Formula Student Group 4

EV Mechanical Challenge – Brake Disc

Eliott Quinney

Rahul Yellamraju

Justin –

Zi Xuan Yong

Mohamad Taraboulsi

Table of Contents:

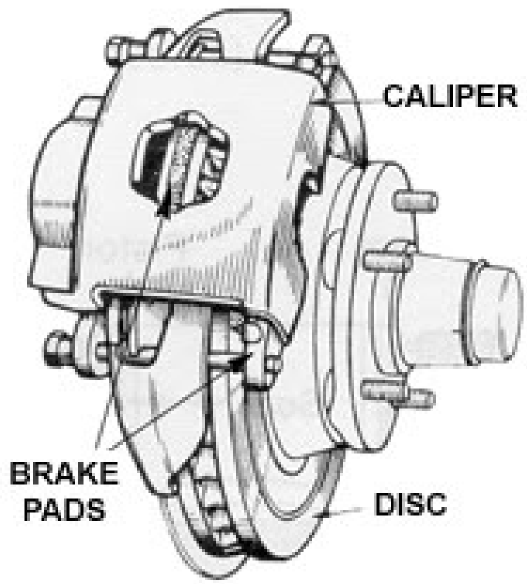
1. Introduction

This report is a summary of our team's work on designing a brake disc for the EV Formula Student Mechanical Challenge.

2. Aim and Objectives

The aim of this challenge was to design a brake disc following the regulations (2022) of the FSUK; the objective was to optimize the following constraints, making compromises and adjustments where necessary:

- Weight
- Cost
- Manufacturing Process
- Strength
- Heat Dissipation



DISK BRAKE

3.Design Phase

To design the best possible disc, we had to figure out all design considerations and find ways to optimize the constraints. These design considerations are listed below:

- Lightweight
- Temperature Resistance
- Strength
- Cost

Weight

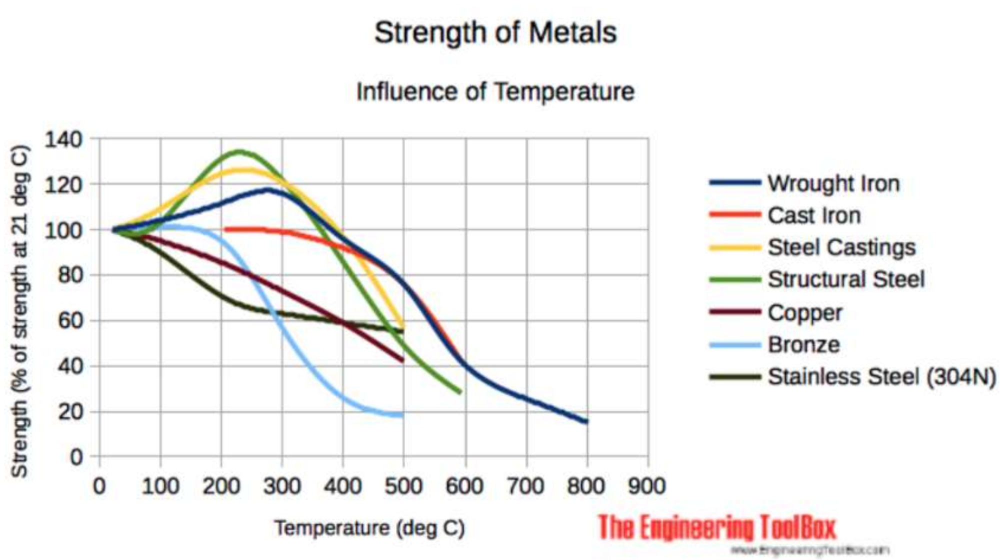
The aim was to make the brake disc as light as possible, this is because electric vehicles are already generally heavier due to being packed with batteries. We aimed to match or better the 2019 Specifications. The general shape of the disc along with the mounting hole in the center were considered constants due to the FSUK rules along with the measurements of the brake pads which make regular contact with the disc. Therefore, the main way to reduce the weight of the disc was to choose a material with a lesser density and to remove substantial amounts of material where they were not needed. This process led to the final weight of our disc being 598 grams which is only 30g heavier than the 2019 spec car.

