LUXFER
MEL TECHNOLOGIES

LIFE CYCLE ANALYSIS

Magnesium Alloy Road Wheel

FORGED
Mg

INTRODUCTION

As the effects of climate change become more prevalent, reducing the carbon dioxide ("CO_2") and carbon dioxide equivalent ("CO_2e") emissions of vehicles has become a priority. Over the course of its lifetime, a standard passenger car releases approximately 138 metric tons of carbon dioxide into the atmosphere. According to the U.S. Department of Energy, a 5% reduction in the mass of a modern automobile leads to a 4% reduction in CO_2 emissions. While much of the focus on reducing emissions has gravitated to electric-powered vehicles, the use of magnesium alloys can help to reduce total CO_2 emissions across a wide range of vehicles.

Alloys of magnesium have considerable advantages over other metals. Magnesium weighs 30% less than aluminum and 75% less than steel. In terms of passenger cars, magnesium's light weight has incredible benefits for speed, maneuverability, and fuel efficiency. Magnesium can be found in some cars' transmission housing, instrument panels, steering columns, and seat frames. However, a widely unused application is the magnesium road wheel ("Mag Wheel").

Luxfer MEL Technologies, a subsidiary of Luxfer Holdings Plc ("Luxfer"), is a manufacturer of magnesium alloys. As part of its efforts to better understand the carbon impact of its products, Luxfer presents this Life Cycle Analysis ("LCA") on its RotaMag® magnesium alloy. While the RotaMag® alloy has a variety of commercial and military applications such as electro-optical devices, this LCA is focused on the RotaMag™ alloy's application as a performance production road wheel.

This analysis purports that the lighter weight of using magnesium in road wheels results in lower CO_2e emissions over the lifetime of the vehicle as compared to the industry standard of aluminum. Due to the light weight of magnesium, reduced emissions of the vehicle combine into a total carbon saving over the lifetime of its use. This LCA will demonstrate that one wheel composed of Luxfer's RotaMag™ alloy emits 385 kg less CO_2e compared to one aluminum wheel, saving 948 kg of CO_2 for a vehicle outfitted with all magnesium wheels over the course of its lifetime.

Magnesium wheels save

948 kg CO_2e

over the course of a vehicle's lifetime compared to aluminum

Luxfer MEL Technologies' RotaMag® magnesium alloy developed for high-performance forged wheel applications.

SCOPE & METHODOLOGY

This LCA will analyze the carbon impact of Luxfer's RotaMag™ magnesium alloy magnesium road wheel from Cradle-to-Grave. Generally, Cradle-to-Grave includes each step in the production process, including the sourcing raw materials, production, assembly, usage, and disposal. In this context, this LCA will examine the carbon impact from sourcing raw materials ("cradle") to the end-of-life disposal ("grave") of a typical performance road wheel. This analysis will measure the CO_2 and CO_2e, or total greenhouse gas emissions, relative to the damage of 1 kilogram of CO_2 in the atmosphere.

This analysis will begin with an overview of the Cradle-to-Grave life cycle. In order to analyze the magnesium wheels, this LCA will segment the life cycle into three stages: the Production Stage, the Usage Stage, and the Grave Stage.

In the Production Stage, this analysis will measure the carbon emissions from processing raw materials and the various manufacturing processes involved in making a magnesium alloy wheel. In the Usage Stage, this analysis will measure the comparative carbon savings between magnesium and aluminum when used as road wheels. In the Grave Stage, this report will consider the typical disposal processes for a magnesium road wheel.

Generally, a Cradle-to-Grave LCA would also incorporate the carbon impact of assembling the finished product, or, in this case, assembling the finished magnesium alloy road wheel on the vehicle. However, the carbon impact of assembling the road wheel is very small and, as a result, vehicle manufacturers do not typically maintain such data. Therefore, the carbon impact of assembly has been excluded from this LCA.

