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Additive manufacturing in Formula One (F1) Cars: A Review on Processes, Applications

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Abstract Additive manufacturing (AM) technology has been developing rapidly in recent years and its use in different sectors is increasing day by day. The working system of AM technology, unlike traditional production methods, is a layer-based production process by creating layers on top of each other. Due to its advantages such as material savings, low cost, production of parts without the need for molds and design flexibility, especially in complex shaped parts, it has found use in many fields, especially in medical, aviation and automotive.

The biggest disadvantage of the AM method is that parts of a certain size can be produced due to the size of the part to be produced. To eliminate this problem in AM technology, it is possible to create large parts by combining small parts. In this research study, the role and development of additive manufacturing in the production and development of Formula One (F1) cars, which is the leading world championship in motor sports, which parts are produced with this method and why, in a system based on continuous improvement, A.M. on what advantages it provides. Examples are given on the parts produced by additive manufacturing in Formula 1 vehicles, and the advantages of being produced with additive manufacturing are explained with sample photographs.

Keywords Additive manufacturing, formula 1 cars, rapid manufacturing.

1. Introduction

Additive manufacturing, also known as three-dimensional printing, rapid manufacturing, is a manufacturing method that is made by combining materials or producing three-dimensionally designed parts in layers, unlike machining methods. [1]. According to the ASTM standard F2792-10, additive manufacturing is "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [2]. There are many different additive manufacturing methods for metals [3-7]. In the graphic below, production methods are classified and terms and abbreviations have been developed in terms of literature. However, 3D printing is the most common term used for additive manufacturing in manufacturing today. There are many classifications of additive manufacturing [2]. In Figure 1, there is a classification related to additive manufacturing. The red colors in the table represent the standardized classification groups. Below are the titles of the sub-production methods belonging to this group [8].

The most important point in this classification is the production method developed according to the material used for the realization of additive manufacturing. These methods are most commonly known by their short names as FDM, SLA, DLP or SLS.

FDM (Fused Deposition Modeling) production method is obtained by overlapping or adding, the material to be used for manufacturing, by flowing it like a fine thread. If it is SLA (Stereolithography) or DLP (Digital Light Processing) production method, layer-by-layer production is performed by solidifying special photopolymer resins sensitive to light with laser or projector light. In the SLS (Selective Laser Sintering) method, powder-like particles are joined by melting [1, 8-11].

Additive manufacturing processes create objects by adding material layer by layer, while in subtractive manufacturing, materials are removed from the manufactured part to create parts. Although these approaches are fundamentally different, subtractive and additive manufacturing processes are often used together because of their fields of application [6].

Due to developing technologies, requirements and production speed; It is used in the fields of aerospace and defense industry, automotive, medical, architecture and jewelry [12-16]. But day by day, they will prefer this production method in different areas. Additive manufacturing helps to produce parts in small dimensions quickly, unlike production methods that take a long time and cost. In addition, complex parts that cannot be produced with traditional production methods are easily produced [17].

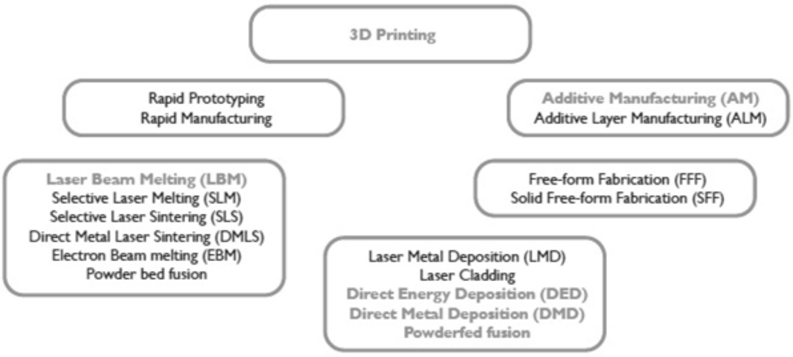

Figure 1: Classification of Additive Manufacturing. Shown in red is the standardized and most common use [8].

In 2017, additive manufacturing specialist Pat Warner from the Renault Formula 1 team stated that the use of SLA 3D printers, which they have been using since 1998, provides significant advantages in various applications [18]. Recently (2017), the Renault team has used additive manufacturing to produce the gearbox case made of titanium and titanium alloys. In recent years, Formula 1 teams have realized the benefits of additive manufacturing technology and have started to invest in additive manufacturing technologies [18,19].

.The McLaren F1 team has been using Stratasys 3D printers since 2017 to save time against their competitors and to provide a quick turnaround in changes to the front, rear wings and body details of the vehicles [18]. In addition, the McLaren team produces both prototype parts and newly designed parts due to changes in vehicles in races, using Fused Deposition modeling (FDM) and PolyJet technologies [18,20].

Richard Braby, advanced digital manufacturing (ADM) team leader for the Williams Formula 1 team, said in an interview in 2018: "If you only buy one component that you would traditionally make as a composite part, you'd have to forgo design. Mold design, fabrication, material selection, and part fabrication are all four parts. When using additive manufacturing (AM), you go directly from design to production and test your part directly, saving both time and a lot of manpower [18].

Renault announced that approximately 100 parts of the two cars in Formula 1 were produced by additive manufacturing. Formula 1 teams have begun researching to manufacture exhausts, engine parts and suspensions with metal additive manufacturing [21]. The experience of the team members has allowed the production of a wide variety of versions of [18], since the time from designing a part to producing parts is very fast. For this reason, the fact that the production was realized in a short time made a great contribution to the design development cycle.

In Figure 2, information about additive manufacturing used in different industries is given [3]. Additive manufacturing has brought a new strategy and a different perspective to the manufacturing challenges of certain parts, especially in the automobile industry.

In the automotive industry, it has allowed the production of complex and light weight parts, freedom of design. It also allows the rapid production of complex parts designed by designers. It is a rapidly growing technology in the automotive industry, as it allows the part to be tested and produced with higher efficiency, optimization and cost-effectiveness where it will be used. Compared to traditional teaching methods, 50-90% time and cost savings are achieved. In this way, both development and production costs are reduced.

