



# Laser Cladding Treatment for Refurbishing Disc Brake Rotors: Environmental and Tribological Analysis

Ulf Olofsson<sup>1</sup> · Yezhe Lyu<sup>1</sup> · Anna Hedlund Åström<sup>1</sup> · Jens Wahlström<sup>1,3</sup> · Senad Dizdar<sup>1</sup> · Ana Paula Gomes Nogueira<sup>2</sup> · Stefano Gialanella<sup>2</sup>

Received: 24 January 2021 / Accepted: 13 March 2021  
© The Author(s) 2021

## Abstract

In this study, grey cast iron disc brake rotors are refurbished by adding a surface layer through laser cladding. Current methods to deal with replaced rotors mainly include remelting, with a minority fraction disposed in landfill. Both approaches result in a huge waste of resources and an increase in CO<sub>2</sub> footprint. From a sustainable point of view, this study aims to evaluate the feasibility of refurbishing brake rotors by a combined environmental and tribological performance approach. A streamlined life cycle assessment is conducted to compare the environmental impacts between producing virgin grey cast iron brake rotors and refurbishing replaced brake rotors by laser cladding. It turns out that the energy consumption and CO<sub>2</sub> footprint of the laser cladding refurbished brake rotors are 80% and 90% less than the virgin brake rotors. The results show that the refurbished brake rotor yields higher friction compared to the original cast iron utilizing the same pad material. The wear and particle emissions of the disc brake contact are in this study higher for the laser-cladded one compared to the original cast iron one.

**Keywords** Disc brake · Laser clad rotor · LCA · Friction · Wear · Particle emission

## 1 Introduction

Disc brake systems are widely used on road, rail and aviation vehicles. For road and rail vehicles, the rotors are mainly manufactured through a casting process using grey cast iron (GCI) [1]. The current routes to manage exhaust brake rotors include remelting them primarily, with only a minority fraction disposed in landfill. Both approaches result in a huge waste of energy resources and an increase in the CO<sub>2</sub> footprint. Another main environmental concern regarding disc brakes arises from their airborne wear particles, contributing to particulate matter (PM) environmental emissions. The PM generated from the transport sector altogether sum up to 50% by mass of the total ones [2, 3] and its relative contribution is

expected to increase due to the legislation driven reduction of aerosols from vehicle combustion processes [4]. A recent overview of the field of disc brake PM emissions and a holistic approach of reducing them by 50% is presented in [5]. In this paper, the effective contribution to reducing PM emission was demonstrated to be provided by a standard hardening heat treatment of the disc. As alternative approaches, the use of wear resistant coatings and surface treatment by a nitriding process were explored [6]. Hardmetal systems, like CoCr [7], Cr<sub>3</sub>C<sub>2</sub>-NiCr and WC-CoCr [8], carbide and oxide based coatings [9] have been deposited onto cast iron using high-velocity oxygen fuel (HVOF) techniques and tribologically tested. The results have highlighted the importance of an appropriate tuning of the surface roughness and relevant skewness, not to have an excessive wear rate of the counterface brake pad friction material [7]. Still to improve the tribological performances of cast iron brake discs, thermal spraying has been used for depositing: NiCrBSi-based [10] Ni-17Cr-2.5Fe-2.5Si-2.5B-0.15C (Metco), Fe-30Mo-2C (Diamalloy), Co-30Cr-12W-2.4C (Stellite), and Zn-50SiC (Zn-SiC) coatings [11]. Furthermore, the tribology and emission performance for lightweight AlSiC metal matrix composite (MMC) rotors were studied [12]. It was found

✉ Anna Hedlund Åström  
aha@kth.se

<sup>1</sup> Department of Machine Design, KTH Royal Institute of Technology, Stockholm, Sweden

<sup>2</sup> Department of Industrial Engineering, University of Trento, Trento, Italy