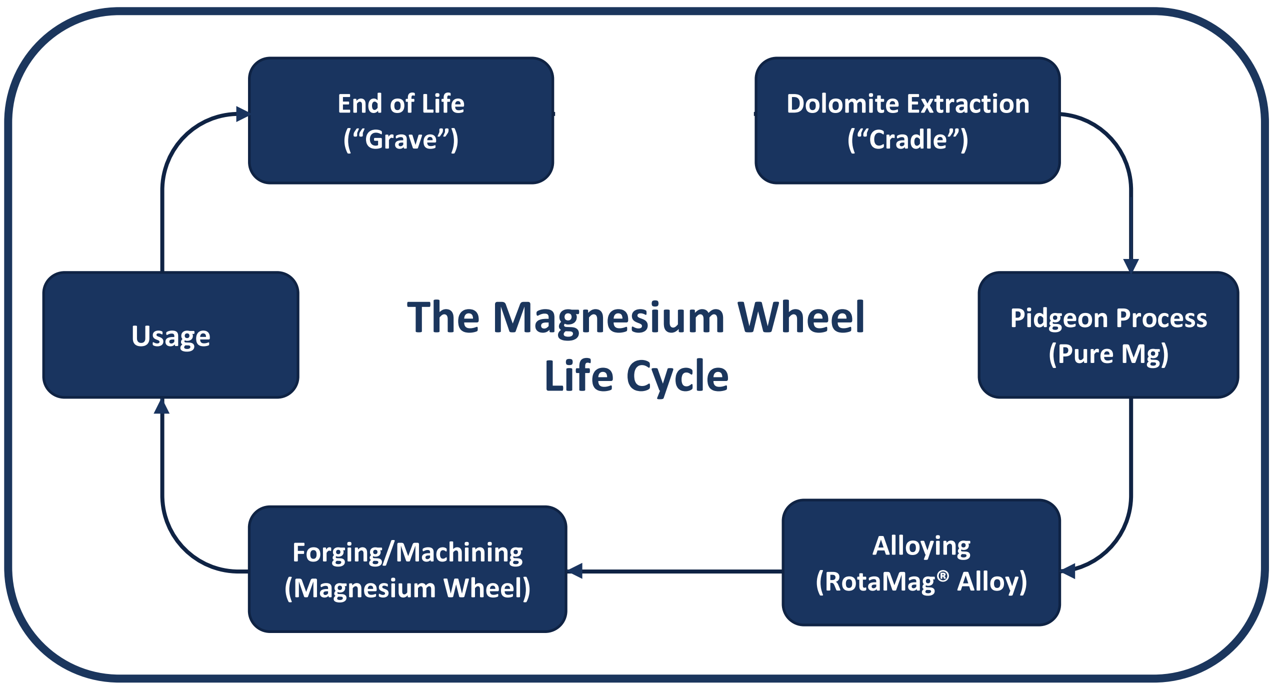
In large part, carbon emissions data was collected internally. However, because 87% of global primary Magnesium production occurs in China, Luxfer also sources most of its magnesium from qualified producers in China. As a result, data from external sources were also incorporated due to lack of availability of certain data points specific to Luxfer's suppliers. This analysis uses data published by the International Magnesium Associated to analyze the carbon impact of raw material extraction by Chinese suppliers. Data collected from external sources are cited on Page 13. The analysis will then detail the comparative carbon emissions of magnesium road wheel production with aluminum wheel production, analyzing the CO_2e output of each.

ROTAMAG® MAGNESIUM ALLOY OVERVIEW

Magnesium most easily comes from raw dolomite, a naturally occurring mixture of calcium carbonate and magnesium carbonate. After mining and extraction, the raw dolomite goes through what is called the Pidgeon Process to extract the primary magnesium. The Pidgeon Process involves a series of chemical reactions required to extract the primary magnesium from the raw dolomite and form magnesium ingots. Details on the Pidgeon Process are described on Page 6.

The magnesium ingots are shipped to a Luxfer MEL Technologies' processing plant, where the ingots are combined with specific amounts of aluminum, zinc, and manganese. This combination creates the RotaMag™ magnesium alloy, which is then cast into a log. The alloy logs are homogenized and then cut into forging billets. The high purity alloy forging billets forms the base of what will later become a magnesium road wheel.

Luxfer then ships the alloy to a third-party forging and machining facility to form the road wheel. Once formed into their desired shape, the wheels are treated and subsequently shipped to the vehicle manufacturer for assembly. The magnesium road wheel serves its desired purpose for the length of the vehicle's life, which is around 350,000 kilometers, or approximately 20 years. At that point, the vehicle reaches its end-of life, and the wheels may be removed and recycled.



