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HOCHSCHULE RAVENSBURG-WEINGARTEN UNIVERSITY OF APPLIED SCIENCES

Scientific Work

PLA Additive Manufacturing Chassis Parts for Small Scale Rovers

submitted by:

Jose Luiz S. Mendonça
Matriculation number: 35756
<js-223959@rwu.de>

Zion Smuts
Matriculation number: 15640111
<zion.smuts@rwu.de>

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Supervising Professor: Prof. Dr. rer. nat. Markus Pfeil <markus.pfeil@rwu.de>

Contents

1 Abstract

In the context of the Canadian International Rover Challenge, teams made up of students from universities from diverse countries must build a prototype rover to simulate what it would be like as an early colony on an extraterrestrial planet. The rovers will be faced with completing various tasks that future rovers will be expected to perform. These include traversing varying terrain, autonomous operations, operating a dexterous arm and much more!

The chassis of each rover is a critical component that must be robust and reliable and must be of easy manufacture, as the teams have limited resources and time to build their rovers. Due to the prototypical nature of the rovers, a lot of custom parts are needed. Traditional manufacturing methods such as milling and turning can be used to produce these parts, but are time-consuming and require expensive machinery, which is not always available to student teams.

3D PLA printing parts with "hobby grade" 3d printers is a great way to prototype small batches of parts, but the produced parts are sometimes considered fragile, or precise enough due to the nature of the production process. However, modern-day 3D printers have come a long way, and the quality of the parts produced by these machines has improved significantly. Is such a 3D printing manufacturing workflow a viable option for the production of rover parts for such a project, or are traditional manufacturing methods still better suited for such an application?

2 Introduction

The purpose of this study aimed to compare the possibility of employing 3D printed PLA components for the rover chassis and other essential parts with conventionally manufactured 6061-T6 aluminium components. Finding an economical and dependable manufacturing technique became important for student teams with usually limited resources.

Tensile strength, elasticity, surface quality, thermal properties, precision, cost, time consumption, manufacturing process complexity, and environmental impact were the main comparison factors in the study. To find the best manufacturing process for rover components, the study carefully examined the factors above.

The results presented helpful information on real-world uses and constraints of PLA 3D printing, helping future project determine the most appropriate manufacturing strategy that corresponded with particular needs and limitations. The purpose of this study was to improve and clarify the decision-making process for creating dependable and efficient rover components by analysing the advantages and disadvantages of each manufacturing technique.

3 Results

Research Findings: This section has been split into nine sections to simplify the comparison of the different materials, and the respective manufacturing workflows associated with them, as well as the properties of the materials themselves. The nine sections are as follows:

- Tensile Strength
- Elasticity
- Surface Quality
- Thermal Properties
- Precision
- Cost
- Time Consumption
- Complexity in Manufacturing Process
- Environmental Impact

3.1 Tensile Strength

A key attribute that determines a material's capacity to resist pulling forces without breaking is its tensile strength. A number of differences were found when 3D-printed PLA (polylactic acid) and 6061-T6 aluminum were compared, emphasizing the distinctive mechanical properties of each material.

PLA is a bioplastic composed of renewable resources like corn starch and from a technical data sheet made by BCN3D Technologies, an ultimate tensile strength of 70 MPa was reported from them.[6] The value shown is the highest possible stress PLA can withstand before breaking down to tension. Due to PLA has a relatively lower tensile strength, being a polymer and having a layer-by-layer deposition while 3D printing, can result in the formation of weak areas along the contact points. Despite its lower tensile strength compared to metals, PLA can be used in situations where mechanical strength is not as important and instead can be used when specified components have to be made.

On the other hand, according to a material data sheet published by ASM International [2] , 6061-T6 aluminum, a commonly used alloy in several industrial applications, showed a significantly greater ultimate tensile strength of 310 MPa. The composition of the alloy and the T6 tempering process, which includes heat treatment and artificial aging to improve the mechanical properties of the alloy, is responsible for its high tensile strength. For structural components and applications that need high amounts of strength, 6061-T6 aluminum is the ideal material due to its better tensile strength. A good example can be the motor-wheel shaft which transmits torque from the motor to the wheel hub and from the wheel hub to the wheel.

