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Life cycle assessment of carbon ceramic matrix composite brake discs containing reclaimed prepreg scraps

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ABSTRACT

In the last years, carbon ceramic brakes are preferred to traditional cast iron ones for their lightweight, high temperature resistance, and long service life, even though their manufacturing involves the use of high temperature processes and energy-intensive materials such as carbon fibers. Within the European Life Project "CIRCE", a novel recovery system for carbon fiber prepreg scraps was developed to reclaim high-quality carbon fibers to use as a substitute of virgin carbon fibers in different application, such as in Ceramic Matrix Composite (CMC) brakes. In order to overcome the lack of scientific literature regarding the environmental sustainability of steel and CMC brakes, in the present paper, the Life Cycle Assessment (LCA) methodology was applied to carry out a detailed analysis of the environmental impacts associated with carbon ceramic brakes realized using the reclaimed prepreg scraps. The functional unit was defined as production, use and disposal of a rear brake disc used for the deceleration of a sport car during its lifetime. Different impact indicators were considered, such as Global Warming Potential, Cumulative Energy Deman and ReCiPe midpoint categories. The results were compared to those given by the sustainability assessment of cast iron disc brakes and traditional carbon ceramic brakes. The proposed LCA is a cradle to grave analysis, as it considers all the relevant inputs and outputs of the manufacturing processes, from the raw material extraction to the materials disposal. The surface of ceramic brakes was observed using Scanning Electron Microscopy to assess the different material structures. The results show that, as far as the production is concerned, cast iron brakes are the most sustainable alternative, with impacts lower than 21% of the composite component ones. However, if a long use phase more than 200,000 km is evaluated, carbon ceramic brakes obtained by reclaimed prepreg scraps are characterized by lower environmental impacts, with impacts that are about 8% lower than those obtained by traditional carbon ceramic brakes.

1. Introduction

Disc brakes are an essential component of modern cars as they enable the vehicle to stop while handling high mechanical and thermal stress. Most cars have disc brakes made of cast iron, which are cost-effective, durable, and easy to produce. However, their weight and thermal resistance restrict their use in high-performance luxury and racing cars, in which the braking performance is more important than economic aspect. In these cases, carbon ceramic brakes are preferred as they are lighter than cast iron ones, with a lightning up to 50%, have a great resistance to high temperatures, and are characterized by a long service life (Li et al., 2020).

Carbon ceramic brakes consist of carbon fibers embedded in a ceramic matrix, forming a Ceramic Matrix Composite (CMC) material (Zivic et al., 2021a). The manufacturing process involves the creation of a Carbon Fiber Reinforced Polymer (CFRP), pyrolyzation treatment, and Liquid Silicon Infiltration (LSI) (Zivic et al., 2021b). This process requires high temperatures (up to 170 0 °C) and non-recyclable materials, making it apparently unsustainable compared to cast iron brakes, which are also fully recyclable (Delogu et al., 2017; Egede, 2017; Kim and Wallington, 2013). However, as far as the service life of a car is concerned, lighter brakes improve the overall efficiency and decrease fuel consumption (Del Pero et al., 2017; Forcellese et al., 2022). Thus, to move towards a more sustainable transportation sector, a comprehensive evaluation of the environmental impact of CMC brakes is necessary.

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Abbreviations list

Abbreviation	*Full Name*
C_f/C	Carbon Fiber/Carbon
CFRP	Carbon Fiber Reinforced Polymer
CMC	Ceramic Matrix Composite
LSI	Liquid Silicon Infiltration
PAN	Polyacrylonitrile
SEM	Scanning Electron Microscopy

In the scientific literature, comprehensive studies regarding the environmental sustainability of steel and CMC brakes are still lacking. Several studies investigate the properties of CMC brakes (Langhof et al., 2016) their use and prospective (Mulani et al., 2022), their mechanical simulation also considering the use of natural fibers instead of carbon fiber (Sri Karthikeyan et al., 2019). However, no research has been found concerning the sustainability analysis of carbon ceramic brakes manufacturing and use in a car, leaving some open questions about the choice of using cast iron or CMC brakes for increasing sustainability of the transport sector. Moreover, no studies concerning sustainability assessments of Ceramic Matrix Composite components can be found in the scientific literature. Indeed, it is well known that carbon fibers are typically associated to high environmental impacts, due to their fossil origin and to their energy intensive manufacturing process (Al-Lami et al., 2018). As far as a typical CFRP component is considered, the environmental load associated to the carbon fiber can be quantified as about 90% of the total impacts (Duflou et al., 2012; Forcellese et al., 2021). As an example, for producing a kilogram of carbon fibers, a quantity of energy between 198 and 595 MJ is required, according to the Cumulative Energy Demand approach (Meng et al., 2018). Furthermore, as far as the end of life is concerned, CFRP are difficult to recycle, and the recovered fibers demonstrate a significant reduction in mechanical performances (Bledzki et al., 2021). In this context, a novel process was developed to reclaim high-quality carbon fibers. It is based on the use of carbon fiber prepreg scraps that, without a proper recovery process, end up in landfill as by-products (Nunes et al., 2018). This composite material, typically in the form of chops, can be used to substitute virgin carbon fibers in CMC production, thus allowing a strong reduction in the environmental impact. Indeed, the high temperature reached during brake production pyrolyzes the organic part of the prepreg leaving high quality chopped carbon fiber ready for the LSI process. The recovery system for carbon fiber prepreg scraps was developed within the European Life Project “CIRCE”, and comprise the following steps: *i)* an innovative and patented machine collect the fresh prepreg scraps resulting from the cutting machine, *ii)* the backing paper is detached by exploiting low temperatures and then recycled, *iii)* an automated system, based on different blades, realizes rectangular chops with different dimensions (in accordance with the requirements). The obtained material, characterized by the same quality of the virgin CFRP, was successfully used for the production of composite toe caps and automotive components (Iacopo Bianchi et al., 2022; I. Bianchi et al., 2022). The replace of virgin carbon fibers with the reclaimed ones lead to a significant reduction of the environmental impacts of the parts (Bianchi et al., 2021).