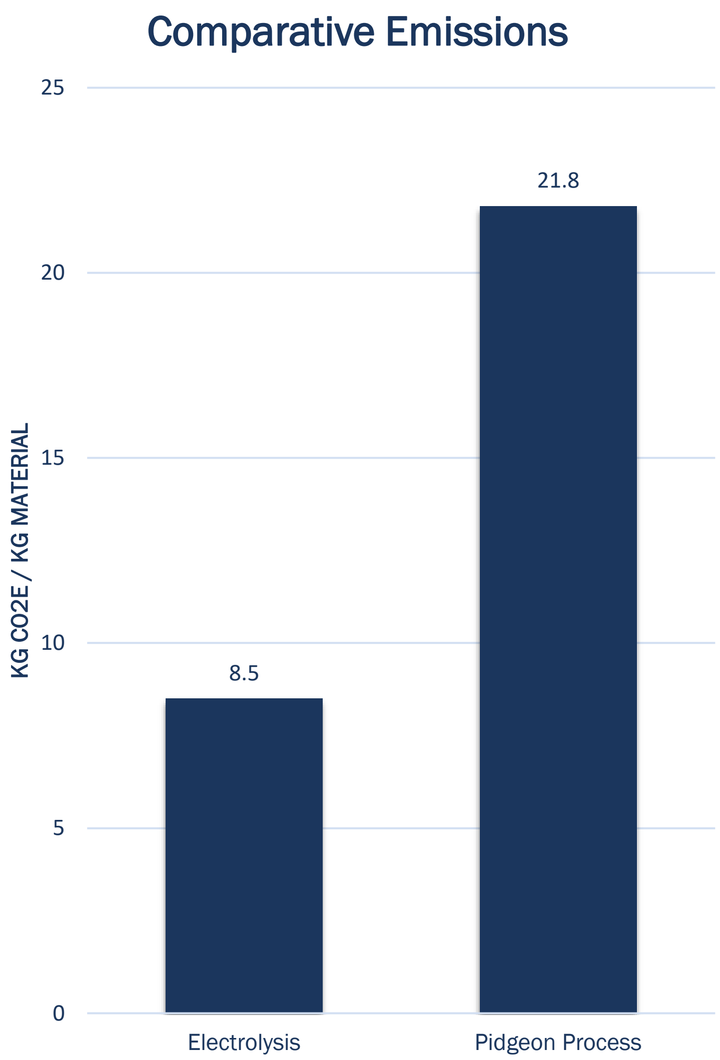
THE PRODUCTION STAGE

The first step in the Production Stage is the production of primary magnesium ingot. The most widely used method to produce magnesium ingot is the Pidgeon Process. There are several steps involved in the Pidgeon Process, each having its own specific carbon footprint. First, the raw dolomite is calcined to produce magnesium oxide. The magnesium oxide then goes through a reduction reaction with ferrosilicon to produce pure magnesium vapor. Next, the vapor is condensed into a solid before it is remelted and refined into high-purity magnesium ingots. The table provides a brief description of the steps involved in the Pidgeon Process, as well as the carbon emissions produced by each.

The Pidgeon Process requires the use of ferrosilicon (FeSi), which facilitates the reduction reactions necessary to isolate the magnesium. The steps to create ferrosilicon are not detailed in this report, however, the carbon footprint of ferrosilicon production has been aggregated and considered in the overall emissions attributable to the Pidgeon Process.

Emissions from the Pidgeon Process

STEP	DESCRIPTION	CARBON IMPACT (kg CO_2e/kg Mg)
Ferrosilicon (FeSi) Production	FeSi is typically created through a reaction between silica and iron in a submerged electric arc furnace	12.5
Dolomite Calcination	$(Ca,Mg)CO_{3(s)} \rightarrow CaO,MgO_{(s)} + CO_{2(g)}$ Under high temperatures, dolomite calcines into a mixture of calcium and magnesium oxide, releasing carbon dioxide as a byproduct.	7.9
MgO Reduction (with FeSi)	$2CaO.MgO_{(s)} + FeSi_{(s)} \rightarrow 2Mg_{(g)} + Ca_2SiO_{4(s)} + Fe_{(s)}$ The oxides react with ferrosilicon to produce the products above. The pure magnesium vapor is extracted from the reaction as a “crown”.	3.7
Refining	The crowns are remelted and refined with salt fluxes to produce clean molten magnesium which is cast into ingots.	0.5
Fuel Credit	Mg producers take coke/semi-coke gas emissions from coal producers and use it to heat their retorts, reducing monetary and GHG costs.	-4.0
Transportation	Road and sea shipping from dolomite mines and primary producers in China to the Luxfer MEL Technologies facility in Manchester, U.K.	0.3
Other Processes (Combined)	Dolomite mining, sourcing more raw materials, briquetting, and casting.	0.9
PRODUCTION TOTAL		21.8



The Pidgeon Process requires significant energy consumption. Temperatures up to 1,200°C must be maintained in order to properly extract the primary magnesium from the calcined dolomite. Such energy consumption invariably produces CO_2, making the Pidgeon Process the most carbon intensive step in the manufacture of the magnesium road wheels. The source of thermal energy can be coal, natural gas, coke oven gas, or semi-coke gas.