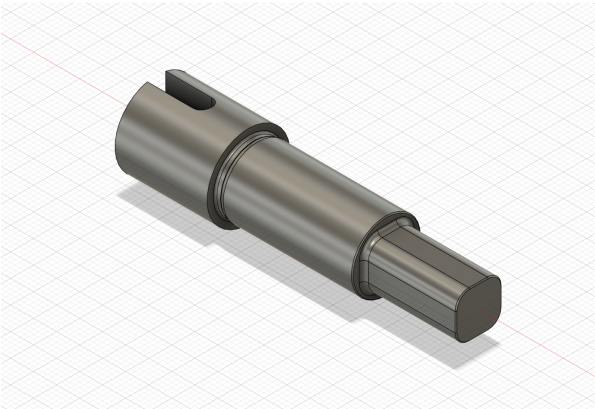

Figure 1: Motor-Wheel Hub shaft, machined out of 6061-T6 aluminum

3.2 Elasticity

The Young's Modulus and Elasticity between PLA and 6061-T6 aluminum showed differences when compared to one another, which suggests their different uses and stress resistance.

Based on BCN3D Technologies' PLA datasheet [6], the material has Young's modulus of 3120 MPa (or roughly 3.2 GPa). The fact that PLA is a semi-crystalline polymer that was intended to be flexible and simple to produce can be seen in its low modulus score (link). The elasticity of PLA was moderate, meaning that it could deform under stress and return to its former shape when the load was released.

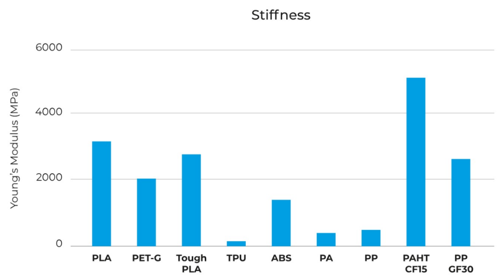

Figure 2: PLA Stiffness
[8]

However, with certain components, the 3D-printed PLA could make it brittle. Therefore, it was appropriate for low-stress applications and prototyping where high rigidity was not a requirement. Elasticity in a material helped so that it could absorb some impact without permanent deformation, making it useful for lightweight and less structurally demanding parts. 6061-T6 aluminum had a much greater Young's modulus of 68.9 GPa [2]. Compared to PLA, 6061-T6 aluminum was stiffer and had a smaller chance to deform under stress, as shown by its higher modulus.

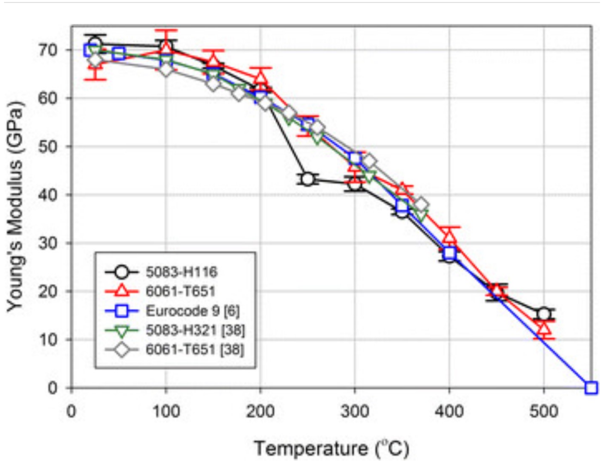

Figure 3: Aluminum Stiffness
[11]

The material was applicable in instances where rigidity and endurance were required due to its decreased elasticity, which allowed it to bear larger loads without experiencing significant deformation. The contrast in elasticity and Young's modulus between PLA and 6061-T6 aluminum showed the different uses for which each material was appropriate.

