International Journal of Advances in Scientific Research and Engineering (ijasre)
ISSN: 2454-8006 [Vol. 03, Issue 4, May -2017]
www.ijasre.net

Engineering Materials And Additive Processes Used In Automotive Engine Blocks

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ABSTRACT

Until recently, cast iron and aluminum alloys have been the preferential materials used to manufacture most diesels and conventional gasoline- powered engine blocks. However, with a greater emphasis on increasing the efficiency of the engine via weight reduction, manufacturers have began to look for alternative alloys that are lighter than cast iron and aluminum alloys, while retaining the necessary strength to withstand the forces of an engine. As of late, new manufacturing processes have been developed that have engendered two new alloys suitable for use in an engine block, magnesium alloy AMC-SC1 and compacted graphite cast iron (CGI).In this paper, the functional requirements of the engine block, the processes used to manufacture the part, and the mechanical properties of the alloys will be discussed.

1. INTRODUCTION

The first successfully working internal combustion engine used in an automobile was built by Siegfried Marcus in approximately 1864 [1]. It was an upright single-cylinder, two- stroke petroleum-fueled engine that also utilized a carburetor to deliver fuel to the engine. The engine was placed on a cart with four wheels and successfully ran under its own power. Not only has Marcus produced the first engine that is the direct predecessor to today’s engines, he had also built the first automobile in history, some 20 years before Gottlieb Daimler’s automobile.

Today’s engines are an integral component of an automobile that are built in a number of configurations and are considerably more complex than early automotive engines. Technological innovations such as electronic fuel injection, drive-by-wire (i.e., computer- controlled) throttles, and cylinder-deactivation has made engines more efficient and powerful. The use of lighter and stronger engineering materials to manufacture various components of the engine has also had an impact; it has allowed engineers to increase the power-to-weight of the engine, and thus the automobile.

Common components found in an engine include pistons, camshafts, timing chains, rocker arms, and other various parts. When fully stripped of all components, the core of the engine can be seen: the cylinder block.

The cylinder block (popularly known as the engine block) is the strongest component of an engine that provides much of the housing for the hundreds of parts found in a modern engine. Since it is also a relatively large component, it constitutes 20-25% of the total weight of an engine [2]. Thus there is much interest in reducing the block's weight.

Many early engine blocks were manufactured from cast iron alloys primarily due to its high strength and low cost. But, as engine designs became more complicated, the weight of the engine (and the vehicle) had increased. Consequently, the desire among manufacturers to use lighter alloys that were as strong as cast irons arose. One such material that was being used as a substitute was aluminum alloys. Used sparingly in the 1930's (due to problems with durability) [3], aluminum alloy use in engine blocks increased during the 1960's and 1970's as a way to increase fuel efficiency and performance. Together, these two metals were used exclusively to fabricate engine blocks. As of late, however, a new material process has made a magnesium alloy suitable for use in engines. The alloy, called AMC-SC1, weighs less than both cast iron and aluminum alloys and represents new possibilities in engine manufacturing. A new manufacturing process have made compacted graphite cast iron (CGI) a viable alternative to gray cast iron for the manufacture of diesel engine blocks. Like magnesium alloys, this material offers a higher strength and lower weight than gray cast iron.

In this paper, materials used to manufacture engine blocks for passenger vehicles will be discussed. The discussion of the component, its functional requirements, and the materials used to manufacture the part are included. The mechanical properties of the individual alloys will be incorporated, as well as the manufacturing processes used to fabricate the component.

2. DESCRIPTION OF THE PRODUCT

What is an engine block?

An engine block is the core of the engine which houses nearly all of the components required for the engine to function properly. The block is typically arranged in a "V," inline, or horizontally-opposed (also referred to as flat) configuration and the number of cylinders range from either 3 to as much as 16. Figure 1 shows engine blocks with "V", inline, and horizontally- opposed configurations.

