in the sector. For parts production with MIM; engine (Figure 16), transmission, chassis and body parts are increasingly needed. As shown in Figure 17, the engine valve seat, various shock absorber parts and parts of the power steering system were manufactured by MIM.

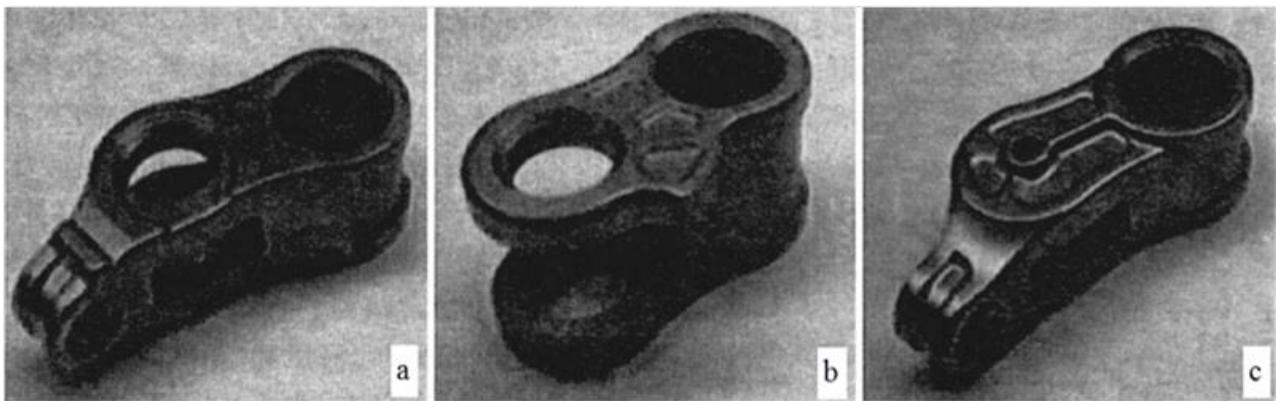


Figure 16. The swing arms manufactured by MIM for VTEC motor (HONDA): a) primary, b) middle c) secondary

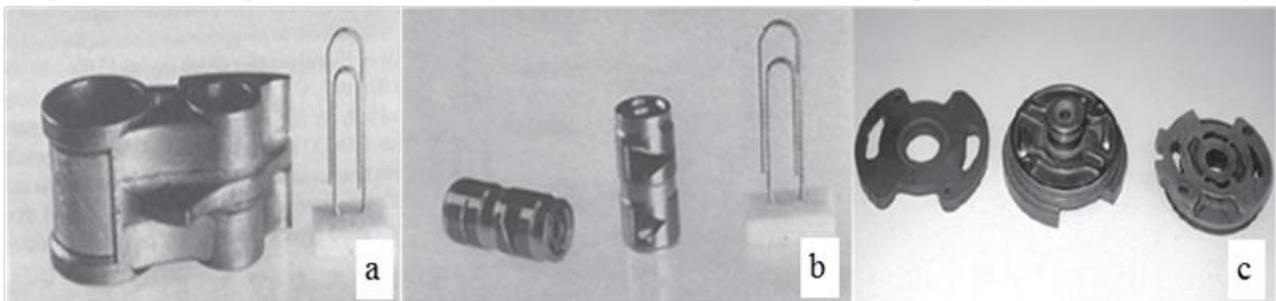


Figure 17. Parts manufactured by MIM: a) engine valve seat, b) shock absorber parts, c) parts of the power steering system

Interest in aluminium foams is increasing day by day because of the fact that their low densities and high deformation energy absorption, as well as being preferred in the areas where it is desired to increase the stability in automobiles. Given the energy absorption properties of metallic foams, in crash tests on automobiles, it has been observed that the maximum impact energy in areas with a high probability of collision is dissipated by metallic foam and also deformation is reduced (Yavuz et al., 2009; Çinici, 2004). The use of metallic foams as a filler in doors, bumpers and similar parts in automobiles is widespread. Figure 18 shows aluminium foam zones used for impact damping on the vehicle. When the acoustic effect of metallic foams is considered, it can be said that they are in a position to compete with various organic insulating materials with low cost at an impressive amount. As shown in the body of the Audi A8 (Figure 18), there are many structural foam parts on the bodywork. Because of these properties, metallic foam materials can be considered absorptive elements of impact energy (Yavuz et al., 2009). A test carried out by Steyr Daimler Puch, an Austrian automotive company, instead of the original absorber element used in the A-column, the Al foam shown in Figure 19 was used as the absorber element and subjected to the top impact test. It had been reported that successful results were obtained for the Al foam absorber element after tests (Yavuz et al., 2009).