In this context, the environmental impacts of carbon fiber silicon carbide CMC brakes, both realized using virgin and recovered carbon fibers, were analysed in this study by means of the Life Cycle Assessment (LCA) analysis (Landi et al., 2020). In addition, the results were compared with those related to the cast iron brakes, in order to determine the most sustainable braking system solution for cars. The LCA analysis, performed in accordance with ISO 14040 and 14,044 standards, took into account all the life cycle phases of the disks, namely from the extraction of raw materials, through the manufacturing processes, to a typical use in a car, and to their disposal. This paper aims at quantifying the environmental impacts of CMC composite and to assess whether or not CMC brakes can represent a sustainable alternative with respect to traditional cast iron brakes. Moreover, this paper investigates the feasibility of using reclaimed prepreg scraps to produce more sustainable CMC brakes, thus providing a useful application for this waste which, at the moment, has no alternative but landfill or incineration. Hence, this paper represents a novelty for scientific literature; it provides the first CMC components sustainability assessment by focusing on different traditional and innovative brake disc alternatives. In addition, it proposes and validates an application of prepreg scraps for high performance components production, with relevant scientific and industrial implications.

The paper is organised as follows: after this introduction (Section 1), Section 2 details the phases of the conducted LCA and image analyses. Section 3 reports the results of the Scanning Electron Microscopy analysis and the comparison between the sustainability of the considered scenarios. Section 4 ends the paper with conclusions and future studies suggestions.

2. Materials and methods

2.1. Life cycle assessment

The Life Cycle Assessment methodology defined by the ISO 14040–14044 standard was followed (ISO-International Organization for Standardization, 2006; organization for standarization, 2004). This methodology is widely used in scientific literature as it provides a holistic view of the impacts of products and processes throughout their entire life cycle; in addition, it allows comparisons between different scenarios to identify the most sustainable solutions and improvement possibilities. The analysis consists of four iterative phases.

- Goal and scope definition: in this phase, the functional unit, the objective of the study, the scenarios and their system boundaries and the impact categories to be considered are defined.
- Life Cycle Inventory (LCI): all the input and output of the system boundaries are identified and quantified. Data can be retrieved from multiple sources such as direct measurements, commercial databases, estimates and literature studies.
- Life Cycle Impact Assessment (LCIA): the data gathered during the LCI phase are translated into potential effects on the environment according to the previously defined impact categories.
- Results interpretation: the results of the LCIA are critically analysed and their reliability is evaluated. Possibilities of improvements for the considered production systems are identified.

The SimaPro software was employed to carry out the study and the Ecoinvent database, provided by default with the software, was used as a source of secondary data.

In the following paragraphs, the phases of the LCA are presented and detailed.

2.2. Goal and scope definition

The present study deals with the complete life cycle assessment of different disc brakes used for the deceleration of passenger cars. A traditional cast iron brake was compared with a ceramic matrix composite alternative obtained by means of a Liquid Silicon Infiltration (LSI) process. Moreover, a further scenario was modelled considering an improved system for the production of carbon-ceramic composite with the use of recovered prepreg as a raw secondary material.

Hence, this study aims at quantifying and comparing the environmental impacts of these three scenarios to determine whether the carbon-ceramic composites can be a sustainable alternative to traditional brake discs. In addition, this study provides a baseline analysis for the sustainability assessment of CMC parts production and the reuse of CFRP prepreg scraps in advanced production processes.

The functional unit was defined as the production, use and disposal of a rear brake disc used for the deceleration of a sport car during its lifetime. The latter was considered equal to 200,000 km, as suggested by previous studies (Duflou et al., 2009). Considering the wide range of distances for cars lifetime proposed in literature, this value was further discussed in a sensitivity analysis in the results and discussion section (Bushi et al., 2019; Tapper et al., 2020).

Since brake discs constituted by different materials (i.e. cast iron and CMC) were considered, the FU is characterized by different weights in the different scenarios.

Different impact categories were employed to obtain a complete vision of the environmental effects of the three scenarios. More specifically, the following impact indicators were considered.

- Global Warming Potential: it quantifies the greenhouse gasses emissions and the possible effects on the climate change of the functional unit expressed in kg of CO_2 eq. The methodology proposed by the IPCC (International Panel on Climate Change) was followed (Solomon et al., 2007).
- Cumulative Energy Demand: it evaluates all the direct and indirect energy consumptions from renewable and non-renewable sources. It is expressed in MJ.
- ReCiPe midpoint categories: this methodology includes 18 impact categories that focus on specific environmental issues (e.g. ozone depletion, terrestrial ecotoxicity, etc.).

These indicators were widely employed in literature studies to evaluate the environmental behaviour of composite and metal parts (Raugei et al., 2015; Umair, 2006; Witik et al., 2013).

2.3. System boundaries and scenario description

The present LCA analysis is classified as “cradle to grave” as it considers all the life cycle phases of the three scenarios from the extraction of raw materials to the final disposal of the disc brakes. More specifically, the following phases were considered.

- Raw materials extraction
- Materials processing and recycling
- Materials transport
- Brake discs production phases
- Brake discs service life
- End of Life of the produced components and production scraps

This approach was selected to provide reliability to the comparison between the three scenarios as they are characterized by distinct use and end-of-life phases (determined by different weights and materials used) in addition to different production processes. For what concerns the use phase of the brake discs, the impacts associated with the fuel production and use were included; the non-exhaust emissions caused by the brake wear still represent a highly debated topic and it was discussed separately in the results and discussion section.

A detailed description of the three considered scenarios is presented as follows.

2.3.1. Scenario 1: cast iron disc brake

The production process of the cast iron disc brake was modelled on the basis of a literature LCA study by Gradin et al. (Gradin and Åström, 2020) and consulting with industrial experts. The cast iron discs are produced by means of traditional sand casting, a versatile process suitable for the manufacturing of complex shaped parts (Yadav et al., 2021) (i.e. brake discs with cooling fins (Jafari and Akyüz, 2022)). Recycled cast iron was selected as the raw material for this scenario; in a sand casting process, the metal is molten and poured into the cavity of a sand mold. The metal cools down and solidifies inside the mold before the cast part is extracted. Machining operations are then required to reach the design dimensions and tolerances (i.e. turning and drilling). The production process of the cast iron disc ends with the application of protective paint.

After the useful life phase (the braking during the lifetime of a car), the brakes are considered to be disassembled and the cast iron disc recycled. Transport of the raw materials and the final component during the production and disposal phases are also considered in Scenario 1.