Additive manufacturing allows designed or developed parts to be designed and manufactured in ways that are simply not possible using traditional fabrication techniques. Additive manufacturing has now moved beyond relatively small and lightly loaded components to produce complex geometries that are traditionally difficult to make, such as roll hoops, flanges, and retractors, built to save weight, maintain strength [16]. It is always eager to use technology that could contribute to Formula 1's creation of faster, lighter and more powerful cars. Because it has to constantly renew itself. Pat Warner, Director of Additive Manufacturing and Renault F1 Team additive manufacturing specialist, said the first 3D printer was purchased in 1998 [18,19].

Formula 1 is one of the first adopters of additive manufacturing (A.M.). More than ten years of research work has been done and then they have started to test and use products produced by additive manufacturing in race cars. Factors such as the complex structure of [18,19,22]. Formula 1 vehicles, the high G-force they are exposed to, polluted air, vibration, downforce, chassis strength, apex errors in driving, DRS are very important. These factors vary on each track and in different weather conditions. That's why the necessary parts, thanks to the rapid production of additive manufacturing, made AM the ideal process for producing F1 parts. In a sport that changes so quickly from one race to the next, the important thing is to be able to design and manufacture complex parts quickly. It allows engineers to reduce the weight of parts and redistribute the center of gravity in the car to achieve a lower center of gravity. This application is constantly being researched and developed since each track to be raced has different characteristics. In this way, it allows the air flow to pass faster through corners formed in vehicles, for example). In general, faster results per piece and lower costs help Formula 1 teams maintain their competitive advantage. In Formula 1, every racing season, cars try to push their limits and be faster than ever before. In addition, it is constantly in development due to the changes made in formula 1 cars before the start of each season. As additive manufacturing technologies evolve, it is seen that Formula 1 teams are producing more and more parts [8]. Also within motorsport, Indycar, Lemans, WRC, Formula 2 & 3 and Formula E take advantage of additive manufacturing technologies [18-23].

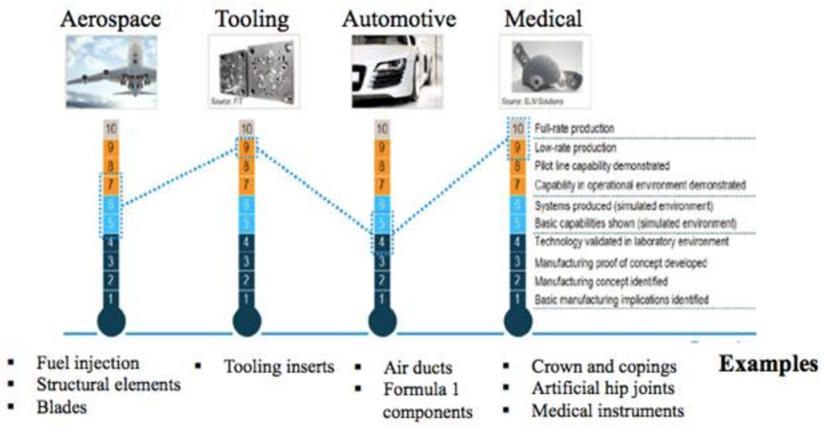

Figure 2: The contribution level of additive manufacturing to production in its various sectors [8].

Additive manufacturing gives part geometries accurate and repeatable and gives designers a wide choice of geometry to optimize performance. Increasing amounts of 3D printing and additive manufacturing will continue to be used in the automotive industry and F1. The future of additive manufacturing in F1 can only go one way, there will be more additive manufacturing parts and it will remain a key component in the fast-paced world of F1 [23]. In order to provide a constantly evolving and competitive racing environment in Formula 1, the FIA and Formula 1 management introduce some changes and limitations for vehicle designs every year. It provides a continuous competitive environment by minimizing the setbacks experienced in the previous racing season and removing some advantageous applications. In this way, F1 teams reproduce their vehicles within the framework of the determined rules and continue their development studies continuously. In the 2021 F1 racing season, Formula 1 management announced that the 2020 chassis will be used this year and radical changes will be made in 2022 [24].

Why does F1 use additive manufacturing? When faced with a question; Being able to quickly design and manufacture complex or interchangeable parts is important for a fast-changing sport, from one race to the next. Since the characteristics of each race and track are different, the designs of the vehicles are constantly changing. With topology optimization, it may be necessary for engineers to reduce the weight of parts and distribute the load closer to the ground, thereby increasing the car's downforce to achieve a lower center of gravity and sometimes increasing the vehicle's downforce, allowing the vehicle to go through corners faster. Faster parts production and lower costs help Formula 1 teams maintain their competitive advantage. For this reason, the use of additive manufacturing continues to increase day by day in the Formula 1 sector [19].

In the production of plastic parts, it is almost impossible to specialize in additive manufacturing, as injection molding offers a more convenient technology, a much wider choice of materials and is more convenient in terms of part size. However, it is generally used as a complementary technology as the need for mold provides an advantage to additive manufacturing. As Pat Warner of the Renoult team defines, "The additive does not eliminate injection molding and machining". All production methods must come together to produce the final stage or part of the parts [21].

2. Additive manufacturing in Formula 1

Changes to Formula 1 cars are shown in Figure 3-5. In Figure 5, we can see that tire sizes, vehicle length and width, front and rear wing lengths, and body width have been changed. The changes made here were requested with the idea that the down force of the vehicle would help the air flow to be more comfortable, the G force effect to be reduced, the polluted air to be discharged more easily and the engine to be cooled more easily thanks to the air flow. For example, it is thought that by increasing the size of the front wing, the brake systems will contact more areas faster and thanks to the air flow. From here, the air will be easily expelled. In the rear wing design, the wing size was increased and it was thought that the vehicle would be controlled more easily due to the air flow. The detail and complexity of these parts is a very advantageous factor in terms of additive manufacturing. After these parts were produced by additive manufacturing, some teams (Sauber and Redbul Honda) set up wind cabins to control the parts. In this way, they could easily see how the air flow occurs. Due to the rapidity of additive manufacturing, it is very easy to make changes in the obtained data [19,22].

No part of the car may be more than 710mm behind the rear wheel centre line or more than 1200mm in front of the front wheel centre line [25].