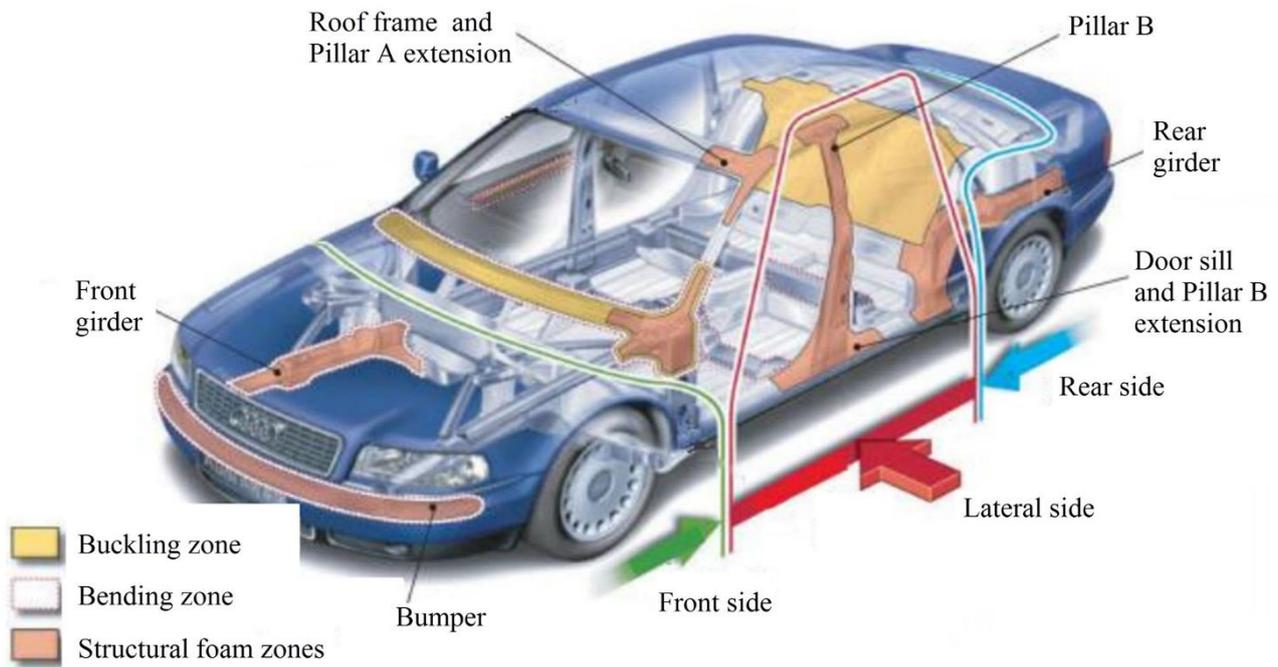


Figure 18. Structural foam materials used on Audi A8

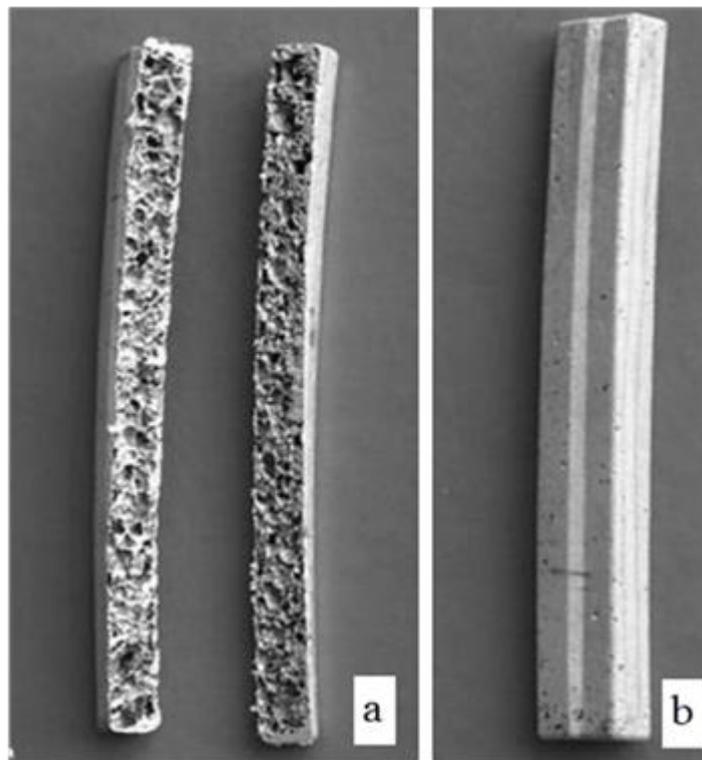


Figure 19. A-column in automobiles: a) made from Al foam, b) made from steel sheet

Also, aluminium foams have been recently used in automotive industry collision absorbers in vehicles. This new reconnaissance has contributed to the development of collision boxes. Collision boxes are usually located between the impact buffers (bumpers) and the front guard rails (Figure 20). These boxes can be deformed by absorbing all the energy in a collision at 15 km/h and they can prevent a more expensive damage that might happen in the car chassis. In Figure 21, the same length of aluminium foamed and non-foamed stainless steel 304 steel is given axial deformation under pressure (Yavuz, 2010; Doğan et al., 2015).