2.3.2. Scenario 2: carbon ceramic brake

Scenario 2 deals with the production of a C–SiC ceramic composite brake disc by means of a LSI process in which the final part is obtained as a result of a chemical reaction of liquid silicon infiltrated into a porous composite preform.

The first phase of the production process is the manufacture of a CFRP preform (the green part); chopped virgin carbon fibers are mixed with powdered phenolic resin and additives and are placed inside an aluminium mold. Then, a compression molding (or warm pressing) process is carried out to cure and consolidate the composite part by means of the combined effects of pressure and temperature. The aluminium tools are coated with a release agent before the molding process to facilitate the extraction of the cured part.

After that, a pyrolytic decomposition of the green part is performed in an oven at a temperature above 900 °C and ambient pressure. This causes a mass loss of about 40% due to the transformation of the polymer matrix and a porous Carbon Fiber/Carbon (C_f/C) preform is obtained (Zhu et al., 2018).

Metallurgical grade raw silicon powder is infiltrated into the porosity of the preform to produce the carbon ceramic composite C_f/C–SiC part. This is done by heating and melting the metal powder at about 1650 °C in an oven and applying light suction to facilitate the infiltration(Bansal and Lamon, 2015). In this way, ceramic brake disc with a density of about 2.4 g/cm^3 are produced. Sanding operations are finally carried out to reach the required dimensions and finishing.

After the service life of the brake disc, the composite part is considered to be sent to landfill disposal.

2.3.3. Recovered prepreg CMC brake

Scenario 3 is very similar to Scenario 2 as it represents the production and use of a C/SiC brake disc. The main difference between the two systems is given by the bulking mix used to mold the green part; as a matter of fact, in this scenario, the raw materials include 10%wt of recovered prepreg scraps as a substitution for virgin chopped fibers. These wastes are obtained during the cutting operations of virgin prepreg for the production of Carbon Fiber Reinforced Polymers (CFRPs) parts and are constituted by short carbon fibers embedded in an uncured thermosetting matrix. These scraps can account for up to 50% of the virgin material used and are currently sent to landfill disposal, with consequent relevant environmental issues (Nilakantan and Nutt, 2015).

A recovery process for these scraps was developed within the European Life project CIRCE with the goal of reusing them instead of just sending them to landfill disposal. The process consists in the use of two appositely developed machines: the first one exploits rotary cutters to transform the scraps into small chips of almost uniform size and shape (cutting machine). The second machine is used to remove the prepreg release paper through a friction system (peeling machine). Details about the recovery system are reported in previous literature studies conducted within the same project (Bianchi et al., 2021; I. Bianchi et al., 2022).

After the reclaim process, the scraps are transported and mixed with the carbon fibers and the resin powder. The involved company tested brake disc with different percentage of recovered material and observed that for small scraps percentage (i.e. up to 10%wt) the physical properties of the obtained components and the virgin alternative ones are the same.

Apart for the raw materials, the rest of the production process for the carbon ceramic brakes can be considered the same as Scenario 2.

Fig. 1 shows the main life cycle phases considered within the system boundaries for the three scenarios.

2.4. Life cycle inventory

The Life Cycle Inventory phase was performed considering both primary measured data and secondary data retrieved from literature research, estimates and the Ecoinvent 3.1 commercial database.

Scenario 1 data were quantified by means of a literature review of previous LCA and consulting with the industrial experts. The considered sport car cast iron brake disc has a weight of 9 kg. Most of the literature data employed were retrieved from the work of Gradin and Astrom (Gradin and Åström, 2020); the literature data were associated with the functional unit by comparing the weight of the reference disc brake and the sport one considered in this study. Transport distances (by truck) were evaluated considering the geographical location of the involved company and its suppliers.

Scenario 2 and Scenario 3 were modelled with the support of the involved company experts. The weight of each constituent of the material mix was evaluated considering an average rear composite brake disc with a total weight of 5.5 kg. Carbon fibers account for about 3.4 kg of the final weight (62%); 2.2 kg of phenolic resin are used in the bulking mix for the compression molding process and 1.5 kg of granulated silicon is needed for the LSI phase.

The production of carbon fibers from a polyacrylonitrile (PAN) precursor was modelled according to a study from Khalil et al. (Khalil, 2017). Phenolic resin and metallurgical grade silicon powder impacts were retrieved from the Ecoinvent database; the database was also employed to model all the emissions of the transport phases (both for maritime and road transport). The transport distance was estimated considering the geographical location of the involved company suppliers. The carbon fibers were considered to be produced in Japan and imported in Italy through maritime and road transport (Forcellese et al., 2020) while the resin and the silicon were provided by local suppliers (distance <200 km). No details about the additives used in the bulking mix for the compression molding process can be reported here due to confidentiality reasons. Moreover, since they are present in very low percentages, their impacts can be assumed to be negligible and were considered out of the system boundaries.

The weight of the aluminium mold and countermold used for the production of the green part were measured (total weight equal to 75 kg); the number of molding cycles that the tools can withstand before replacement is needed (750 cycles) were estimated according to relevant literature studies (Forcellese et al., 2020; Vita et al., 2019). The aluminium tools were considered to be recycled after their service life with a recycling efficiency of 80% (European Aluminium, 2015).

The gaseous emissions associated with the pyrolysis process were estimated considering the work of Cunliffe et al. (2003a) and are reported in Table 1. In their work, they evaluated the emissions related to the pyrolysis of carbon fiber reinforced phenolic resin and other composite materials. The quantities of each emitted gas were calculated by comparing their results with the weight of the analysed CMC brakes. For what concerns the nitrogen inert atmosphere, a gas flow rate of 200 cm^3/min per kg of composite material (Naqvi et al., 2018) was considered and the total gas consumption was calculated considering the processing time.

The energy consumption of the compression molding, pyrolysis, Liquid Silicon Infiltration and machining operations were directly measured during the production process.

For what concerns Scenario 3 prepreg recovered scraps, their impacts were evaluated considering the energy consumption of the reclaim process (the cutting and peeling machines) and the road transport. No

Table 1
Emissions related to the pyrolysis process estimated from (Cunliffe et al., 2003b).