3.3 Surface Quality

For 3D printed PLA, the noticeable layer lines on the surface were a result of the layer-by-layer deposition used in FDM (Fused Deposition Modelling) technology [4]. The print resolution determined how smooth the surface was; surfaces with thinner layers at higher resolutions were smoother while at lower resolutions, layer lines were more apparent. To smooth and minimize roughness, post-processing methods like coating and sanding were used. Despite these initiatives, 3D-printed PLA had rougher surfaces than machined metals.

Figure 4: 3D Printed PLA Surface vs 6061-T6 Aluminum Surface

Next, components were made of 6061-T6 aluminum, which had a smoother surface and very little roughness (commonly at Ra 0.4 μm)[2]. The components were produced with a certain degree of surface consistency and homogeneity due to the machining process. Moreover, surface quality could be improved by applying anodizing and polishing treatments, which would add a layer of protection and improve the appearance. 6061-T6 Aluminium has a glossy natural finish and could possibly be polished even more to get a mirror- like surface, which makes it appealing and ideal for higher-end applications.

In terms of aesthetics, 3D printed PLA parts could have had a matte to semi-glossy appearance, and depending on the filament used, there were a wide range of color options available, from typical white or transparent to several different colors available on the market.

However, the components that were made from 6061-T6 aluminum had a silver-grey, natural glossy finish. This could have also had the possibility to be anodized in several colors, increasing the component's adaptability (get a link from MS chapters). If necessary, aluminum can be polished to a shinier finish which could increase the visual attractiveness and enable it for uses where performance and aesthetics are equally important.

3.4 Thermal Properties

When choosing a material for a specific application, especially one where temperature changes are active, its thermal characteristics are important. Several differences between the thermal characteristics of 6061-T6 aluminum and 3D-printed PLA are apparent. Compared to metals, PLA has a lower melting point of 145 °C to 160 °C, which makes it acceptable for low-temperature applications. PLA components are also more prone to dimensional changes with temperature variations, which could impact their stability and precision in some applications. The coefficient of thermal expansion [6] for PLA ranges from 68 to 100 x 10^2 °C. In addition, it loses its mechanical qualities and structural integrity due to thermal breakdown, which starts at temperatures higher than 200 °C.

6061-T6 aluminum, on the contrary, has a much higher melting point between 582 °C and 652 °C making it ideal for high-temperature applications. Approximately 23.6 x 10^2°C is the coefficient of thermal expansion of 6061-T6 aluminum, which is significantly lower than that of PLA and indicates a higher dimensional stability during temperature fluctuations. Furthermore, 6061-T6 aluminum retains its mechanical qualities and structural integrity across many circumstances and does not break down at normal operational temperatures. This comparison between the two materials emphasizes how important it is to choose the correct thermal requirements for an application. [2]

3.5 Precision

An analysis of the precision of parts manufactured from PLA using a Prusa MK4 3D printer and from 6061-T6 aluminum using CNC machining or milling demonstrated differences in the two materials and processes in terms of dimensional accuracy, repeatability, complexity, and customization potential.

With the Prusa MK4 dimensional accuracy for 3D printed parts usually varied between ±0.1 and ±0.2 mm [3], depending on variables which included: layer height, print speed, nozzle diameter, and printer calibration. The overall precision of the items was impacted by the inherent unpredictability introduced by the layer-by-layer deposition process of 3D printing. On the other hand, components made from 6061-T6 aluminum that were CNC machined or milled showed much better dimensional precision, with tolerances usually ranging from ±0.01 mm to ±0.003 mm [9]. The machining procedure, equipment calibration, tool wear, and thermal expansion could have been variables that affected this precision.