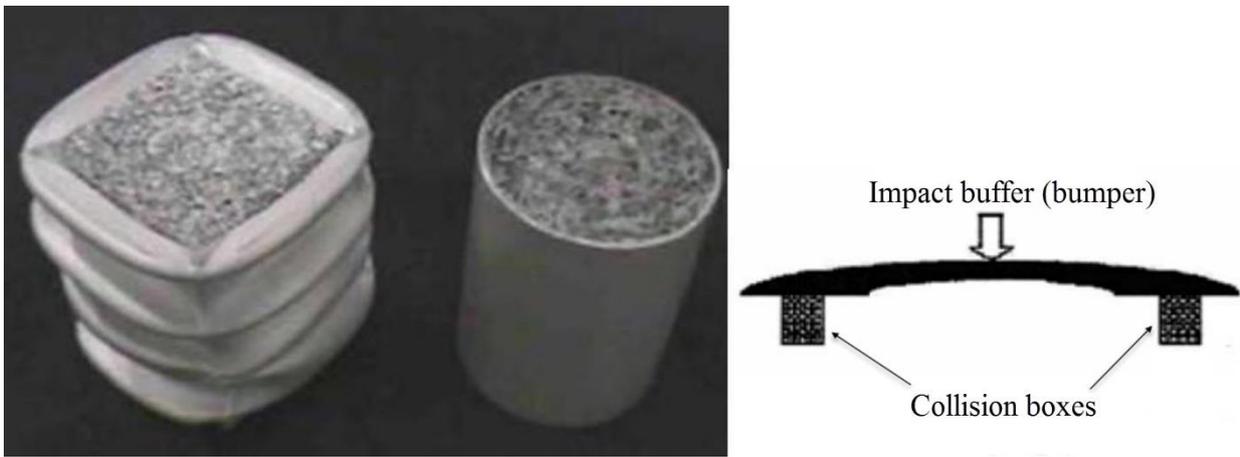


Figure 20. Collision boxes used in automobiles

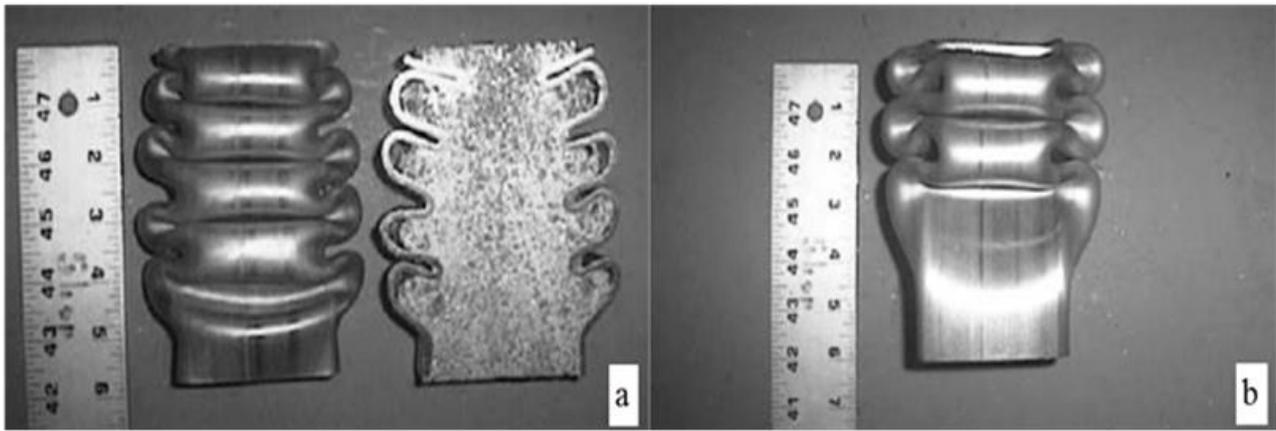


Figure 21. Deformation images of stainless steel 304 under axial pressure: a) in aluminium foam filled state, b) in non-foam state

As can be seen in Figure 21a, the aluminium foam-filled steel has undergone further deformation in the axial direction and it is folded up to 4 stratum. In Figure 21.b, the non-foam steel can only be folded 2 stratum. According to this result, it can be clearly seen that the aluminium foam padded steel can better absorb the impact energy.

In the internal combustion engines, non-stationary parts carrying moving parts such as crankshaft, camshaft, which allow linear motion of the piston to be turned into rotational motion, are given the name "bearings" and their surfaces are called "bearings surface". Sliding bearings used in motors work under difficult conditions such as variable load, temperature and pressure. In order to be able to respond to the specified challenging conditions, bearing metals are made from alloys. The most important of these are; white metals, copper-based metals and bronzes. White metals consist of elements such as lead, tin and aluminium. They are soft compared to copper-based metals and they are preferred in high-speed engines due to their good lubrication properties. Copper and bronze bearings are preferred for high power and low speed engines. Bearings in this type are difficult and costly to manufacture. To increase the resistance of the main bearings and to eliminate other problems during engine running, the researches on this subject are continuing at a rapid pace. Manufacture of bearings to be used in internal combustion engines by conventional methods is expensive and labour-intensive. Many problems are encountered in the manufacture of