Pyrolysis emissions		
Gas	mol/kg	g/kg di CFRP
Carbon dioxide	0.46	20.24
Carbon monoxide	0.431	12.07
Hydrogen	1.018	2.04
Methane	0.465	7.44
Ethane	0.052	1.56
Propane	0.004	0.18
Propene	0.005	0.21
Butane	0.001	0.058
Butene	0.001	0.06
Butadiene	0.002	0.11

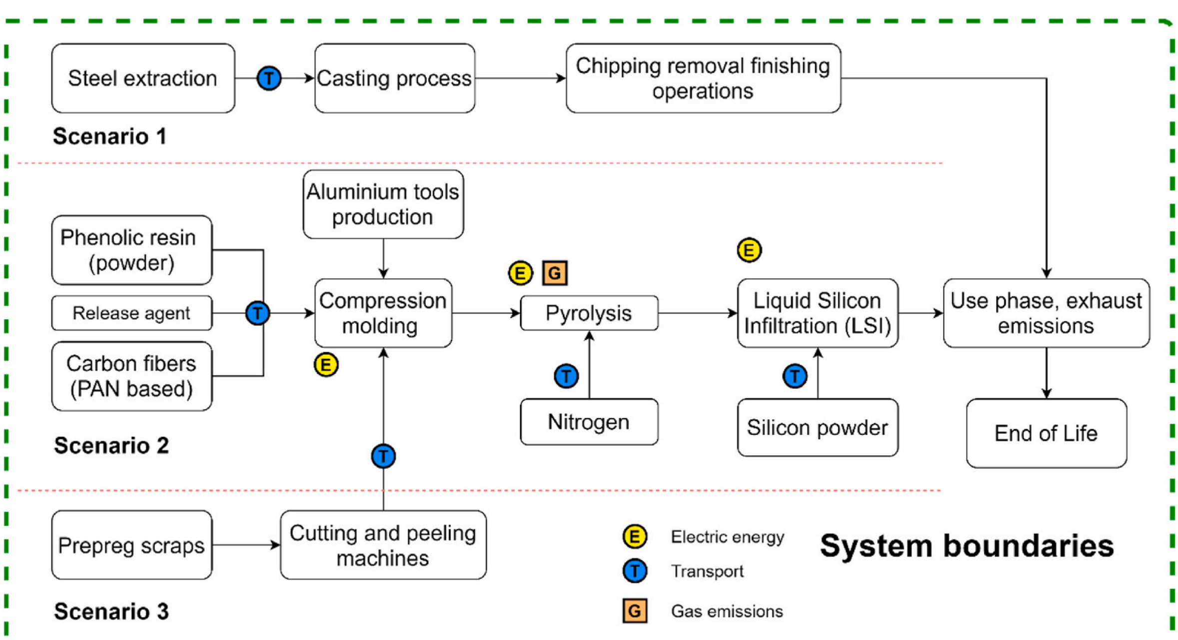

Fig. 1. Life Cycle phases considered within the system boundaries of the three scenarios.

environmental burden related to virgin material production was allocated to the prepreg scraps; in fact, the latter currently have no commercial value and they are typically disposed of in landfill facilities.

The following inputs were modelled on SimaPro by using the Ecoinvent 3.1 database.

- The extraction of the raw materials used for the production of the brakes (powdered phenolic resin, metallurgical grade silicon, scrap cast iron) and polyacrylonitrile fibers.
- The extraction of raw aluminium for the production of the mold and countermold in Scenario 2 and Scenario3.
- Impacts related to the finishing operations of the cast iron brakes (i.e. machining operations).
- Electric energy consumption according to the reference energy mix.
- Sea and road (EURO 5 lorry) transport impacts.
- End of life option for the brakes (either recycling or landfill disposal).

Impact related to the production of the machines used (oven, press, recovery process machines, etc.) were considered negligible as their service life is much longer than the considered brake discs production time. This is a well established practice in Life Cycle Assessment analyses (Germani et al., 2014).

For what concerns the service life of the brake discs, emissions related to petrol production and combustion were included in the study. A model proposed by Hakamada et al. was considered (Hakamada et al., 2007):

$$Use\ emissions\left(\frac{kg\ CO_2}{kg}\right) = \frac{\left(c_{g-use} + c_{g-prd}\right) \times life\ \ time}{\varepsilon \times M}$$

where.

- M is the curb weight of the vehicle. A weight of 1600 kg was considered for Scenario 1 whilst for scenarios 2 and 3 it was calculated considering the weight reduction achieved by means of the carbon ceramic brake discs.
- ε is the fuel efficiency (km/L), calculated according to Sullivan et al. (1998) as:

$$\varepsilon = 6,4 \times 10^4 \times M^{-1,2}$$

- c_{g-use}, and c_{g-prd} are the emissions related to petrol use and production (2.36 kg/L and 0.5 kg/L respectively).
- *life time* is the service life of the vehicle, expressed in km.

The impacts of the use phase were allocated to the functional unit considering the weights of the discs compared with the total curb weight of the vehicle.

It was assumed that, due to wear phenomena, the cast iron rear brake disc requires to be replaced every 70,000 km, so more than one disc is needed throughout the life cycle of the car. On the other hand, C/SiC discs are characterized by a much higher wear resistance (up to 300,000 km) and no substitution is typically needed during the lifetime of the passenger car (Krenkel and Langhof, 2017).

Table 2 reports all the relevant LCI data for the three considered scenarios.

2.5. Scanning Electron Microscopy

The surface of C_f/C–SiC ceramic brakes was analysed by means of a Scanning Electron Microscopy (SEM) analysis; a section of both the standard carbon ceramic brake and the one produced with recovered material (10%wt of prepreg scraps) were analysed and compared. A JEOL IT300 scanning electron microscope was employed to conduct the test in high vacuum conditions. An operating electron acceleration voltage equal to 20 kV was set and images were acquired with a 100x magnification.

Table 2
Relevant Life Cycle Inventory data for the three considered scenarios.