<sup>3</sup> Department of Mechanical Engineering, Lund University, Lund, Sweden

that worn pad material was transferred to the brake rotor surface, forming a protective third body tribo-layer, resulting in a negative specific wear rate of the brake disc. Another challenge for mechanical disc brakes in a future electrified car fleet is the GCI rotors low corrosion resistance when exposed to atmospheric humidity and road salt. Corrosion can shorten the useful service life and lower the braking performance of mechanical disc brakes because of the porous and easily detached red oxide layers on the braking surfaces [13]. Laser cladding [14] is an overlay welding technique suitable for depositing coatings onto GCI rotors in disc brakes. It affords weld deposits with metallurgical bonding to the base metal and low thermal deformation of the weld blank [15]. In a recent study [16], disc brake rotors laser-cladded with a powder mix of Ni-self fluxing alloy + 60% spheroidized fused tungsten carbide were evaluated for their tribological and PM emission behaviour. The laser-cladded rotors, in comparison to the reference GCI counterparts, achieve halved mass loss and the particle number concentration (PNC) decreases from over 100 to some 70 (1/cm<sup>3</sup>). Moreover, the fraction of particles below 7 µm is approximately halved. One drawback with this powder alloy is that it contains large percentage of conflict and critical elements, such as W and hazardous classified materials, such as Ni [17]. Another possible candidate as welding consumable are stainless steel powder alloys [18]. This sort of powder alloy opens for wear and corrosion resistant hard faces for disc brake rotors, with the important advantage of being principally free from conflict, critical and hazardous materials [17].

From a sustainable point of view, this study aims to evaluate the feasibility of refurbishing GCI disc brake rotors with laser cladding using a stainless steel powder. A combined environmental and tribological performance approach is used in the evaluation of its performance in relation to

standard GCI disc brake rotors. A streamlined life cycle assessment ranking CO<sub>2</sub> footprint and energy consumption is utilized in comparison to the friction, wear and PM emission behaviour of the disc brake materials.