Another important factor was repeatability, or the ability to consistently make the same parts. When applying the same print parameters, the Prusa MK4 showed good repeatability, though small differences could happen due to environmental factors and the grade of the filament. Even though they are small, these differences could affect the way parts made in large quantities turn out. In contrast, high precision was provided by CNC machining 6061-T6 aluminum, guaranteeing almost identical parts within predetermined tolerances. This constancy would be essential for applications that needed accuracy and consistency between different units.

Additionally, there were also notable differences in each manufacturing method's complexity and customization. Complex interior structures and geometries that were difficult or impossible to machine might be produced using the Prusa MK4. This feature, along with the simplicity and affordability of modifying and improving designs, enabled 3D printing a compelling choice for specific components and prototypes.

Nevertheless, CNC machining could have had limitations and frequently be needed for specialized equipment, despite its ability to handle complicated geometries. In conventional manufacturing, customization would be more costly and time-consuming as it required much more labor and funds to change designs after the tooling was put up.

3.6 Cost

Made from 3D Printing PLA:

- 4x Motor-Wheel Shaft: €0.76
- 2x Rocker Axle: €1.92
- 2x Boogie Axle: €1.48
- Total: €4.16

Made from 6061-T6 Aluminium:

- 4x Motor-Wheel Shaft
- 2x Rocker Axle
- 2x Boogie Axle
- Total: €201.28

When comparing the price of parts produced of 6061 T6 Aluminium and PLA printed by a Prusa MK4, there was a noticeable price difference. The same components - 4x motor-wheel shafts, 2x Rocker Axles, and 2x Boogie Axles - were made with both materials. The entire cost of employing PLA 3D printing to produce these components was €4.16. The motor-wheel shafts cost €0.76, the rocker axles €1.92, and the boogie axles €1.48 according to the breakdown. This is a visible difference to the same components made out of 6061-T6 aluminium which came to a total cost of €201.28.

Despite the higher expense associated with 6061-T6 aluminum, it came down to the quality of the components that were produced. Aluminium was stronger, more resilient, and more durable than PLA, which when it came to specific components, was generally weaker than what was needed and was more prone to deterioration over time. Long-term cost-effectiveness was ensured by superior performance and fewer replacement needs for aluminum components, which nearly made up for their higher original cost.

3.7 Time Comsumption

3D-P PLA:

- On Prusa MK4
- 2x Rocker Axle
- 2x Boogie Axle
- 4x Motor-Wheel Shaft
- All components were also made in one print (which means they all fit on the board)
- Total time (in hrs): 11 hours and 30 minutes

6061 T6 Aluminium:

- Went to Muharraq Engineering located in Manama, Bahrain
- Made the order on 25.05.2024 at 11h30
- Received all components 29.05.2024 at 15h30
- Total time (in hrs): 100 hours

There was an evident difference in the time efficiency when the production durations of the components made from 6061-T6 aluminum and PLA were compared. Using a Prusa MK4, the parts - which included 4x motor-wheel shafts, 2x rocker axles, and 2x boogie axles - were created in a total of eleven hours and 30 minutes. This quick processing time and useful efficiency of 3D printing technology were shown by the rapid output that was achieved in a single print run. When it came to manufacturing the same components out of 6061-T6 aluminum, it took much longer. The parts were manufactured by Muharraq Engineering is located in Manama, Bahrain and took a total time of around 100 hours for the components to be produced. The order placement was made on May 25, 2024, at 11:30, and the component delivery was made on May 29, 2024, at 15:30.

According to this comparison, the 3D printing method using PLA produced the components 8.7 times faster than the conventional manufacturing method using aluminum. 3D printing is a very useful technique for projects that have a tight deadline because of its speedy manufacturing capabilities, which enable quicker prototyping and shorter lead times. It should be mentioned nonetheless that the manufacturing time for the 6061-T6 aluminum components may change depending on the engineering firm and the particulars of the order. The aluminum components provide better strength and durability despite the longer production time, highlighting the balance between material quality and speed.