	Scenario 1	Scenario 2	Scenario3
Input	Quantity		
Raw materials[a]			
Brake disc weight	9.0 kg	5.5 kg	5.5 kg
Final part density	7.9 g/cm^3	2.4 g/cm^3	2.4 g/cm^3
Cast iron input	16.23 km	/	/
Virgin carbon Fibers	/	3.40 kg	3.06 kg
Silicon (metallurgical raw)	/	1.50 kg	1.50 kg
Phenolic resin (powdered)	/	2.20 kg	2.20 kg
Recovered prepreg scraps	/	/	0.36 kg (10%)
Release agent	/	0.021 kg	0.021 kg
Nitrogen (inert atmosphere)	/	3.95 kg	3.95 kg
Tools			
Aluminium tools (mold and countermold)		75 kg	75 kg
Aluminium removed by milling		22.5 kg	22.5 kg
Molds service life (number of parts) [b]		750 parts	750 parts
Production phases cast iron brake[a]			
Rough machining	3.68 kg		
Finishing	3.4 kg		
Balancing	0.14 kg		
Energy consumptions			
Aggregated energy consumptions (CMC discs)		16.5 kWh	16.5 kWh
Transport	**Typology**		
Carbon fibers	Transoceanic ship		~16,800 km
	Truck 16–32 ton, EURO 5		~150
Phenolic resin	Truck 16–32 ton, EURO 5		~200 km
Aluminium tools	Truck 16–32 ton, EURO 5		~200 km
Cast iron raw material	Truck 16–32 ton, EURO 5		~50 km

[a] Cast iron input materials and production phases were retrieved from (Gradin and Åström, 2020) and modelled accordingly using the Ecoinvent database.
[b] Molds service life for the compression molding process was retrieved from (Forcellese et al., 2020; Vita et al., 2019).

Specimens for the microscopy observation were obtained from the side area of appropriately cut circular sectors of the brake discs, as shown in Fig. 2.

3. Results and discussion

3.1. Scanning Electron Microscopy results

Fig. 3 shows the SEM images of the virgin brake and the recovered material brake. From a macroscopic point of view, no difference can be observed between the virgin carbon ceramic brake and the recovered material one. In both cases, the three main constituent of the composite structure are clearly visible: carbon fibers (the dark regions), metal silicon (the light shade) and SiC regions (mid shade, obtained as result of the reaction between the carbonised resin and the molten silicon). The carbon fibers are visible in the form of chops with variable inclinations with respect to the image acquisition direction. These results are in line with what was found in scientific literature for what concerns SEM images of carbon fiber reinforced silicon carbide composites (Krenkel, 2005; Wang, 2011).

A prepreg scraps region with the fibers oriented perpendicularly to

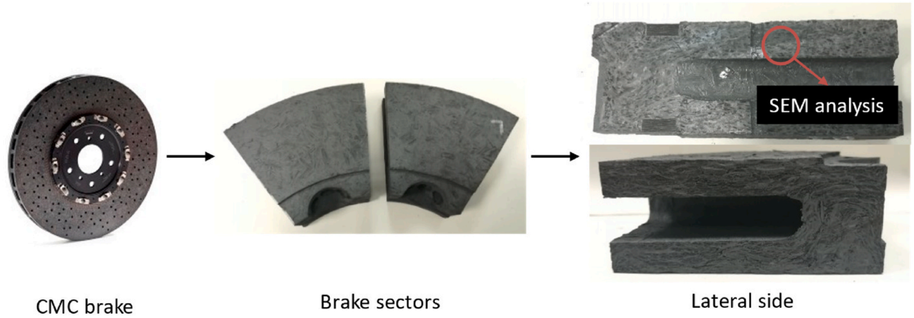

Fig. 2. Procedure for the specimens realization for SEM analysis.

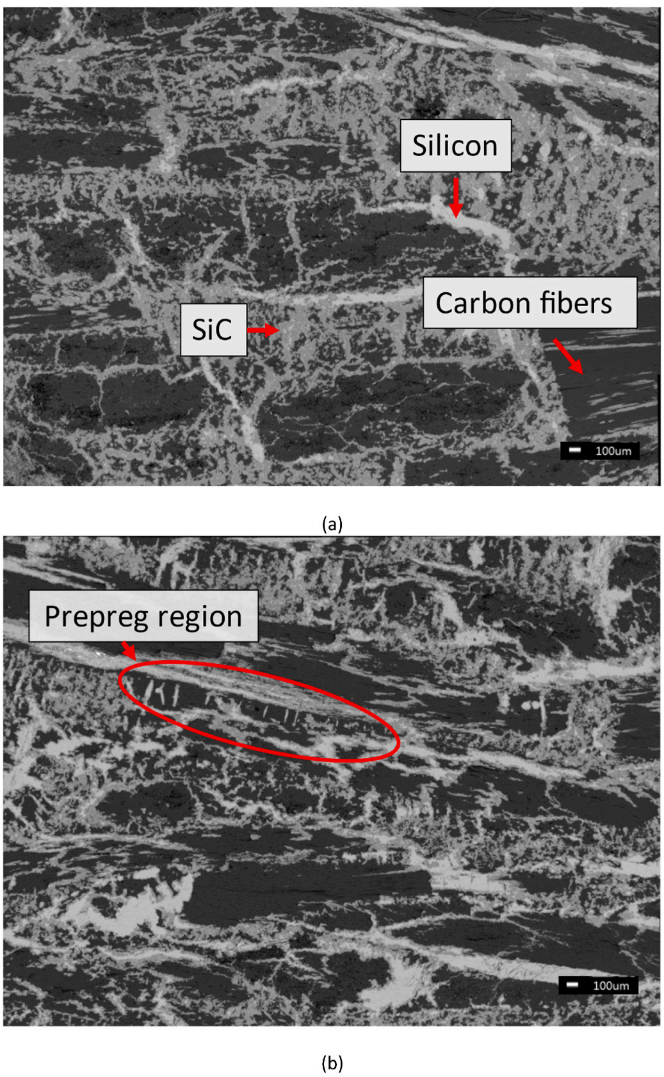

Fig. 3. SEM images of the carbon ceramic brakes: (a) virgin brake (0% recovered material), and (b) brake with 10% of recovered prepreg.

the image acquisition direction is highlighted in Fig. 3b. It is an elongated area in which the carbon fibers are alternated with Si/SiC bands obtained during the silicon infiltration process. This configuration is typical of CMC composites produced from virgin carbon fiber fabric precursors (Ding et al., 2019).

Indeed, the prepreg regions are well integrated within the material and the uncured resin of the scraps reacted completely with the molten silicon. No defects or voids are visible within the prepreg regions and from a microstructure quality perspective the recovery material is basically equivalent to the virgin one. These considerations are highlighted in the zoomed view of the prepreg scraps reported in Fig. 4.