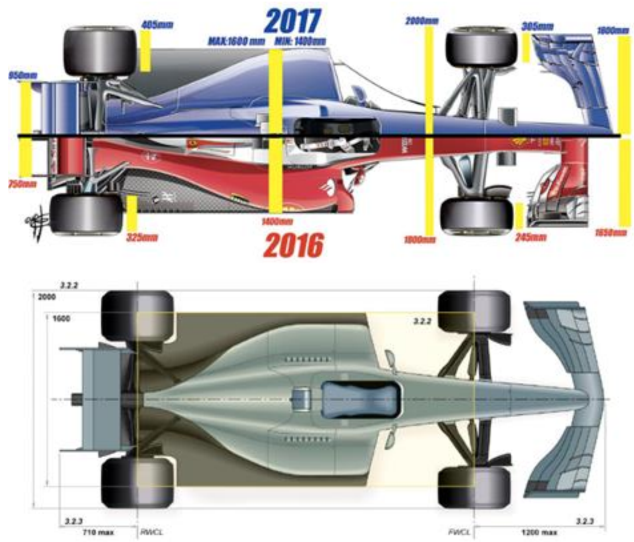

Figure 3: Desired basic vehicle dimensions regarding the 2016-2017 Formula 1 car regulations. [22, 25].

In Figure 4, the front view of the Formula 1 car is given. As can be seen from this picture, we can see how complex and detailed the front wing part is. Since it is possible to produce such a detailed part much more easily and quickly with additive manufacturing, Formula 1 teams have preferred the additive manufacturing method day by day. The positive results obtained from the produced parts thought that other parts of the teams could be produced with additive manufacturing and they could develop their tools quickly [22].

Figure 4: Requested updates to 2016 and 2017 Formula 1 car [19,22].

Figure 5 shows the detail of the front wing. These parts were also made with additive manufacturing. With the wing design of the formula 1 vehicle in 2017, it is aimed to increase the downforce of the vehicle. In addition, the distance of the body to the ground has been reduced, but the distance of the body to the ground has been increased. With this design, air flow is provided in a different way and the downforce is increased. Here, how the air will move can be seen with the tests carried out by the teams in the wind tunnel facility laboratories.

Figure 6 shows an F1 vehicle prepared for testing at the wind tunnel facility. In this facility, the forces created on the vehicle and the air flows in the rear-front wing are observed by providing air circulation determined from different directions. According to the results obtained, teams prefer additive manufacturing for development and new designs for parts. F1 teams have established additive manufacturing laboratories to produce these parts. The first F1 teams to establish the additive manufacturing laboratory are Renault, Sauber, Williams and Mc Leren. In addition, these teams provided special environments to try the pieces they produced. Especially for the front and rear wing parts, a closed environment was established that allows wind at 300 km speed and they made their experiments here (Figure 6) [19,22].

The Red Bull team disclosed some of their knowledge on additive manufacturing to Trusted Reviews in 2014. In particular, he explained that they used 3D printing to produce prototype parts and tested these parts in a wind tunnel. They produced the first parts for a 60% scale race car that allowed Red Bull to measure the effectiveness of the part before producing the core part.

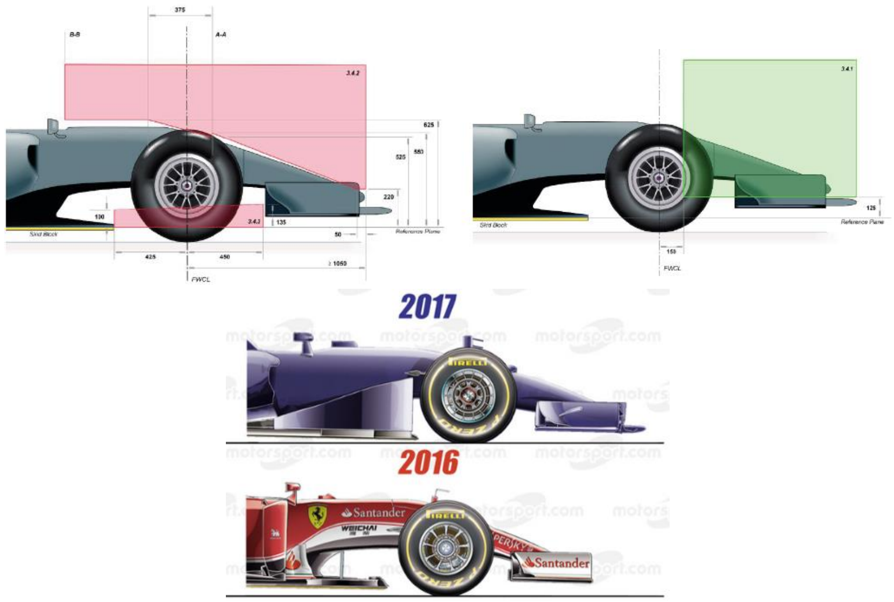

Figure 5: Changes in the nose design of the Formula 1 car. The front part obtained by the production of the new design by additive manufacturing [19,22]

Ten of the Formula 1 teams use additive manufacturing to produce their parts [8]. Metal additive manufacturing is the first choice for F1 tools where lightweight components with complex structures and geometries are subjected to high mechanical loads or high temperatures. The complex structure of the F1 vehicles, the high pressure-force factors they are exposed to, and the exposure to high temperatures are the most important issues they deal with in the design of the parts [2].

F1 teams constantly strive for the ideal balance of lightness, weight, power and driver safety. AM production has helped them achieve these goals, and they have only been achieved through the flexibility of the AM process. It has allowed the parts in Formula 1 cars to be designed and manufactured in ways that are simply not possible using traditional manufacturing techniques. AM Production allows parts to be produced where the material is placed only where it is needed, not as a result of the physical or financial limitations of the production process. In addition, part geometries are accurate and repeatable, giving designers a wide range of geometry options to optimize performance [26].

The automotive industry and F1 will continue to use increasing amounts of 3D printing and AM production. As the seasons close, teams will evaluate their successes and failures on the track to improve their standings for the next year. As we enter the winter break, teams will build on what they learned from the previous season. Ready for the new season, they will refine the designs of existing AM parts while developing new and additional AM parts for their cars. The future of AM production in F1 can only go one way, there will be more AM parts and it will remain a key component in the fast paced world of F1 [26,27].

Figure 6: A 2021 Formula 1 car ready for testing at the Sauber team's wind tunnel facility [18].

The photographs of the parts where additive manufacturing takes place in the formula 1 vehicle of the Sauber team are given in Figures 7 and 8. In these photographs, it is seen that which parts of the vehicles are produced by additive manufacturing of formula 1 kits in general. Some formula 1 teams are constantly working on research and development studies and the production of other parts other than these parts. Formula 1 is a motor sport that always renews itself and never stands still. After the production of the parts they designed after the research and development studies carried out by the teams, the team personnel assemble these parts and give information about the part by preparing a report about the system. Accordingly, they continue their improvement work. When the parts produced by additive manufacturing in the Formula 1 vehicle and the materials they are produced with are examined, it is seen in Figure 7 that the materials used for the cooling ducts for electric, rool hoop, frontwing benzing, brake duct sccops, upright covers parts are produced [28].