bearings by traditional methods. In traditional methods; it is unfortunately not possible to produce bearings having a low surface roughness, easy process able and easy to cast. Also, in traditional methods, the bearing metal is spun or normally cast. The connection rod is chemically cleaned and tin plating is done. The bearings prepared in this way are milled and the ring bearings are cut in half right through the middle. The flat one is cut along the bearing and pressed into a half circle. This situation not only reduces the productivity of the production but also increases the cost considerably in terms of time. FSM, one of the surface coating methods developed in recent years, is successfully used in many areas. In FSM, elements with different chemical and physical properties are mixed homogeneously and the surface can be easily coated with a powder spray gun (Figure 22) (Halamoğlu, 2003; Öner & Can, 2007).



Figure 22. Crankshaft master bearings coated by FSM using a new alloy of Pb, Sn, Cu and ZrO₂ powders

4. CONCLUSION

In this study, the theoretical knowledge about the processing principles of PM methods and the developments of these methods in the automotive sector are given. The innovations and advantages that PM methods bring to the automotive sector are explained in detail by examples. It has also been extensively involved in the study why automakers have chosen PM methods in vehicle production. As a general conclusion, automakers focus on; weight reduction efforts in vehicles, the discovery of new materials that will provide fuel efficiency and the reduction of emission values. These requirements have been successfully implemented by PM methods in recent years. In the coming years, it is thought that PM will provide contributions to many areas in automotive sector.

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