3.2. Production of the disc brakes

Fig. 5 reports the results in terms of Cumulative Energy Demand and Global Warming Potential for the production processes of the three considered scenarios. In order to improve the graphs readability, the results were aggregated into three impact items: raw materials, production phases and End of Life. The raw material phase includes the cast iron impacts (Scenario 1), phenolic resin, carbon fibers, release agent, silicon (Scenario 2 and 3) and the recovered prepreg scraps (Scenario3) while the EoL phase includes the disposal and recycling of all the tools used during the production process and the final components.

Indeed, if the service life is not considered, the cast iron disc resulted as the most sustainable alternative, determining only a fraction of the environmental impacts of the CMC products (34.84 kg CO_2 eq and 442,88 MJ, between 15% and 21% of the total impacts of the other two scenarios, depending on the considered impact category). Scenario 2 resulted the most impactful scenario with impacts that are about 8% higher than those of Scenario 3.

For Scenario 1, the major contribution is determined by the raw materials and cast production (29.50 kg CO_2 eq and 335.16 MJ), closely followed by the chip removal finishing operations. The recycling phase of the cast iron brake allows to reduce the use of virgin materials (pig iron), resulting in overall negative impacts and a reduction of the scenario impacts higher that 30%.

For all three scenarios, the transport of the raw materials and the tools resulted in negligible impacts if compared to the other production phases. This is in line with what was found in literature studies focused on Life Cycle Assessment analysis of metals and composite components (I. Bianchi et al., 2022).

Given the lack of literature LCA analyses on Ceramic Matrix Composites, the production phases of the SiC/C discs were analysed in greater detail. Fig. 6 reports the percentage contributions on the total Global Warming Potential value of the manufacturing of the Scenario 2 component. Similar values can be obtained for the CED impact indicator.

The bulking mix materials for the compression molding process account for 86% of the total impacts; of those, the majority (82%) is associated with the production of the PAN based carbon fibers which require energy-intensive and high-temperature production processes (Das, 2011). The powdered phenolic resin accounts for only 4% of the total impacts; in fact, despite the high amount of resin used (2.20 kg) its impact unitary values are much lower than those of the other raw materials.

The production of the aluminium tools (tooling phase) for the compression molding phase represents only 2% of the GWP total value. This is much lower than what can be found in the scientific literature, where the tools production can account for more than 15% of the total impacts (Bianchi et al., 2021; Forcellese et al., 2020). When prepreg

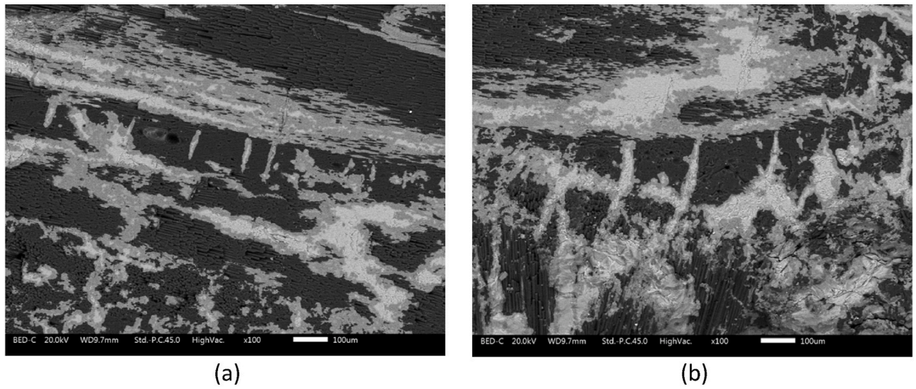

Fig. 4. Details of the prepreg scraps in the recovered brake.

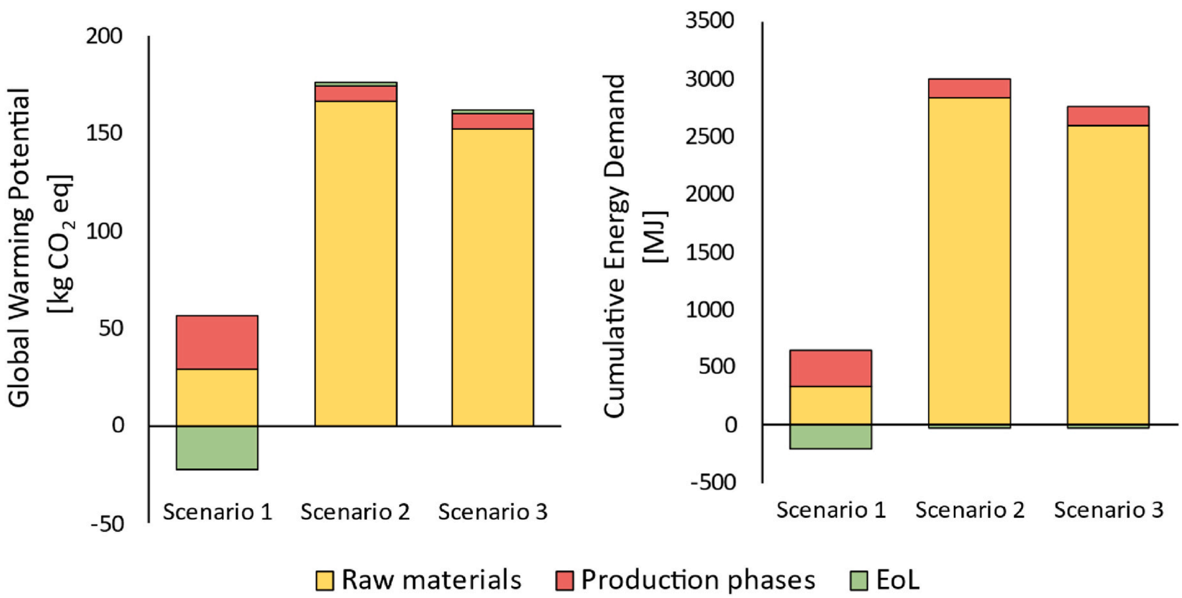

Fig. 5. LCIA results in terms of Global Warming Potential and Cumulative Energy demands for Scenario 1, Scenario 2 and Scenario 3. The impacts are presented in an aggregated form for raw materials, production phases and EoL. The service life impacts are excluded from this graph.