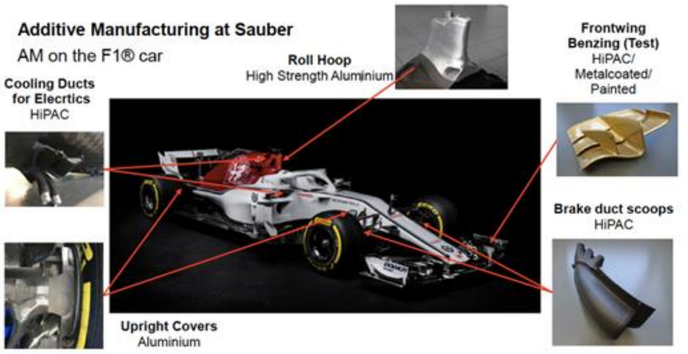

Figure 7: Formula 1 of the Sauber team [28].

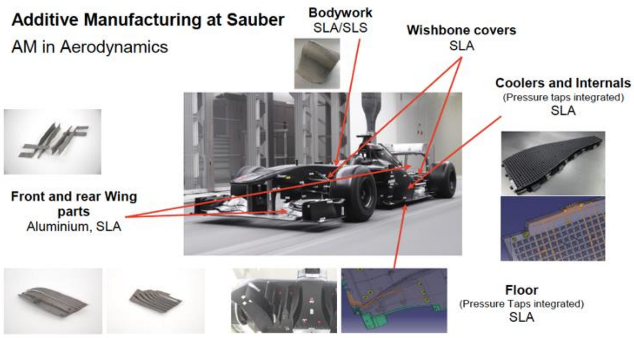

Figure 8: The additive manufacturing method used to produce the parts of the Formula 1 vehicle designed by the Sauber team [28].

When Figure 8 is examined, we can see by which additive manufacturing method the parts of a Formula 1 vehicle belonging to the Sauber team were produced. SLA and SLS methods are preferred in the additive manufacturing method. The properties of the materials used in these two methods used by the Sauber team are given in the table (Figure 9,10). [28].

Parameter	HiPAC (SLS) 1)	Bluestone (SLA) 2)	HPC (SLA) 2)	Xtreme (SLA) 2)
Density sintered at 25°C	approx. 1,2g/cm³			
Density solid at 25°C		1.78g/cm³	1.61g/cm³	1.19g/cm³
E module bending	7327MPa	8300 - 9800 MPa	9000-9700MPa	1520 - 2070MPa
Flexural strength	132MPa	124 - 154 MPa	137-157 MPa	52 - 71 MPa
E module tensile force	8304MPa	7600 - 11700MPa	8700-1200MPa	1790 - 1980 MPa
Tensile strength	85MPa	66 - 68 MPa	66-89MPa	38 - 44MPa
Crack expansion	2.7%	1.4 - 2.4 %	0.8-1.9%	14-22%
Melting point	172-176 °C			
Heat resistance	ca. 170°C			54°C
Glass transition temp.		71 - 83 °C	62-73°C	

1) HiPAC® developed by Sauber Engineering AG 2) Accura® Bluestone / HPC / Xtreme - 3DSystems product

Figure 9: Additive Manufacturing at Sauber, Material Selection Plastic Additive Manufacturing [28].

Parameter	AlSi10Mg (DMLS)	Titanium Ti64 (DMLS)
Relative density	>99.5%	>99.5%
Absolute densitiy	2.67 g/cm3	4.43g/cm3
Ultimate tensile strength horizontal	400 MPa	950 MPa
Ultimate tensile strength vertical	400 MPa	950 MPa
Yield strength horizontal	200 MPa	880 MPa
Yield strength vertical	230 MPa	880 MPa
Elongation at break horizontal	3%	7%
Elongation at break vertical	3%	7%
Youngs modulus horizontal	70 GPa	100 GPa
Youngs modulus vertical	65 GPa	100 GPa
Hardness	100 HV	400 VV

Figure 10: Additive Manufacturing at Sauber, Material Selection Plastic Additive Manufacturing [28].

The information on both the mechanical and chemical compositions of the materials used by Sauber to realize the products designed for use in their automobiles with metal additive manufacturing is given. In Figure 11, photographs of molds, lamination cores, trim and bonding gauges made with additive manufacturing are given. Sometimes the auxiliary parts (molds, etc.) required for the production of the parts to be produced can be realized by using additive manufacturing instead of part production with the additive manufacturing method. In this way, a comprehensive cooperation with different production methods is realized.

Figure 11: Pictures of molds, lamination cores, trim and bonding gauges made by additive manufacturing [28].

Figure 12 shows the exhaust components (a) manufactured by Sauber for use in its automobiles by additive manufacturing, the roller pulley (b) with complex internal structures that protect the driver in the event of the car turning, the race car cooler unit (c), and the radiator inlets and outlets (d). [28]. Figure 13 shows the EOS 3D printed F1 brake pedals. Brake pedals, made as part of the Materialize 3-matic project, were made on an EOS M290 additive manufacturing machine with EOS Titanium Ti64 material. The challenge in manufacturing was to produce it from titanium, which is harder than the aluminum normally used.

Figure 12: Parts of exhaust components in a Formula 1 cars [29,30].

At the end of the production, a hollow structure with 80 g weight savings and a reduction in the displacement of the stresses from 1.8 mm to 0.6 mm were achieved [22]. Weight savings and greater strength, which are important for Formula 1 vehicles, are eliminated by additive manufacturing. Parts are developed with the feedback received by using the produced parts for a certain period of time. It is also very important for the production to be fast in development studies, in terms of testing the parts. That's why the Formula 1 industry uses additive manufacturing more and more.

McLeren team produced a bracket to connect the hydraulic line to the MCL32 race car using FDM (Fused Deposition Modeling) technology (Fortus 450 mc 3D printer) with additive carbon fiber reinforced nylon material (Figure 14a) [31].

Figure 13: F1 Brake pedal designed for the 2016 Redbull Formula 1 car (Photo by Michael Petch) [22].