Functional Requirements of a Cylinder Block

Because engine blocks are a critical component of an engine, it must satisfy a number of functional requirements. These requirements include lasting the life of the vehicle, housing internal moving parts and fluids, ease of service and maintenance, and withstand pressures created by the combustion process.

Required Material Properties

In order for an engine block to meet the functional requirements listed above, the engineering material(s) used to manufacture the product must possess high strength, modulus of elasticity, abrasion resistance, and corrosion resistance. High strength is a particular concern in diesel engines, since compression ratios are normally 17.0:1 or higher (compared to about 10.0:1 for conventional engines). The material should also have a low density, thermal expansion (to resist expanding under high operating temperatures), and thermal conductivity (to prevent failure under high temperatures). Good machinability and castability of the metal alloy are also important factors in selecting the proper material, as the harder it is to machine the product, the higher the costs of manufacturing. In addition to the previously mentioned properties, the alloys must possess good vibration damping to absorb the shuddering of the moving parts.

Based on the functional requirements of the cylinder block and the material properties required to meet the functional requirements, industries have used cast iron and aluminum alloy to manufacture the blocks. Cast iron alloys are used because of the combination of good mechanical properties, low cost, and availability. Certain aluminum alloys combine the characteristics of iron alloys with low weight, thereby making the material more attractive to manufacturers who are seeking a competitive edge. Compacted graphite cast iron is lighter and stronger than gray cast iron, making the alloy a more attractive alternative to the latter in the production of cylinder blocks, particularly in diesel engines. Magnesium alloys, which were previously unsuited for use as an engine block material, have the advantage of being the lightest of all the mentioned metals, yet still retains the required strength demanded by a block.

3. MANUFACTURING THE CYLINDER BLOCK

Mechanical Properties of the Alloys

Both conventional and diesel-fueled cylinder blocks are subjected to thermal strains, aggressive wear conditions, and high fatigue stresses that an alloy must be able to endure. Engineers must be able to select the proper material that meets the mechanical requirements previously set. For example, the required mechanical properties for a typical aluminum engine block includes an ultimate tensile strength of 245 MPa, yield stress of 215 MPa, and fatigue strength of 60 MPa [7]. Listed in the following sections are alloys that are current being used to cast engine blocks and their mechanical properties.

Gray Cast Iron Alloys

Gray cast iron alloy have been the dominant metal that was used to manufacture conventional gas-powered engine blocks. Though extensive use of aluminum alloys has diminished the popularity of this material, it still finds wide use in diesel-fueled blocks, where the internal stresses are much higher. Gray cast iron alloys typically contains 2.5-4 wt.% carbon and 1-3 wt.% silicon, 0.2-1.0 wt.% manganese, 0.02-0.25 wt.% sulfur, and 0.02-1.0 wt.% phosphorus [8]. It has excellent damping capacity, good wear and temperature resistance, is easily machinable, and is inexpensive to produce. However, gray cast irons are relatively weak and are prone to fracture and deformation. Due to these problems, compacted graphite iron has recently begun to compete with gray cast iron as the choice material to produce diesel engine blocks. Figure 2 shows the BMW S54 inline-6 used in their high performance M3 coupe. It is interesting to note that the cylinder block for this engine is constructed from gray cast iron, whereas the block for the BMW M54 engine, the basis of architecture of the S54, was made of aluminum alloy. One possible reason why the S54 block was made from gray cast iron was the need for a stronger material that could tolerate the higher performance levels (the S54 produces 333 brake horsepower and has a maximum engine speed of 8000 rpm, whereas the M54 produces 184-225 brake horsepower with a maximum engine speed of 6500 rpm).

Figure 2: BMW's S54 inline-6 engine, which uses a gray cast iron engine block[9]

Compacted Graphite Cast Iron

Compacted graphite cast iron (CGI), which was accidentally discovered while trying to produce ductile cast iron, possesses higher tensile strength and elastic modulus than gray cast iron due to the compacted graphite found on the microstructure of CGI. Table 1 shows the comparison between the strengths and modulus of elasticity of gray cast iron and CGI. As seen in Table 1, gray cast iron has a lower tensile strength than CGI, despite its higher weight.