Material Selection

Material selection was an important aspect in the design phase of our brake disc. Choose the wrong material and our design could go wrong very quickly, particularly the lack of durability. A problem we often ran into was that every material would fit the majority of our considerations but there were certain downsides to the fact that it could not be utilized. We researched the mainstream choices but also worked on alternative “outside the box” materials. To summarize our research, the table below highlights the strengths and weaknesses of these:

Material:	Strength(s):	Weakness(es)
Aluminum Matrix Comp	High strength at 1200MPa with relatively low density (3.4g/cc)	High cost of $33 per kg reduces financial viability
Aluminum	Low density (2.7g/cc) and cheap at $2.33 per kg	Intensity at higher temperatures would deform the brake disc due to malleability
Carbon Fiber	Lightweight (1.75g/cc) and strong at high temperatures with melting point at 3600C	Relatively expensive at $21.5 per kg (non-aerospace grade; would be higher)
Bronze & Brass	High melting point that could safely operate up to nearly 900C	High densities would make brake disc heavy in comparison to other materials (8.13 g/cc); relatively prone to deformation due to lower tensile strength

Cast Iron	Cheap but strong material with 428MPa tensile strength on average, resistance to mechanical wear – very sustainable; optimal thermal conductivity to dissipate heat from braking	High Density (6.8-7.8 g/cc, 7.3 average)
Magnesium (Alloys only), pure magnesium has no use in stressed applications	Suitably strong (280MPa) and Lightweight (1.74 g/cc)	Creeping and deformation prone to occur at temps lower than 500C – easily damaged;
Nickel	High melting point approaching 1455C and Yield strength of 70MPa	Density (8.8 g/cc); recent prices indicating an increase to $22.36
Stainless Steel	Strong composition at up to 620 MPa, relatively cheap at approximately $1.7 per kg	High density (7.8-8 g/cc), low thermal conductivity that will experience issues related to overheating in braking process



A final decision was made after considerable research on said materials. The decision involves a tradeoff between cost and density, subsequently the gross weight. The team settled on Cast Iron which has an average density of 7.3 g/cc but at a temperature of 500C still retains 80% of its strength at 21C (Engineering Toolbox (2008)), as shown on the diagram above. The outcome meant that although the disc might be heavier, its properties are more capable of withstanding critical scenarios, such as emergency braking. Production of said material is relatively cheaper and easily maintained for prolonged periods. The former issue of weight could be addressed in the design process.

Disc Types

Disc design can be put in 4 different categories, Solid, Drilled, Slotted and Drilled and Slotted. A Table was created to analyze the strength and weaknesses of each disc design.

Type:	Strength:	Weakness:
Solid	Easy to manufacture, provides large area for braking pads	Thermal conductivity, wear and traps dirt and gases
Drilled	Easy to Manufacture, good in wet conditions,	Uneven wear and crack development in constant race conditions
Slotted	Provides cooling and space for gases to leave	Shorter life when compared to other brake disc types
Slotted & drilled	Consistent braking performance, good in wet conditions, thermal conductivity to increase heat dissipation	Prone to cracking in race conditions with more gaps and pores, manufacturability implying lower availability

(Partially referenced from R1 Concepts 2019)

The table above concludes that none of the discs fulfilled our requirements. This led to a challenging situation in conjunction with the FSUK Regulations. Though, an exception for EV Teams stated in T6.1.10 is the following:

"[EV only] The first 90 % of the brake pedal travel may be used to regenerate brake energy without actuating the hydraulic brake system. The remaining brake pedal travel must directly actuate the hydraulic brake system, but brake energy regeneration may remain active. (IMECHE Formula Student 2022 Rules)".

With this information in hand, we opted for the slotted & drilled as even though it may be prone to wear and tear, this information in the rules indicated that the mechanical braking discs will only be used for the 10% of the pedal travel in cooperation with the regenerative braking system. This meant that over time, our braking disc would not be put under as harsh conditions as ICE Vehicles and would not be worn as much due to decreased usage.

Furthermore, upon researching Disc types, we came along a paper written in IRJET on the design & analysis of brake rotors for Formula Student Vehicles. For this purpose, we'll stick to the analysis of brake disc type, where they found Slotted & Drilled Rotors to have a greater thermal conductivity, be within the limits for Stress & deformation whilst still have holes and slots everywhere. They used Ansys 19.0 to perform static structural analysis on each type of brake disc ((Goshikwar et al.)