Produced in about two weeks using traditional manufacturing processes, the bracket was produced in just four hours thanks to additive manufacturing. A large rear wing designed to increase the pressing force behind the Formula 1 car was produced from carbon fiber reinforced composites by 3D printing technology based on FDM (Fortus 900 mc 3D printer). The 900 mm wide rear wing is made of high temperature (> 350°F /177°C), autoclave-cured composite material (ULTEM 1010 3D), saving three days of time (Fig. 14b) [31]. The fact that additive manufacturing provides a great advantage in terms of time is a unique production technology especially for Formula 1 teams that are racing against time.

Figure 14: The McLeren Formula 1 team's MCL32 race car a. bracket b. rear wing [31].

With the latest innovations and changes, the Mcleren team has added a new bidirectional communication and data system to the MCL32 race car. But these cables distract the driver's attention. It is manufactured by utilizing the ability of the Stratasys J750 brand 3D printer to print on flexible materials, by designing a rubber-like sheath to join the wiring harnesses for the communication system. Three different designs were made in one day. In this way, it offered the opportunity to try on the vehicle thanks to every cover made and fast production (Figure 15 a). Brake cooling channels are designed to efficiently control the temperatures of brake components, provided they are made of hollow composite material. In order to produce a hollow composite part, additive manufacturing was considered to be the most ideal production method. It was 3D printed using ST-130 soluble material specially developed for the application and then wrapped with carbon fiber reinforced composite material and autoclaved at high temperatures. In this way, the wrapped material was dissolved and only the wrapped material remained and part production was ensured. A tubular piece with very smooth inner surface coatings to provide the required airflow was additively fabricated (Fig. 15 b) [31,32].

Figure 15: Relating to Mcleren team's MCL32 race car a. sheath, b. flexible part manufactured using soluble material [31,32].

Aston Martin Red Bull Racing began a collaboration in 2005 with Siemens Digital Industries Software's NX ™ software and Teamcenter® software for additive manufacturing. Aston Martin Red Bull Racing continues its efforts to improve its F1 vehicles with additive manufacturing. In Figure 16, they added about 70 percent of the wind tunnel front wing used in their F1 cars by additive manufacturing. NX and Teamcenter have been the digital backbone of the team since it was founded in 2005, and Aston Martin Red Bull Racing continues to integrate new vehicles and improve processes with additive manufacturing [33].

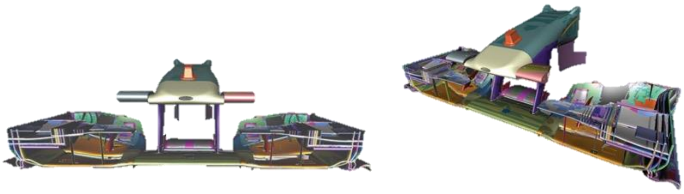

Figure 16: Additive manufacturing wind tunnel front wing on Aston Martin Red Bull Racing F1 cars [33].

In 2013, Force India reported that it has started test studies for additive manufacturing of some parts of Formula 1 team vehicles. Force India has tested its 3D-printed parts in a wind tunnel to evaluate their aerodynamic properties. Force India deputy team manager Bob Fernley (2013-2018) explained that additive manufacturing has significant value for their tooling and that is why they have partnered for 3D systems. Fernley said that with the development of 3D printing technology, the use of additive manufacturing in Formula 1 will increase, and that with the production of larger parts, many more parts can be produced with additive manufacturing. In 2013, Red Bull Racing reported that very few additive manufacturing uses it on their teams, apart from Force India and Williams. There is no data or information about which formula 1 parts are produced with additive manufacturing. Work continues behind closed doors to improve their vehicles. Due to the advantages of additive manufacturing, teams do not inform each other about which parts they have produced with additive manufacturing and which parts can be produced in the future [34].

Alfa Romeo Racing Orlen F1 team reported that they produced 143 parts in the 2020 race car with additive manufacturing. The C39 formula 1 vehicle to be used in the 2020 F1 season was tested on February 19, 2020 at the Barcelona F1 track in Spain, where test drives were carried out before the start of the season. In this tested vehicle, of the 143 additively produced metal parts, 58 were made of titanium, 19 of high-performance aluminum alloy and 66 of AlSi10Mg. Additively manufactured parts include chassis attachments, cooling circuit piping, safety structures, electronic component assemblies and more [35].

Alfa Romeo Racing Orlen reports that in industries using additive manufacturing (for Formula 1), it benefits the vehicle's performance and provides a 2% weight savings. They estimate that 304 metal parts in the new C41 2021 race car are produced by additive manufacturing and the vehicle will accelerate even more. Compared to the amount of additive manufacturing parts produced on the C39 vehicle (143 parts) last year (2020), the 2021 vehicle increased to 304 parts. More than twice as many additive manufacturing parts were produced between the two vehicles. Considering the materials from which these parts are produced, 22% Ti64Gd23, 36% Scalmalloy, 40% AlSi10Mg, 2% Stainless Steel were used. The total weight of these metal parts produced using the MetalFAB1 system was approximately 14860 grams, a relatively small increase from 13140 grams last year, given the large increase in the number of parts. Compared to parts that were previously produced with or without chip removal, a cost reduction of approximately 90% was achieved. In this way, Alfa Romeo Racing has given the Orlen F1 team a significant advantage in terms of cost savings [23,28,35].

In the Formula 1 industry, the cost savings are due to the fact that they have additive manufacturing machines, rather than producing light metal parts and higher productivity, to take immediate production-related operations. The Sauber team has agreed to work with Additive Industries to build a metal 3D printing center within three years. Christoph Hansen, Director of Technology and Innovation at Sauber Engineering, said: "The initial plan is to have two of these machines installed within three years and currently use four additive manufacturing machines. The reason they have so many machines is in different materials and sizes. is to produce parts [29].

The Federation International Automobile (FIA) is constantly making changes to Formula 1 racing and the work of teams. As the reason for the changes made, the main factor is to increase the competition among the teams and to get the teams closer to each other. One of these changes imposed restrictions on the use of wind tunnels, allowing crews to work in wind tunnels for more than 25 hours per week and use only 60 percent scale models. Figure 6 and 16 shows the wind tunnel model produced by the Alfa Romeo Racing Orlen F1 team with 60 percent scale additive manufacturing. Formula 1 teams have reduced production times by allowing multiple variations of the car to be created at the same time, thanks to additive manufacturing. They had the opportunity to try them by making multi-option designs. For these reasons, additive manufacturing is an indispensable production method for formula 1 parts [36, 37].