It is possible to produce pure magnesium through methods other than the Pidgeon Process. Electrolysis, for example, is an alternative method of primary magnesium production which, as shown in the chart, is significantly less energy intensive compared to the Pidgeon Process. Electrolysis replaces the dolomite with magnesium chloride. These materials are heated with direct electrical current. Further, Electrolysis does not involve the calcination required in the Pidgeon Process. For these reasons, Electrolysis is less energy intensive than the Pidgeon Process. However, neither Electrolysis nor other alternatives to primary magnesium production are widely used because, like most other metals, China dominates the global magnesium market and relies almost exclusively on the Pidgeon Process. Weighted averages across the Chinese Pidgeon Process producers are used in the table.

Emissions produced by the Pidgeon Process have dropped 10% in the last decade as a result of switching to coke furnaces to natural gas or semi-coke gas powered furnaces. While this change symbolizes an improvement to the Pidgeon Process, further improvements to magnesium ingot production can be achieved through the use of Electrolysis as opposed to the Pidgeon Process. Although still dependent on a source of local electrical power, emissions from Electrolysis are, on average, 8.5 kg CO_2e/kg Mg, compared to the Pidgeon Process' 21.8 kg CO_2e/kg Mg.

Once the magnesium ingots are formed, they are shipped to the Luxfer MEL Technologies' alloying facility. Here, the magnesium ingots are melted and combined with aluminum, zinc, and manganese. To properly assess the carbon impact for alloying, this LCA must consider the carbon footprint of both the alloying of other materials and the cost of sourcing them. The table (right) shows the carbon impact from all other materials that are combined with the magnesium ingot to produce the RotaMag® magnesium alloy. Because magnesium is the most prevalent metal in the alloy, emissions from magnesium comprise the bulk of the CO_2e attributed to the alloy. In the case of one magnesium wheel comprised of 10.6 kg of RotaMag® magnesium alloy, the carbon emissions attributed to the Production Stage is 256 kg CO_2e per wheel.

Emissions from RotaMag® Magnesium Alloy Production

STEP FOR ROTAMAG PRODUCTION	KG CO_2E/KG MATERIAL	ATTRIBUTED KG CO_2E/KG ROTAMAG
Magnesium Production	21.8	19.9
Aluminum Production	11.5	0.96
Zinc Production	3.5	0.01
Manganese Chloride	6.0	0.03
Transportation (from alloying facility to casting facility to assembly)		0.15
Casting		2.1
TOTAL		**24.15**

Competitors could use a wide range of primary aluminum products and forming methods. As such, this LCA will use a low carbon primary estimate to preserve integrity. Aluminum alloys can be made and commercially sold with a carbon footprint of 4.25 kg CO_2e/kg Al. It is assumed that the forging and machining impacts for both the aluminum and magnesium downstream processes are similar. A standard aluminum road wheel weighs 16.6 kg. Based on these assumptions, a road wheel comprised of primary aluminum will have a carbon footprint of at least 108 kg CO_2e. Using this number, magnesium road wheels have a carbon footprint at the Production Stage which is 148 kg CO_2e higher than a comparable aluminum wheel.

THE USAGE STAGE

To analyze the Usage Stage, the carbon footprint of magnesium alloy road wheels is compared to its main alternative, aluminum. While a magnesium wheel can be more carbon intensive in production than aluminum, the comparatively lighter weight of magnesium reduces carbon emissions after the wheel is in use. The selected aluminum-wheeled vehicle weighs 1,364 kg. Each magnesium road wheel weighs 6 kg less than an aluminum cast alloy wheel – a 24 kg or 1.8% reduction in weight. This reduction corresponds to a 1.4% decrease in fuel consumption. A vehicle emits around 0.3 kg CO_2/km and, over a lifetime of 350,000 km, a vehicle outfitted with standard aluminum wheels can be expected to emit 110,000 kg of CO_2. However, using magnesium road wheels as an alternative to aluminum, the fuel emissions decrease by 1.4%, which amounts to a reduction of 1,540 kg CO_2 per car, or 385 kg CO_2 saved per road wheel over the course of its lifetime.