Table 1: Comparison of tensile strength and modulus of elasticity of gray cast iron and compacted graphite cast iron.

	Gray cast iron	**Compacted graphite cast iron**
Tensile strength, MPa	160-320	300-600
Modulus of elasticity, GPa	96-110	170-190

Like gray cast iron, compacted graphite cast iron has good damping capacity and thermal conductivity, but its difficulty to machine has limited the wide-scale use of CGI. A new manufacturing process, however, has opened the way for larger applications of CGI. The development of rotary insert tools has increased the life of the tools used to machine the metal, thus allowing manufacturers to use CGI without worrying about purchasing new tools [10]. Initial projections of 150,000 diesel engines produced (by Ford and Peugeot) per year are an indication that manufacturers are embracing the use of CGI as the material to produce cylinder blocks [11]. Figure 3 shows Ford/Peugeot's diesel engine that contains a block made of compacted graphite cast iron.

Figure 3: Ford/Peugeot's 2.7-liter V6 uses a cylinder block manufactured out of compacted graphite cast iron [12]

Aluminum Alloys

Aluminum alloy use has gained popularity since the 1960's as a way to reduce the overall weight of the vehicle. There are two practical implications: improved performance-to-weight ratio and increased fuel efficiency. The drawbacks of using aluminum in engine blocks are that they are more expensive to manufacture than cast iron alloys. However, the strength-to-weight ratio of aluminum alloys is hard to ignore, and manufacturing processes developed throughout the years have minimized the cost disparity between aluminum and cast iron. There are two aluminum alloys that are mainly used in the manufacture of cylinder blocks: 319 and A356.

Aluminum alloy 319 has a composition of 85.8-91.5 wt.% aluminum, 5.5-6.5 wt.% silicon, 3-4 wt.% copper, 0.35 maximum wt.% nickel, maximum 0.25 wt.% titanium, maximum 0.5 wt.% manganese, maximum 1% iron, maximum 0.1 wt.% magnesium, and maximum 1 wt.% zinc [13]. The alloy has good casting characteristics, corrosion resistance, and thermal conductivity. When heat treated with the T5 process, it possesses high strength and rigidity for engine block use. The LS1 engine of the 5th generation Chevrolet Corvette (1997-2004) is an example of an engine that utilizes aluminum alloy 319-T5 as its block, shown in Figure 2.

Figure 2: The Chevrolet Corvette LS1 V8 engine which utilizes an aluminum alloy 319-T5 cylinder block [14].

Aluminum alloy A356 has a composition of 91.1-93.3wt.% aluminum, 6.5-7.5 wt.%silicon, 0.25-0.45 wt.% magnesium, and maxima of 0.2 wt.% copper, 0.2 wt.% titanium, 0.2 wt.% iron, and 0.1 wt.% zinc [13]. Mechanical properties are similar to that of aluminum alloy 319. However, when heat treated with a T6 treatment, it possesses higher strength than 319. Table 2 compares the tensile strength and modulus of elasticity of both alloys. Note the lower elastic modulus of A356-T6 compared to that of 319-T5. Figure 3 demonstrates an example of an engine using A356-T6 for its block.

Table 2: Comparison of strength and elastic modulusof aluminum alloys 319-T5 and A356-T6

	Aluminum alloy 319-T5	**Aluminum alloy A356-T6**
Tensile strength, MPa	178	215
Modulus of elasticity, GPa	74	215

Figure 3: General Motor’s inline-5 engine which uses aluminum alloy A356-T6 as its engine block [7].