3.8 Manufacturing Workflow Complexity

The process of producing a component using 3D printing PLA was considerably more straightforward compared to manufacturing the same component from 6061-T6 aluminum. The Prusa MK4 was simply loaded with an STL file to initiate the 3D printing process. Since no further technical procedures were needed to translate the digital content into a physical thing, this method required minimal preparation.

In contrast, making a component out of 6061-T6 aluminum required a far more involved and repetitive procedure. The design had to be created in Fusion360, where detailed technical drawings were drawn up. For both accuracy and operation to be guaranteed, certain tolerances had to be finished and sent to an engineer for assessment. Several rounds of comments and revisions were frequently made during this review process. The developer would put the improvements into place after the engineer reviewed the drawing and made any necessary suggestions; occasionally, this might need multiple iterations before final permission was given.

In the final stages, the component would be approved and then put in a manufacturing queue to wait to be made. Compared to the process of 3D printing with PLA, the procedure of design, review, correction, and approval, followed by scheduling for production, added a significant amount of time and complexity.

3.9 Environmental Impact

Since the introduction of 3D printing and the use of PLA, it has gained a number of environmentally beneficial characteristics along the way. PLA had a sustainable material source as it was made from renewable resources like sugarcane and corn starch In general, 3D printing PLA required less energy than conventional manufacturing techniques for small quantities. Moreover, there was very little waste produced by additive manufacturing techniques. PLA has low biodegradability in ordinary landfill sites, but it could be biodegraded under industrial composting conditions when its lifespan comes to an end[7][5].

When it comes to the ecological impact of manufacturing with 6061-T6 aluminum was different. Bauxite ore was extracted to provide the raw material for aluminum, a process that is extremely energy-intensive during the mining and processing stages. As a result, the energy required to produce 6061-T6 aluminum was much higher because of the machinery and energy it required for both mining and refining. Additionally, substantial amounts of waste were produced by subtractive manufacturing techniques often used to produce aluminum, including shavings and off-cuts. But 6061-T6 aluminum was highly recyclable at the end of its lifespan without losing any of its qualities. Aluminum recycling uses just around 5% of the energy needed to make new aluminum from ore, making it a very energy-efficient process[1][10].

Under certain circumstances, PLA was recyclable and biodegradable, but its actual recyclability was constrained by the capabilities of infrastructure. However, the recycling process for 6061-T6 aluminum was well-established and resulted in notable energy savings while preserving the material's characteristics. This comparison reinforced the necessity for sustainable practices in material selection and production processes by highlighting the importance of also choosing materials based on the environment and the potential to be recycled.

4 Discussion

The findings of this study, 6061-T6 aluminum had a tensile strength of roughly 310 MPa, but PLA components had a tensile strength of just 70 MPa. This distinction highlighted the limitation of PLA in high-stress applications where mechanical strength was important. PLA was found to have higher elasticity, as displayed by its Young's modulus of 3.2 GPa, which is lower than that of aluminum at 68.9 GPa. This suggests that PLA was more flexible and could have been used in low-stress scenarios.

Also, what was found in previous research was that the results were consistent. This indicated that PLA was not as mechanically superior to 6061-T6 aluminum. For instance, we discussed in [Results] that aluminum alloys have greater tensile strength and endurance in structure applications. This comparison emphasizes how important it is to choose materials according to the particular requirements of the application.

The outcomes imply that although PLA 3D printing has many benefits in terms of price, speed, and versatility, it is not an ideal choice for parts that need to have a high degree of mechanical strength. PLA can only be used for less demanding structural purposes due to its higher flexibility and lower tensile strength. On the other hand, the robustness of 6061-T6 aluminum makes it perfect for important parts in the rover design, assuring performance and dependability under demanding circumstances. One limitation of this study was its focus on a single type of 3D printer and particular methods for treating aluminum. To provide a more thorough comparison, future research should take into account a wider range of 3D printing technologies and alternative aluminum alloys. Additionally, there has not been much research done on how environmental elements like humidity and temperature can impact PLA's characteristics.