Figure 16: Wind test of rear wings designed at 60% scale [37].

To meet the cost cap set by the FIA, Alfa Romeo etc. teams have reduced their costs by switching to additive manufacturing. Sauber has decided to partner with Additive Industries to establish the Metal 3D Printing Competence Center. At the first stage, it is aimed to establish two machines and to start additive manufacturing within three years. They reported that they produced approximately 22,000 parts per year in the MetalFAB system, which includes 13 polymeric 3D printers as Sauber additive manufacturing. With these investments, they expect Alfa Romeo's Sauber name to become more competitive as it used to be. They declared that they are successful even now, despite the adoption of partnerships with additive manufacturing throughout the team. With the investments completed, the team will not have to wait long to find out how they are performing. Since it started in 2021, they predict they will outperform their rivals this year as Alfa Romeo's 2021 F1 car (Fıgure 17) has more than 300 3D-printed parts. Since the 2021 season has ended when this research article was prepared, it was seen that Alfa Romeo took the 9th place with 13 points out of 10 teams. It can be predicted that they got 5 points more than the previous year and they will get more points over time [27,28].

Figure 17: Alfa Romeo's C 39 2021 F1 vehicle produced by additive manufacturing of more than 300 parts [28].

The Renault F1 team stated that they produced nearly 100 parts of the Formula 1 cars they used in 2019 with additive manufacturing. Production engineers in Formula 1 have declared that using only one additive manufacturing technology will not be enough. There are no certain limits in additive manufacturing. The designed part determines the limits of production. With additive manufacturing, it can sometimes occur in the form of producing and combining two or more parts. In this way, formula 1 also prefers the piecewise production style. Fused Deposition Modeling (FDM) is one of the first technologies adopted that can create rapid samples, molds and prototypes with the additive manufacturing method. While nylon and other engineering plastics tend to be very suitable materials to be used with this technology, high performance polymers such as PEEK and PEKK have been used in recent years (Figure 18). The main reason for the use of these materials is high heat resistance. Because the temperature around the engine in Formula 1 cars can reach 2,600 °C (~4700 Renault F1 °F). FDM is limited to these applications as it lacks the ability to support functional and featured parts. It has been determined by the study, production and designs that it is quite ideal for the production of parts such as electrical boxes, cooling channels and covers.

Figure 18: Electronic cooling channel made of Carbon fiber reinforced Nylon designed by Renault F1 team engineers [19].

The Formula 1 industry uses stereolithography (SLA) additive manufacturing. It is a suitable method for parts with complex geometries (Figure 19). However, it is preferred in the production of parts that do not require much strength. Therefore, additive manufacturing companies and material manufacturers are constantly trying to develop new materials that can be used in this method. Simon van de Crommert reports that they are collaborating with two Formula 1 teams (Renault and Williams) to develop a ceramic filled epoxy SLA resin for this particular manufacturing method. The manufacturers of additive manufacturing machines and the users in the sector contribute to the development of the method in cooperation. Currently, large-capacity stereolithography machines have become standard for producing wind tunnel parts in scale mode designated for all Formula 1 teams (Figure 6) [19,22].

Figure 19: A hydraulic manifold produced with CNC machining (at the top) and with SLA (at the bottom) (below) by the Renault F1[18].

Formula 1 vehicles, using numerically controlled machine tools (CNC) and my welding method (above) and Stereolithography (SLA) method. Powder-based additive manufacturing technologies such as Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) are the most widely used method in the Formula 1 industry. The production method realized by powder-based fusion has many advantages over FDM and SLA [18].

It is very ideal for creating more homogeneous parts. According to the data and experience obtained by John Dulchinos, Vice President of 3D Printing and Digital Production at Jabil; "Functional parts for Formula 1 cars are usually made in SLS/DMLS. In the time it takes to produce one piece in FDM, you can produce 10 in SLS." gave his statement. When 3-4 kinds of optional parts are produced according to the design you think is the most suitable, it provides a lot of advantages to teams or designers. Formula 1 teams manufacture exhausts, engine parts and suspensions using the Selective Laser Sintering (SLS) method [18].

3. Discussion

Formula 1(F1) teams have established additive manufacturing laboratories to produce parts for their vehicles. The first F1 teams to establish the additive laboratory were Renault, Sauber, Williams and Mc Leren. In addition, these teams provided special environments for testing the pieces they produced. Especially for the front and rear wings, a closed environment that allows 300 km of wind was created and they carried out their experiments here. McLaren Formula 1 Team signed a partnership agreement with Stratasys company in 2017 and with Sauber Hansen company in 2015 [28,33].

Renault F1 Team and Jabil have entered into an additive manufacturing agreement to develop parts for the Renault R.S.19 competing in the 2019 Formula 1 World Championship and to enable cars to be produced faster. The Aston Martin Red Bull Racing team entered into an additive manufacturing collaboration with Siemens Digital Industries and Teamcenter software in 2015 [34].

In order to provide a constantly evolving and competitive racing environment in Formula 1, the FIA and Formula 1 management have introduced some changes and limitations in vehicle designs every year. Changes are made at the beginning of each season in order to ensure a continuous competitive environment by minimizing the disruptions experienced in the previous racing season and eliminating some advantageous practices. Due to these changes, the production of the designed vehicles and the trials are almost instantaneous. In this way, F1 teams reproduce their vehicles within the framework of the determined rules and continue their continuous development studies. For example, in the 2021 F1 racing season, Formula 1 management announced that the 2020 chassis will be used and a radical change will be made in 2022 [23,38].

With the desired changes in Formula vehicles in recent years; Changes were requested with the thought that the downforce of the vehicle would help the air flow to be more comfortable, the G force effect to be reduced, the polluted air to be discharged more easily and the engine to cool more. For example, by increasing the size of the front wing, it is thought that the brake systems will contact more areas faster and faster thanks to the air flow. From here, the air will be easily expelled. In the rear wing design, the wing size was increased and it was thought that the vehicle could be controlled more easily thanks to the airflow. The detail and complexity of these parts is a very advantageous element in terms of additive manufacturing. After these parts were produced by additive manufacturing, some teams (Sauber and Redbul Honda) set up wind booths to control the parts. In this way, they can easily see how the air flow is formed. Due to the speed of additive manufacturing, it was quite easy for the tools to modify the data obtained [21].