Magnesium Alloys

Magnesium alloys have been used in engines before, but not for cylinder blocks. Rather, they were used as valve covers, cylinder head covers, intake manifolds, rocker arm covers, air intake adaptors, induction systems, and accessory drive brackets [15]. The biggest attraction for manufacturers is that the material is much lighter than cast iron and aluminum alloys and has the same strength as cast iron and aluminum alloys. Material scientists and engineers were determined to exploit these characteristics of magnesium alloy and use it to fabricate engine blocks. There were a number of magnesium alloys available that met or exceeded the requirements demanded by manufacturers for an engine block, but insufficient material stability at high temperatures hindered their actual use. However, in 2003 material scientists and engineers from the Cooperative Research Center for Cast Metals Manufacturing and the Australian Magnesium Corporation presented their discovery of sand-cast AMC-SC1 magnesium alloy [16]. This grade of magnesium alloy contains two rare earth elements, lanthanum and cerium, and was heat-treated with T6.This stabilizes the strength of the alloy at high engine operating temperatures, which is a necessary requirement for a cylinder block material [16]. Bettles et al. had performed experiments to determine the yield and creep strengths of AMC-SC1 and their results are shown in Table 3 [17]. From Table 3, the most significant point is that the yield strength of AMC-SC1 essentially stays the same at 177ºC as it does at room temperature. This means that the material is able to tolerate a wide range of operating temperatures without a loss in strength. Other properties of the magnesium alloy 10 include good thermal conductivity, excellent machining and casting qualities, and excellent damping characteristics.

To demonstrate the significant weight savings of magnesium alloy over cast iron and aluminum alloy, consider BMW’s inline-6 R6 (shown in Figure 4), which replaced the company’s M54 aluminum engine. Its cylinder block is made of AMC-SC1 and is said to have decreased the weight of a comparably-built gray cast iron and aluminum alloy block by 57% and 24% [18]. So far, BMW is the only company to have used magnesium alloy cylinder blocks in production vehicles. But, with a significant weight advantage over the current alloys used today and negligible increase in cost, other manufacturers will begin to consider the use of AMC-SC1 and possibly other grades of magnesium alloys for engine blocks.

Table 3: Yield and creep strengths of magnesium AMC-SC1 at room temperature, 150ºC, and177ºC [17].

	Room temperature (24ºC)	**150ºC**	**177ºC**
Yield strength, MPa	120	116	117
Creep strength, GPa	-	120	98

Figure4: BMW's 6-cylinder R6 powerplant uses a magnesium alloy AMC-SC1-fabricated cylinder block [18].

Casting Processes

There are two methods used to cast engine blocks for all materials: green sand molding or lost foam casting. The latter, pioneered by General Motors for their Saturn vehicles, have become more popular due to its capability to produce near net shape components, provide tight tolerances for critical components, and reduce machine maintenance and cost [19]. Green sand molding, however, is still widely used in industry as material costs are low and most metals can be cast by this method [20].

Green Sand Molding

Apart of the sand casting family that also includes dry-sand molds and skin-dried molds, green sand molding the common method to cast engine blocks. The term "green" denotes the presence of moisture in the molding sand [20]. Figure 2 demonstrates the first stage of green sand molding. From Figure 2, a combination of silica sand, clay, and water poured in one-half of the block pattern with a wood or metal frame. The mold is then compacted by squeezing or jolting, and the process is repeated for the other half of the mold. A core consisting of hardened sand is used for support. Then, molten cast iron, aluminum, or magnesium alloy is poured into the combined molds and solidifies. Once the latter part has been completed, the molds are removed, and the cylinder block is cleaned and inspected. Heat treatment of the block is then undertaken to improve the mechanical properties of the alloy for suitable use.

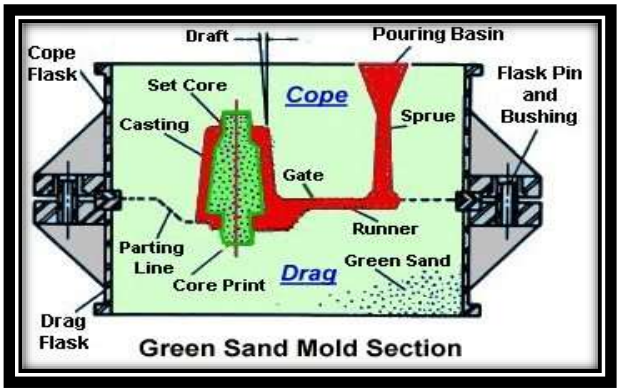

Figure 4: The first stage of green sand molding, a mixture of silica sand, clay, and water is poured into a defined pattern framed with metal [7].