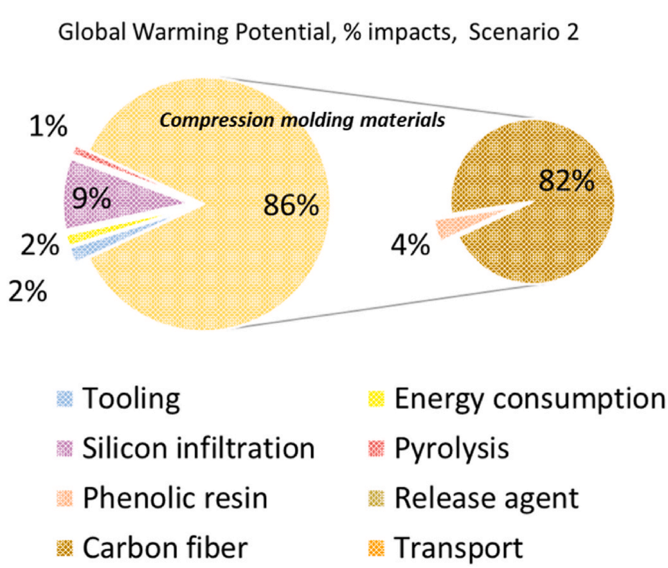

Fig. 6. Percentage contribution on the total impacts of Scenario 2 with focus on the bulking mix for the compression molding process.

fabrics are used in compression molding processes, the resulting CFRP parts are typically characterized by low thickness (few mm) with respect to their surface area; this implies the use of very large and heavy weight molds with high of environmental impacts. However, since brake discs are more massive, the use of low-weight and more environmentally friendly molds is possible. For the same reason, raw materials production results in the highest impact contribution.

The electric energy consumption of the molding, pyrolysis, infiltration and finishing phases is responsible for only 2% of the total impacts; no other energy sources were used during the production phases. Despite the fact that the process is quite energy intensive with an energy consumption equal to 3 kWh per kg of composite material produced, the electric energy impacts are overall much lower than those of the raw materials.

Another relevant production phase is the Liquid Silicon Infiltration phase which includes the metallurgical grade silicon extraction and transport (9% of the total impacts). The impacts of the pyrolysis process are almost negligible, accounting for only 1% of the GWP impacts. Of those, 40% are associated with the nitrogen use for the inert atmosphere and 60% with the gaseous emissions formed due to the cracking of the phenolic resin matrix (Naqvi et al., 2018).

For what concerns Scenario 3, the recovery process of the prepreg scraps has basically zero impacts as it accounts for less than 0.1% of the values of CED and GWP. Even though the scraps are used to replace only a small percentage of the raw materials (10%), their reuse represents a relevant improvement of the CMC production process from an environmental perspective. In fact, raw materials are the main environmental damage item in the reference scenario for the ceramic composite disc so, overall, Scenario 3 shows impacts more than 8% lower than those of Scenario 2.

Fig. 7 presents the results of the three scenarios for the 18 midpoint categories of the ReCiPe methodology. For most of the impact categories, the results are in line with what was observed for the CED and GWP indicators. The virgin carbon ceramic brake disc is typically the most impactful alternative and the reuse of the prepreg scraps provides a good reduction in environmental impacts. However, for categories such as terrestrial ecotoxicity, human carcinogenic toxicity and mineral resource scarcity, Scenario 1 has greater impacts than those of scenarios 2 and 3. Considering the ReCiPe endpoints, Scenario 1 showed the highest impact in terms of Human Health damage potential (5.2*E−03 DALY vs 4.0*E−3 DALY for Scenario 2 and 3.7*E−3 DALY for Scenario 3). This behaviour is primarily associated with cast iron raw material use.

3.3. Brake discs service life

Considering the service life defined in the functional unit (200,000 km), the emissions related to the use phase of the cast iron and CMC discs are equal to 145.14 and 88.54 kg CO_2 respectively (Scenario 2 and Scenario 3 service life impacts are considered to be the same). For Scenario 1, the petrol production and use represent the highest contribution item on the GWP, with a total value that is more than 4 times higher than those of the production phases impacts. The reduction in weight achieved with the composite discs (scenarios 2 and 3) strongly reduced the use emissions related to the FU (−39%).

Fig. 8 shows the total quantity of CO_2 eq emissions as a function of the service life mileage of the three considered scenarios. It is evident that the higher emissions related to the production phases of the ceramic composite parts can be counterbalanced by the reduction in impacts obtained by means of weight reduction. Moreover, several cast iron brakes are required during the life cycle of a car and this contributes in increasing the scenario emissions.

A Break Even Point (BEP) can be observed between the cast iron disc and the recovered composite disc for about 200,000 km; hence, considering the FU, these two scenarios are basically equivalent from a

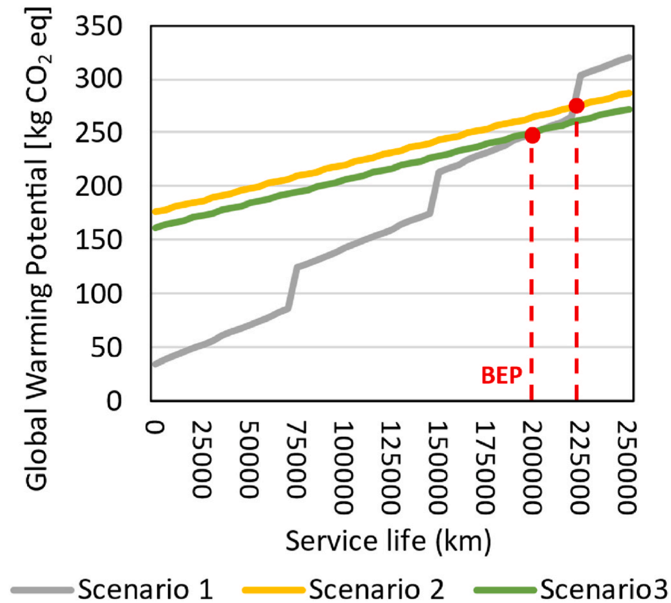

Fig. 8. Environmental impacts related to the service life of the three analysed scenarios.

global warming perspective. For a higher mileage, the recovered composite part became more and more sustainable. Considering the virgin CMC disc, it reaches a BEP with the metal counterpart for around 225,000 km.

The non-exhaust emissions associated with the wear of the discs were not included in the present analysis. As proved by numerous studies, the use of carbon ceramic discs can greatly reduce the particulate (PM2.5 and PM10) emissions of vehicles if compared to traditional solutions (Fussell et al., 2022; Seo et al., 2021); this could further improve the sustainability of scenarios 2 and 3.