When we examine the Formula 1 teams in the 2021 season, we encounter Mercedes, Red Bull Racing Honda, Mcleren Renault, Ferrari, AlphaTauri, Aston Martin, Alpine F1 Team, Alfa Romeo Racing Ferrari, Williams Mercedes, Haas Ferrari. When we examined the investments, studies and laboratory studies of these teams in additive manufacturing in detail, very interesting results were encountered. In terms of the application of metal additives in F1, an average of forty to sixty parts per car was estimated in 2015 [18]. Where the use of AM was kept secret in F1 a decade ago, today teams and Additive Manufacturing technology providers are announcing their partnership.

In a dynamic environment like Formula 1, speed is crucial, both on and off the track. Optimization of a race car's design is important for any Formula 1 team, as the difference between a win and a loss is determined by mere seconds, sometimes splits.

Some teams have to quickly respond to the ever-changing regulations and both change and improve their designs each season while maintaining a competitive advantage. For this reason, continuous research, innovation, new designs and optimization of the obtained data is the most important point for Formula 1 design and engineering teams. Additive manufacturing, which is the most ideal production method for rapid production and producing complex parts, is very important for designers and engineers to accelerate the product development cycle. How Formula 1 teams use additive manufacturing to increase performance and innovation is explored in detail below [39,40].

4. Faster prototyping

The rules in Formula 1 races and the technical features of the vehicles are determined by the FIA (Fédération Internationale de l'Automobile), the governing body of motor sports, and the Formula 1 management. There are two basic elements in the development of the racing car in Formula 1. 1. Rapid consolidation of production, 2. Reduction of costs. Therefore, it is crucial to both adapt and develop prototypes before producing the final final part. Additive manufacturing is the most suitable method to produce prototypes with the same or similar features as the final part. Formula 1 design engineers design new vehicles based on the data obtained each year and the changes to be made. In an environment where such a rapid change is foreseen, it is important to design a prototype and put it into production immediately or as soon as possible. Additive manufacturing provides a much faster production opportunity than parts produced with traditional manufacturing. With the development of technology, both design engineers and technical personnel in production have eliminated the time factor in model preparation, mold design and production before producing the part. The reason for this is that the process starts in a very short time when the parts desired to be produced with additive manufacturing are sent to the device from the digital CAD file in which they are designed or the technical drawing is drawn. To give an example of these processes, engineers at the Williams team's base stated that they produce more than 2,000 additive manufacturing parts per month. If these parts were to be produced with traditional production methods, it would not have been possible [39,40].

5. Greater design flexibility

With additive manufacturing, it offers the opportunity to change parts both in terms of design and cost. It can be produced immediately with the part changes to be made in the design and the design flexibility can be realized with additive manufacturing. It allows engineers to find faults in the parts they designed in a shorter time and make changes in the design immediately. For aerodynamic advantages, race cars are designed to be pleasing to the eye. However, these features sometimes make easy access to the interior of the car difficult during pit stops. That's why they are constantly working and researching to produce styles that facilitate movement optimally with so many designs. with additive manufacturing

engineers have to get recycling by trying new designs right away. It offers more flexibility in developing optimal configurations [39,40].

6. Enhanced wind tunnel testing

One of the most important ways to evaluate the aerodynamic properties of race cars (Formula 1) is wind tunnel tests. Thanks to the additive manufacturing technology, while the aerodynamic properties are determined by wind tunnel tests, it is possible to produce durable, design-appropriate and accurate parts thanks to additive manufacturing technology. With the changes to be made depending on the data obtained from the tests, the production of new parts is faster with additive manufacturing. In this way, the data about the parts are received immediately. Aerodynamics is an essential element for motorsport. By evaluating the potential forces on the vehicle and how it will change and be affected by speed, it is determined which elements will gain or lose. In this way, you can easily see the differences between the designs and engineers can do research on them.

Wind tunnel tests must be carried out on a model that is 60% larger than the designed vehicle. This rule has been set and standardized by Formula 1 and the FIA. It is accomplished by placing the F1 car on a treadmill to make an adjustment and simulate the conditions (high speeds, wind forces, etc.) that the F1 car will encounter during the race. The replica technique most commonly used in additive manufacturing is used to create parts to be tested in a racing car. Especially in wind testing, additive manufacturing offers a faster, cheaper, and more efficient option to manufacture parts compared to machining and modeling. If a design change is envisaged, additive manufacturing enables components that can be tested in the wind tunnel to be produced much faster.

For example, the Alfa Romeo Sauber F1 Team uses SLS and SLA additive manufacturing techniques extensively to produce parts for wind tunnel car models, including front wings, brake ducts and suspension covers, as well as engine covers, interior ducts and hand deflectors. The Alfa Romeo Sauber F1 Team stated that they produce an average of 200-300 plastic parts per day with additive manufacturing technology and that "it would be impossible to produce this with any other method than additive manufacturing part production" [39,40].

7. Fast tool production

Additive manufacturing is also emerging as an invaluable technology for producing tooling equipment, from gauges and fixtures to composite tools. With this technology, manufacturers have eliminated the high costs and long delivery times associated with traditional tool manufacturing. In addition, they can easily produce special and unique sets. For example, using FDM technology, F1 teams are comfortable producing their insertion tools faster and more cost-effectively using high-strength materials such as ULTEM. The McLaren Formula 1 Team built a docking vehicle for a large rear wing extension using FDM' additive manufacturing technology and realized that additive manufacturing provides a lot of benefits.

The Mcleren team produced the parts they designed to increase the back pressure in Formula 1 vehicles with ULTEM 1010 material in three days, significantly shortening the delivery time. Additive manufacturing also offers the advantage of producing vehicles in different designs by speeding up both production and assembly. Some F1 teams use additive manufacturing to produce vehicles to assist with last-minute changes during races. In this way, it offered the advantage of eliminating the transportation incident [39,40].

8. Enhanced part performance

When engineers in Formula 1 teams want to increase reliability and efficiency in a race car, they can easily improve their performance thanks to additive manufacturing.

As a result of the changes made every year before the racing season of Formula 1 vehicles, the element of lightness comes to the fore and therefore some parts of the vehicles are made of aluminum materials made from the most commonly used metals and some of them made of carbon fiber.

Lightweight, complex thermoplastic and metal components, which are the most important advantage of additive manufacturing, are preferred more because they can be produced. In theory, the weight savings offered by additive manufacturing parts can make the difference between winning and losing.