Lost Foam Casting

Lost foam casting is a more reliable and efficient casting technique of the manufacture of engine blocks than green sand molding. The technique begins with the use of polystyrene beads placed in pre expanders for wet expansion to control bead size and density to produce four separate block moldings to be glued together to form the final mold [7, 19]. Next, the metal tool is preheated to remove any moisture and then filled with the beads. The tool is then heated via steam and placed in an autoclave, where it is subjected to high pressures in order to create the molds [7]. The tool is removed from the autoclave and immersed in water to finish the moldings. Precise control over the heating and cooling aspect ensures dimensionally accurate, smooth and strong molds [7]. If the tool was not heated before the beads were injected, the results would be rough finishes in the molds with low-strength sections. If the tool and beads stay heated for an extended period of time, or is not cooled enough, the beads become “overfused,” which produces surface variations in the moldings. If the tool has been inadequately cooled, the molds will contain variations in dimensions [7]. Figure 3 shows the final half stages of the lost foam casting method.

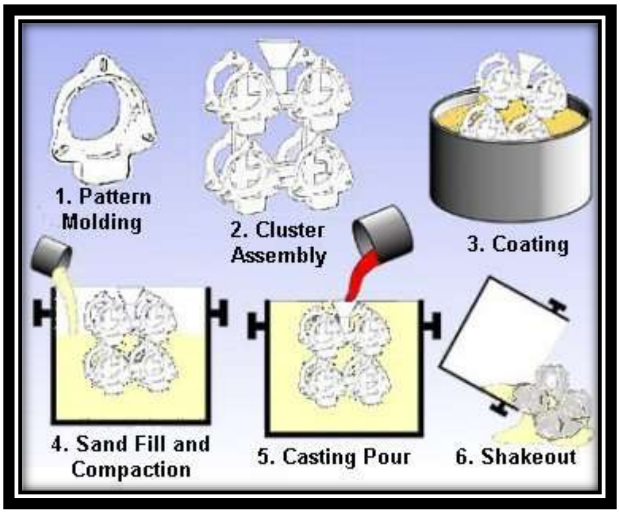

Figure 6: Graphical description of the last 6 of 7 methods of the lost foam casting method [7].

From Figure 3, once the individual molds are glued together, the assembly is placed in a vat with water-based ceramic liquid to prevent molten metal from destroying the mold, stiffen the assembly, and provide a smooth finish [7]. The assembly can also be sprayed with the ceramic liquid, but is a time-consuming process. Next, the coated foam engine block is filled with sand, compacted, and immersed in the molten metal alloy. Once cooled, sand is removed from the metal casting, cleaned, and undergoes heat treatment to increase the mechanical properties of the block. Finally, coolant and oil passages are machined into the block.

4. CONCLUSION

While aluminum and cast iron alloys have dominated the market for engine block materials for many years, new materials that were either once impossible or too expensive to consider have now become reality. Over the past couple of years, new machining processes and material fabrication have increased the use of compacted graphite cast iron over gray cast iron as

the material of choice to produce cylinder blocks for diesel- and regular petroleum-fueled vehicles. But perhaps the greatest innovation in engine block technology is the production of a magnesium alloy that is able to perform under the difficult conditions an engine is put through.

AMC-SC1 magnesium alloy will be able to increase fuel efficiency and power-to-weight ratios of automotive engines while decreasing emission levels. Though this may be a significant impact for the internal combustion engine, it faces new challenges. Engines powered by fuel cells, hydrogen, and electricity are extremely efficient vehicles that have become viable within the last decade. As automobiles advance further into the 21st century, the role of the internal combustion engine may possibly diminish due to these new advances, despite the use of lighter alloys.

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