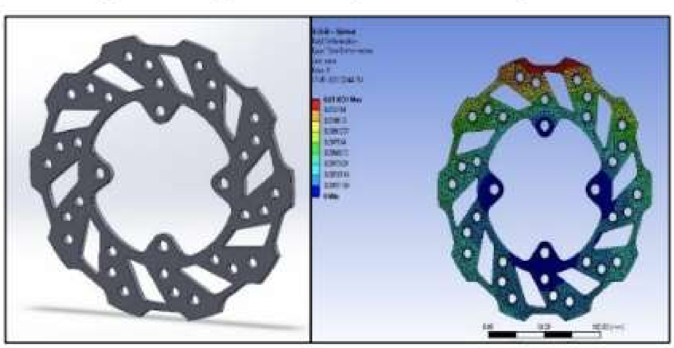


Fig – 6: Design and analysis of drilled-slotted profile

Table -1: Design selection result for all design

Design type	Stress (MPa)	Deformation (mm)	Heat flux (w/mm²)	Mass (kg)
Solid	72.213	0.0066592	0.29192	0.65632
Drilled	91.774	0.00841	0.41268	0.48457
Slotted	101.6	0.01975	0.5713	0.45012
Slotted And drilled	109.4	0.0136	0.96302	0.42932

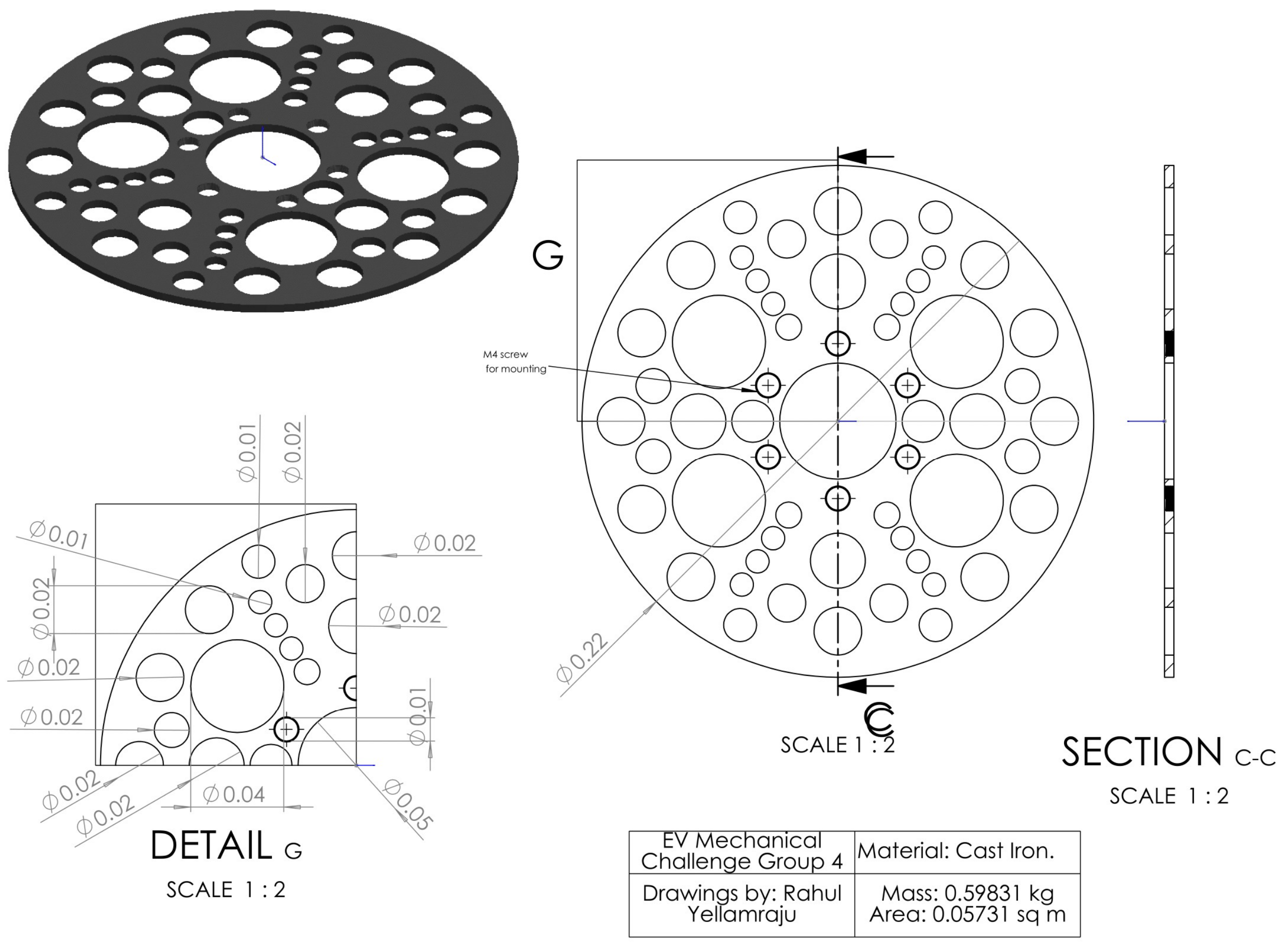
As can be seen, it had the greatest Heat Flux ("the rate of heat energy transfer through a given surface" (Gidik et al.)), which means that heat would disperse and flow faster. Although it had higher stress and deformation than other designs, this is not something significant for our application as the brakes will only be used in the final 10% or in emergency situations. This also meant we could counter our issue of disc weight as removing amounts of volume from the disc would make it more lightweight.