For example, the Alfa Romeo Sauber Formula 1 Team manufactures uprights, garage equipment, exhaust components, cooler and radiator inlet-outlet sets with metal component additive manufacturing.

The advantages of additive manufacturing in motor sports, especially Formula 1, were explained above. A number of difficulties were encountered in the production process of additive manufacturing in the Formula 1 sector as well. This negativity is explained and analyzed in the following items. Despite the current uses of additive manufacturing in Formula 1 and motorsport as a whole, many challenges still remain when it comes to maximizing the technology's full potential [39,40].

*** Ensuring consistency**

Final finished parts produced by additive manufacturing can often vary when it comes to material and dimensional properties. As motorsport teams often outsource some or most of the additive manufacturing process, this means we can't get the exact same part every time. However, due to the advantages of additive manufacturing, many motorsport teams are encouraging more additive manufacturing to be carried out in-house in order to have more command and control of the production process. For this reason, investment costs are required to create additive manufacturing technology within their own structure. These costs strain some teams and push them to outsource additive manufacturing [39,40].

*** Education**

Formula 1 teams may feel a lack of additive manufacturing technical expertise in-house. Even if the training of the machines to be used for additive manufacturing is carried out, when some problems are encountered over time, there is a problem of intervening at that moment. Although additive manufacturing has been around for more than a decade, its adoption both in manufacturing and prototyping and as a production tool has been gradual.

For this reason, the development of trained and experienced designers about additive manufacturing occurs in a certain process. It means that many designers do not have extensive experience or are not interested in additive manufacturing. As a result, motorsports wishing to reap the benefits of 3D printing must also be prepared to invest in training programs to build the necessary knowledge and skill base [39,40].

*** Managing 24-hour production**

Formula 1 and motor sports teams are increasing their experience and abilities day by day in the additive manufacturing centers they have established within their own structure. In this way, as time progresses, the volumes of parts produced and planned to be produced by additive manufacturing also increase. It uses more than 10 different additive manufacturing machines per week and produces thousands of parts and prototypes. If there is no workflow management system in parts production at such high volumes, teams will inevitably face the challenge of managing parts to be produced by additive manufacturing.

With these challenges, inefficiencies can arise and large volumes of requests scheduled on a daily basis are difficult to manage manually. The workflow is therefore considered to lack both visibility and traceability across facilities and locations. It means that teams cannot efficiently monitor their projects throughout the production process.

Automating the workflow phase as much as possible is one of the best ways to meet this challenge. Custom workflow automation software is seen as a useful tool for tackling many of the problems motorsport companies may encounter when managing additive manufacturing. Therefore, new studies and programs related to the workflow are being developed. Based on the problems faced by Formula 1 teams in solving the problems in the workflow, additive manufacturing companies are trying to produce solutions. The workflow automates the request management process, making it easier to schedule work and track parts from request to production and beyond [39,40].

9. Conclusion

Additive manufacturing is widely used in different fields and is constantly renewing itself in terms of production methods. After the Formula 1 industry accepted additive manufacturing and discovered that it offers great advantages, its usage rate increased a lot. Formula 1 is the most dynamic fast automotive environment where advanced technologies can truly make a difference. In order to achieve the highest performance, the car is designed, manufactured, tuned and various tests are carried out. The faster these processes are, the faster the research and development work takes place. The only method that allows this is additive manufacturing.

About 30 parts were produced in the first applications of additive manufacturing in Formula 1 vehicles. With the development of different production methods in additive manufacturing, approximately 300 parts of the vehicles are currently produced.

The biggest advantage in Formula 1 vehicles is that it allows the production of complex, geometric and especially light parts that cannot be produced by machining. There is also a significant reduction in cost. In the production of complex and large parts, piece by piece production was carried out and then these parts were combined.

When a design team is under pressure to produce a new engineering design, additive manufacturing has come in handy, allowing engineers to use additive manufacturing technology for prototyping and testing, which helps make quick engineering decisions. For Formula 1 teams, part geometries and composite material selection play a vital role in the car's performance.

Since additive manufacturing is most widely used for prototype products in the motorsport industry, there is a widespread but misconception that the technology is not suitable for producing parts with sufficient strength and durability for use in high-performance applications such as race cars. With additive manufacturing, it is always already used at its highest levels as an alternative to produce machine parts that are heavier, less costly and take more time to manufacture.

In this study, which parts are produced in Formula 1 vehicles using different production methods of additive manufacturing were examined. In addition, explanations have been made about the sample parts where additive manufacturing has been used so far in the field of Formula 1. Depending on the design, additive manufacturing parts are preferred when it is desired to obtain porous and non-porous parts with high fatigue strength, light weight and good mechanical properties.

There are many internet resources that provide information on the use of additive manufacturing in the field of Formula 1. However, no article study was found. With this research study, researches were carried out in the field of Formula 1 on which parts are produced with the additive manufacturing method and why. In general, information is given about the advantages and disadvantages of the parts produced by additive manufacturing in the Formula 1 sector. As a result, the Formula 1 industry has adopted the additive manufacturing method. They are constantly researching and investing in different additive manufacturing methods. Formula 1 teams cooperate with various companies to establish additive manufacturing facilities by making agreements with various companies. As additive manufacturing methods develop and the use of different materials increases day by day, the parts produced by additive manufacturing in Formula 1 vehicles will also increase. For this reason, the production and design engineers of the teams will continue to do research and development.

In Formula 1, some changes are made in the vehicles and in the race for each season. These changes are aimed at increasing competition. Saying that nothing will change as a rule in the 2021 season, Formula 1 management has determined the changes to be made in vehicle designs compared to the previous year. Among the changes to be made in the design of Formula 1 vehicles in the 2021 season, the ones related to additive production are as follows. 1. Changes in the floors of the cars, 2. Changes in the rear brake duct fins, 3. Reduced the diffuser fences, 4. Cost limit introduced, 5. Minimum weight of cars and power units increased 6. Exhaust systems usage limits changed, 7. New materials allowed. The changes mentioned above directly concern additive manufacturing. Formula 1 teams have started design and production work with these changes. Additive manufacturing is the biggest supporter of Formula 1 teams in terms of reaching the designs to production and objects quickly. When this research paper was written, it was seen that these changes were also reflected in the races. It is inevitable for Formula 1 teams to use additive manufacturing.

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