Magnesium wheels decrease fuel emissions by

1,540 kg CO_2

over the course of the vehicle's lifetime

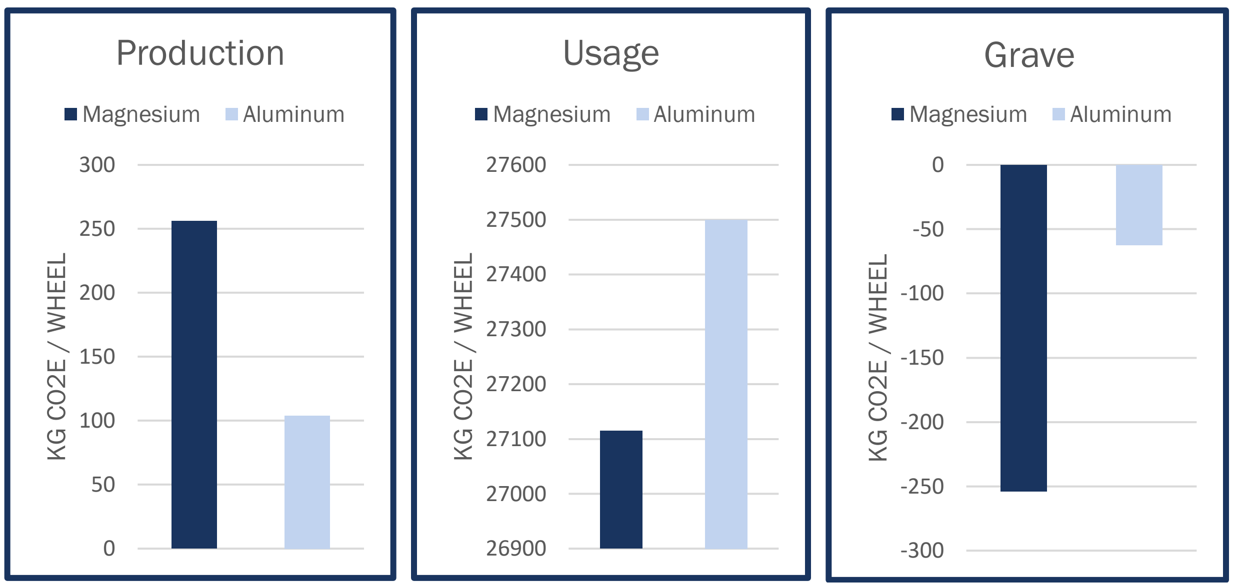
Luxfer MEL Technologies' RotaMag® magnesium material technology specially developed for high-performance forged wheel applications.

THE GRAVE STAGE

When a typical performance vehicle is scrapped for parts, the magnesium wheels enter their end-of-life, or Grave Stage. Due the limited number of magnesium wheels in use today, a dedicated end-of-life disposal or recycling procedure has yet to be widely adopted. Under U.S. federal guidelines, those in charge of magnesium disposal should recover or recycle the magnesium whenever possible. The wheels can easily be separated from the vehicle before the car goes to a metal shredder. All shredded metals end up in a composite mixture of lighter alloys including aluminum, magnesium, and zinc. The magnesium in these mixtures is often burnt off with chlorine, causing the magnesium to lose its value.

The separated wheels can be returned to the manufacturer for recycling, in which case the recycled RotaMag alloy will have a carbon footprint of only 2.1 kg CO_2e/kg Mg as opposed to the standard 21.8 kg CO_2e/kg Mg. Alternatively, the wheels can be sent to a magnesium recycling plant to produce a 90:10 magnesium:aluminum master alloy which is used as feedstock in aluminum wrought alloy production. Although the volumes for this process remain low, this alloy can act as a substitute for primary magnesium with an equivalent CO_2e reduction benefit as in the former example. In contrast, aluminum has a standard recycling process at a cost of 0.5 kg CO_2e/kg Al.

Emissions from Magnesium and Aluminum Wheels by Life Cycle Stage



CONCLUSION

This Life Cycle Analysis has shown that the magnesium wheel can cement itself as a lightweight and durable alternative to aluminum. The production of the magnesium wheel involves 256 kg CO_2e per wheel. However, when compared with the production of aluminum, the incremental carbon impact reduces to 148 kg CO_2e. When accounting for the comparative carbon savings of the vehicle throughout the Usage Stage, magnesium wheels save 237 kg CO_2e over the lifetime of the vehicle. This means that a vehicle outfitted with all magnesium wheels will save the environment 948 kg CO_2e emissions, nearly one metric ton. With a wider range of end-of-life recycling, the magnesium road wheel has the potential for even greater carbon savings.

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