Table and Photo both taken from (Goshikwar et al.)

Disc Design

With material and disc type chosen, we proceeded with our initial disc design. We started with deciding on the dimensions of the disc. Referring to the 2019 Car Specifications, the 2019 brake calipers and brake pads were compatible with a disc of diameter 220mm and 4mm in thickness. It also features a 50mm outer diameter for the wheel bearing and 6 holes for M4 Bolts to mount. Our disc design is entirely a match of drilled holes with slot concepts. Slot designs were completed by the members' preference.

Instead of traditional rectangular and geometric slots, we replaced with circular gaps with larger diameters to allow gases and dirt to flow through promptly while leaving enough material for structural integrity. The smaller drill holes allow water to flow smoothly when driving in wet conditions and theoretically provide a considerate amount of 'bite' in the brakes. The SolidWorks drawing represents the team's concept below.



Manufacturing Process

After careful consideration, we finalized 3 viable processes to producing the brake disc; sand casting, die casting and investment casting. We eventually opted for investment casting to be the method of manufacture, with further details elaborated below.

Die Casting

Although die casting is the most accurate method in comparison, it is not possible for production of ferrous metals like cast iron, which was our material of choice. This is because the casting is made up of stainless steel, implying that its melting point is highly similar to cast iron.

Sand Casting

Although sand casting is cheap and suitable for ferrous metals, it has a relatively low accuracy in terms of modelling, which totally contradicts our aim to produce precise brake discs with regards to safety. The end products also often have textural imprints, causing undesirably rough surfaces.

Investment Casting

Although investment casting is slightly more expensive, its advantages combined with the fact that the brake discs are not expected to be mass produced in our scenario. Investment cast components are highly detailed, precise, and accurate. Once freed from the ceramic mold, they exhibit smooth finishes that generally require little to no finishing as well as processing. Comparing to other methods, die cast parts may need post-processing to achieve the desired dimensions and finishes. Most importantly, investment casting is highly suitable for processing and manufacturing ferrous metals.

Process	**Advantages**	**Limitations**
Sand	Almost any metal can be cast; no limit to part size, shape, or Weight; low tooling cost	Some finishing required; relatively coarse surface finish; Wide tolerances
Investment	Intricate part shapes; excellent surface finish and accuracy; almost any metal can be cast	Part size limited; expensive patterns, molds, and labor
Die	Excellent dimensional accuracy and surface finish; high production rate	High die cost; limited part size; generally limited to nonferrous metals; long lead time

(Table from Manufacturing Engineering 1 (University of Manchester))

Owing to these features of investment casting, we conclude that the pros out-weigh the cons.

Tolerance to Brake force and temperature

One of the points of focus was how the disc would fare against the high forces and temperatures supplied by pad-disc contact. First of all, the IMechE states that the first 90 % of the brake pedal travel may be used to regenerate brake energy without actuating the hydraulic brake system. Cast iron has a very high melting pressure and doesn't lose strength at temperatures of over 500 C and can be a recipient of high temperatures and forces, the symmetry of the disc also increases the strength. The drilled holes in the disc offer ventilation when the temperatures get too high. Permanent mold casting also creates stronger castings than die casting.

Cost

A key aspect of engineering is to maximize cost efficiency, we did this by being efficient with our Bill of Materials and only using parts and processes which were required. The final cost of our disc was 31.13 $ per Disc.

Process/material	Amount	Unit cost	Unit	Cost per disc
Cast iron	1.109	$ 1.00	kg	$ 1.11
Investment Casting	1.084	$ 8.00	kg	$ 8.67
Drill (Center Hole) 50mm	1	$ 0.70	per hole	$ 0.70
Drill (Slots) 40mm	4	$ 0.70	per hole	$ 2.80
Drill (Holes + Mounting holes)	51	$ 0.35	per hole	$ 17.85
Total per Disc				$ 31.13

Individual Contributions:

Eliott Quinney – Material and Disc Design, Paper Research & Report writing

Rahul Yellamraju – Material Research & Manufacturing, Report writing & 3D Disc Design

Justin - Disc Design, Cost & Manufacturing Research

Zi Xuan Yong- Material Analysis, Research, Report Writing and Editing

Mohammed Taraboulsi - ???????