In order to understand more about PLA components' long-term durability in many environmental scenarios, more research is required. Studies may also look into the viability of hybrid manufacturing techniques, which combine the advantages of traditional manufacturing techniques with 3D printing for quick prototyping and high-strength component production. Furthermore, studies into more environmentally friendly and biodegradable 3D printing materials may provide long-term substitutes for PLA and aluminum.

In conclusion, the specific requirements of the task at hand will determine whether to use CNC-machined 6061-T6 aluminium or 3D printed PLA. For non-industrial and prototype components, 3D printing offers flexibility, cost savings, and swift development capabilities. However, 6061-T6 aluminum is still necessary for applications needing greater strength, precision, and lifespan. This study showcases how important it is to consider the effects of manufacturing efficiency, mechanical qualities, and the environment when it comes to choosing materials for engineering projects

5 Conclusion

This study examined the viability of manufacturing small-scale rover chassis parts from 3D-printed PLA as opposed to 6061-T6 aluminum. The analysis showed that while PLA has important benefits in terms of cost-effectiveness and speedy prototyping, its use is restricted to low-stress applications because of its mechanical properties, which include a lower tensile strength and a higher degree of elasticity. Whereas, 6061-T6 aluminum offers more strength, precision and thermal stability, making it appropriate for demanding applications subjected to severe stress.

PLA is suitable for prototyping and non-structural components due to its faster production time and reduced production costs. However, two major disadvantages are that it is more prone to deformation in higher temperatures and has inferior durability. In contrast, structural components made of aluminum are way more reliable, but oftentimes inaccessible to small organizations due to the high costs of production, and students due to the complexity of the manufacturing process.

Based on the results of this study, and the concrete case of the Ravensburg Weingarten University of Applied Sciences Rover to Mars Project, the 3D printing workflow comes out as a viable option for the development of small-scale mobile robots. The use of PLA for parts such as joints, small housings, and other semi-structural components can significantly reduce the production time and costs of a project, and make the construction of custom designs more accessible to students, and other organizations with limited resources.

Bibliography

[1] *Aluminum Industry and Environmental Impacts*. https://airqoon.com/resources/aluminum-industry-and-environmental-impacts/. Accessed: 2024-05-31.

[2] *Aluminum Specification and Information*. https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6. Accessed: 2024-05-31.

[3] *FAQ - Frequently Asked Questions*. https://help.prusa3d.com/article/faq-frequently-asked-questions_1932. Accessed: 2024-05-31.

[4] *Fusion Deposition Modeling Definition*. https://www.hubs.com/knowledge-base/what-is-fdm-3d-printing/. Accessed: 2024-05-31.

[5] *How Sustainable is PLA?* https://www.filamentive.com/how-sustainable-is-pla/. Accessed: 2024-05-31.

[6] *PLA Specification Data Sheet From Ultimaker*. https://thes3d.gr/wp-content/uploads/2016/09/TDS-PLAv2.001.pdf. Accessed: 2024-05-31.

[7] *Sustainable 3D Printing Insight*. https://www.elegoo.com/en-de/blogs/learn/sustainable-3d-printing-insight. Accessed: 2024-05-31.

[8] *Tensile Strength table for different 3D printed materials*. https://www.bcn3d.com/guide-to-filament-properties/. Accessed: 2024-05-31.

[9] *The Benefits of Using a CNC Milling Machine*. https://metrom.com/the-benefits-of-using-a-cnc-milling-machine. Accessed: 2024-05-31.

[10] *The Environmental Impact of Aluminum*. https://trayak.com/the-environmental-impact-of-aluminum. Accessed: 2024-05-31.

[11] *Thermal Conductivity table for different 3D printed materials*. https://www.researchgate.net/figure/5083-H116-and-6061-T651-elevated-temperature-Youngs-modulus-Data-reported-in-Eurocode-9_fig4_276129344. Accessed: 2024-05-31.