The chemical composition and emissions rate of the wear particles can vary depending on the braking severity and frequency and, most importantly, on the materials of the discs and the pads (Grigoratos and Martini, 2015). Hence, it was decided not to consider a general set of wear inventory data such as the one proposed within the Ecoinvent database (derived from (Ntziachristos and Boulter, 2016)) as it would

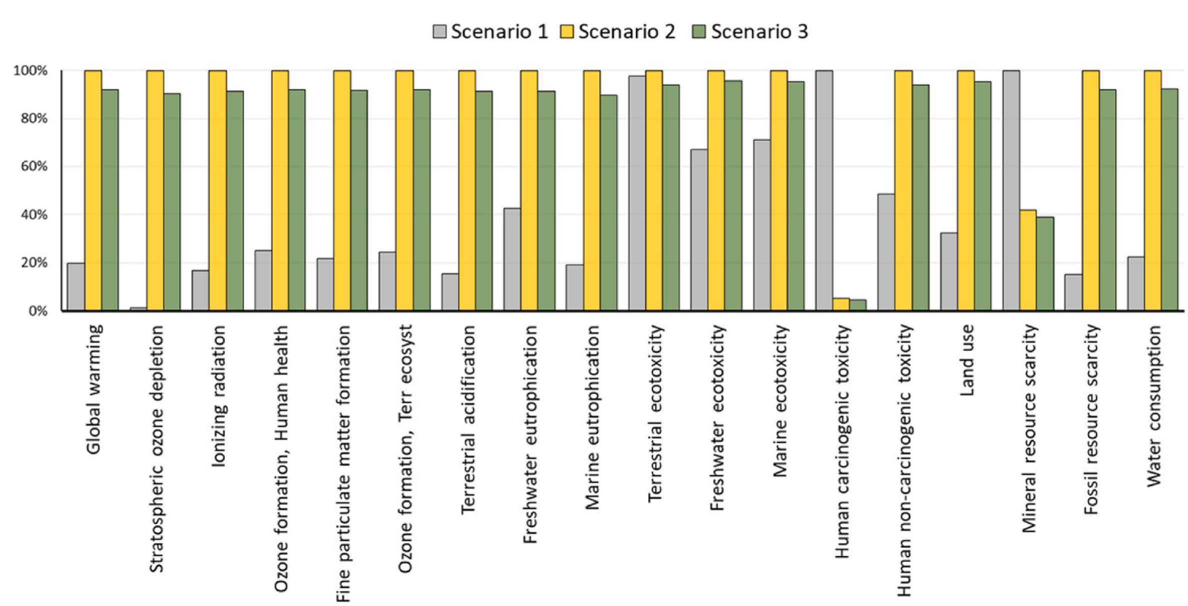

Fig. 7. Comparison between the three scenarios for the 18 midpoint categories of the ReCiPe methodology.

not have considered the differences between the iron and composite brake systems. However, the commercial database is still useful to make some observations. The transport impacts of a medium size EURO 5 petrol passenger car (Ecoinvent) were appropriately adjusted by removing the non-exhaust emissions items; the new process was evaluated and compared with the standard database process. In terms of Global Warming Potential, the non-exhaust emissions account for only 4.0% of the transport phase impacts; for this reason, the GWP results above presented can be considered fairly reliable even though the brake wear was not accounted for. The same applies for most of the 18 ReCiPe midpoint categories; some exceptions are represented by the terrestrial acidification, fine particulate formation, ionizing radiation and mineral resource scarcity impact categories for which the non-exhaust emissions can determine the majority of the indicator value (up to 85%). In these cases, the use of a wear resistant materials such as the C/SiC composite could dramatically reduce the overall environmental damage. Further experimental procedures and sustainability assessments are required and left as future work to better investigate these aspects.

4. Conclusion

In this paper, a comparison between the environmental sustainability of car brake discs realized with different materials was presented. The Life Cycle Assessment methodology was employed to compare cast iron, ceramic matrix composite and ceramic matrix composite with reclaimed fibers car brake discs. Primary and secondary data were used to realize the life cycle inventory. The environmental behaviour of the discs was evaluated considering CED, GWP and ReCiPe midpoint and impacts from a cradle to grave perspective were included. The main results can be summarized as follows.

- As far as the production is concerned, the cast iron brake disc is most sustainable alternative, showing between 15% and 21% of the impacts of the composite components.
- The impacts related to the production of the CMC parts are mainly caused by the raw materials used for the compression molding process (up to more than 86% of the total) and in particular by the high quantity of carbon fibers. The second highest contribution is represented by the silicon used in the infiltration process. Electric energy consumption is not an impactful item if compared with the others (2%).
- The recovery process of the prepreg scraps has almost negligible impacts and it allows to reduce the use of virgin carbon fibers. This improves the sustainability of the CMC production process, with a reduction in impacts of about 8%.
- The weight reduction provided by the composite discs strongly reduces the impacts associated with the brake use phase; overall, the ceramic matrix discs can be the most sustainable choice in terms of Global Warming Potential if a sufficiently long use phase is considered (more than 200,000 km).

Considering other impact categories, the reduction in non-exhaust emissions associated with the high wear resistance of the C/SiC parts could bring noteworthy environmental benefits.

In future works, the limitations of this paper will be addressed. In particular, other primary data which are not considered in this study will be measured, as well as detailed evaluations about the use phase of the brakes will be conducted. Moreover, other recovered scenarios could be added to the study (e.g. considering recycled carbon fibers instead of recovered prepreg).

CRediT authorship contribution statement

Iacopo Bianchi: Software, Writing, Formal analysis, Investigation, All authors read and approved the final version of the manuscript. **Archimede Forcellese:** Funding acquisition, Project administration, Supervision, All authors read and approved the final version of the manuscript. **Michela Simoncini:** Writing – review & editing, Investigation, All authors read and approved the final version of the manuscript. **Alessio Vita:** Methodology, Investigation, Visualization, All authors read and approved the final version of the manuscript. **Lucia Delledonne:** Data curation, Formal analysis, Reviewing, All authors read and approved the final version of the manuscript. **Vincenzo Castorani:** Supervision, Project administration, All authors read and approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used to conduct the analyses are available within the paper

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