Citations:

- Gidik, H. et al. "Developing Thermophysical Sensors With Textile Auxiliary Wall". *Smart Textiles And Their Applications*, 2016, pp. 423-453. *Elsevier*, https://doi.org/10.1016/b978-0-08-100574-3.00019-9. Accessed 10 Oct 2022.
- https://www.imeche.org/events/formula-student/team-information/rules
- "How To Choose Brake Rotors". *R1 Concepts*, 2019, https://www.r1concepts.com/blog/how-to-choose-the-right-brake-rotor-pattern-blank-vs-drilled-and-slotted-vs-drilled-only-vs-slotted-only/.
- Engineering ToolBox, (2008). *Metals - Strength vs. Temperature*. [online] Available at: https://www.engineeringtoolbox.com/metal-temperature-strength-d_1353.html
- Goshikwar, Yash et al. "DESIGN AND ANALYSIS OF BRAKE ROTOR FOR FORMULA STUDENT VEHICLE". *IRJET International Research Journal Of Engineering And Technology*, vol 08, no. 08, 2021, https://www.irjet.net/archives/V8/i8/IRJET-V8I826.pdf. Accessed 8 Oct 2022.
- Density of Stainless Steal, ThysenKrupp Materials https://www.thyssenkrupp-materials.co.uk/density-of-stainless-steel
- finanzen.net GmbH (2019). *Aluminium PRICE Today | Aluminium Spot Price Chart | Live Price of Aluminium per Ounce | Markets Insider*. [online] markets.businessinsider.com. Available at: https://markets.businessinsider.com/commodities/aluminum-price.
- Google.com. (2022). [online] Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjIuIaax9b6AhVTQEEAHYWhBXQQFnoECAgQAw&url=https%3A%2F%2Fwww.americanelements.com%2Fcarbon-fiber-7440-44-0&usg=AOvVaw0f87SpR9wBEuHAKe3k-_vP [Accessed 10 Oct. 2022]
- Google.com. (2022). [online] Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiLivGxx9b6AhWlnVwKHQ95AK0QFnoECBIQAw&url=https%3A%2F%2Fwww.infosys.com%2Fengineering-services%2Fwhite-papers%2Fdocuments%2Fcarbon-composites-cost-effective.pdf&usg=AOvVaw1SOy_diDGOINQkGMheFfyG [Accessed 10 Oct. 2022].

- www.totalmateria.com. (n.d.). *Magnesium and Magnesium Alloys*. [online] Available at: https://www.totalmateria.com/Article138.htm [Accessed 10 Oct. 2022].
- AZoM.com. (n.d.). *Properties: Nickel - Properties, Fabrication and Applications of Commercially Pure Nickel*. [online] Available at: https://www.azom.com/properties.aspx?ArticleID=2193.
- Ulbrich. (n.d.). *Grade 304 Vs. 316 Stainless Steel: What's the Difference?* [online] Available at: https://www.ulbrich.com/blog/grade-304-vs-316-stainless-steel-whats-the-difference/.
- Density of Materials, Spectro Analytical Labs, https://spectro.in/Densities-of-Materials.html
- Stainless Steel Yield Strength: https://material-properties.org/what-is-strength-of-stainless-steels-yield-uts-definition/#:~:text=Yield%20strength%20of%20stainless%20steel,Grade%20440C%20is%20450%20MPa.
- Nickel yield strength: https://material-properties.org/nickel-mechanical-properties-strength-hardness-crystal-structure/#:~:text=Yield%20strength%20of%20Nickel%20is%2070%20MPa.
- Magnesium & alloys yield strength: http://www.totalmateria.com/Article138.htm
- Cast Iron yield Strength: https://www.matweb.com/search/datasheet_print.aspx?matguid=6291a24572754cae94ff365ed99b96f9
- https://www.epsa-team.com/index.php/en/competitions/formula-student
- https://apracing.com/special-vehicles/motorcycle/brake-calipers/cp4227-2s0
- https://apracing.com/special-vehicles/motorcycle/brake-calipers/cp4226-2s0?switch=1
- https://apracing.com/cdn/drawings/cp4226-1cd.pdf
- http://newengineeringpractice.blogspot.com/2011/08/manufacturing-of-brake-disc.html
- https://online.manchester.ac.uk/webapps/blackboard/execute/content/file?cmd=view&content_id=_13556487_1&course_id=_68167_1
- https://diecasting.com/blog/die-casting-vs-sand-casting/
- https://www.improprecision.com/investment-casting-vs-die-casting/
- https://www.texmoprecisioncastings.com/advice/comparisons/investment-casting-vs-sand-casting/