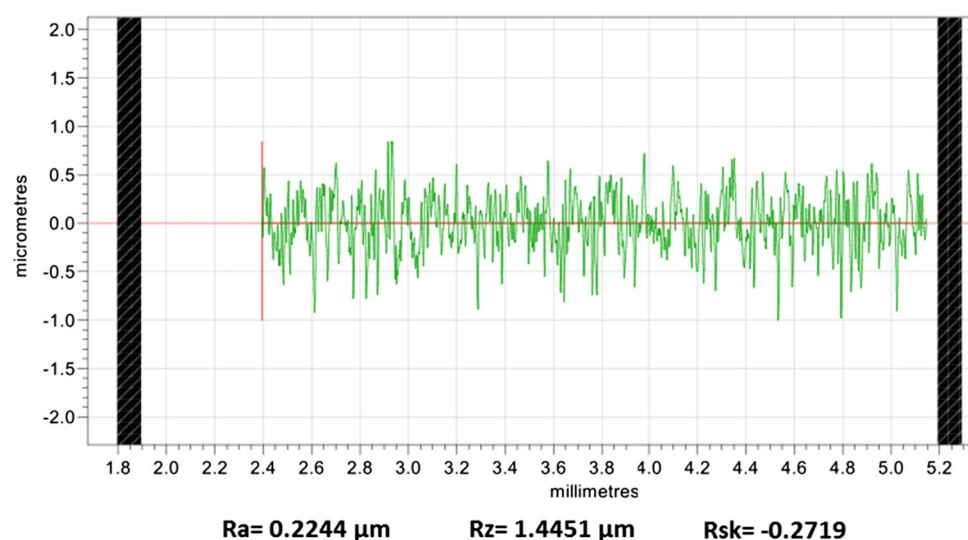
## 2 Experimental Setup

### 2.1 Cladding Process of Rotor

A batch of GCI discs is laser-cladded using a 7 kW fibre-coupled diode laser (Laserline LDF 7000-40). This laser has a high beam quality expressed as 44 mm\*mrad allowing the laser beam to be transported by a process fibre, as small as 400 µm in diameter, to the processing laser head. When reaching the target surface, it will have a quasi-uniform energy distribution within 2 mm diameter of circular laser spot. The metal powder was injected into the process zone by a coaxial powder nozzle (Three-jet, Fraunhofer ILT) allowing a stand-off distance of 16–17 mm. For the present test discs, the following parameters were used: laser spot ø3 mm, laser power 950 W, weld bead overlaps 50%, laser head travel speed 8 mm/s and powder feed rate 7 g/min. The combination of the laser cladding parameters is chosen to minimize the heat entering the 6-mm-thick disc substrate and relevant temperature raise. Neither preheating nor annealing are performed on the test discs. The cladded discs are then super-abrasively ground with a vertical axis grinding machine (Göckel G50elT) with 6A2-type 126-FEPA grit CBN grinding wheel. Figure 1 shows the roughness profile achieved after the grinding step on the surface of the coating with average roughness  $R_a$  of 0.2 µm.

The as-ground cladding surface reached 55 HRC in hardness and, as expected, 5% iron dilution, evaluated by an XRF-hand held analyzer (Thermo Scientific Niton XL3t

**Fig. 1** Roughness of the laser-cladded disc, after the post deposition mechanical grinding



GOLDD + XRF Analyzer), having  $\varnothing 8$  mm analysis spot and 50 kV energy range. The metal powder consumable is Rockit 401, a martensitic stainless steel powder (Höganäs AB), with sieve cut of 53–150  $\mu\text{m}$ .

## 2.2 Tribological Experiment

### 2.2.1 Pre-tests

The pre-tests are designed so that all contact combinations had the same tangential force. This is done to enable direct comparison of the measured wear and particle emission from different material combinations. If the tangential force differs in the full application, the real brake system will apply a higher normal load on the pads to compensate for the lower coefficient of friction (CoF), which might result in an increase of wear and particle emissions. In the pre-tests, the laser-cladded disc exhibited a larger CoF than the uncoated cast iron disc. Accordingly, the normal load for the laser-cladded disc is set to 25% lower than that for the GCI disc to reach an equivalent tangential force, i.e. laser-cladded disc (0.45 MPa) and GCI (0.6 MPa). This normal load lowering is assumed not to significantly affect the wear mechanisms. The sliding speed for each test run is 2 m/s and the duration is 2 h. For each contact combinations four repetitions are performed.

### 2.2.2 Pin-on-Disc Tests

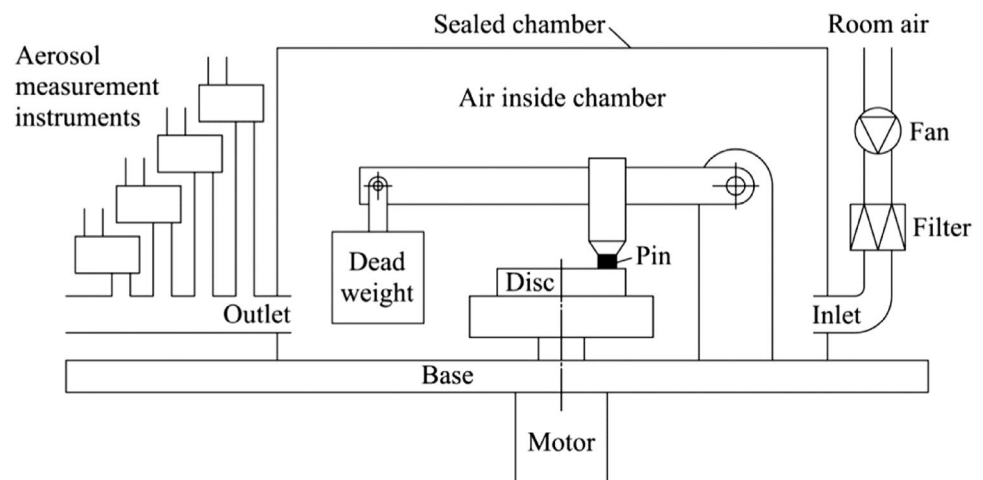
A pin-on-disc (PoD) tribometer, especially designed for studying both the tribological properties as well as airborne particles generated from tribological contacts [19], was used in this study, see Fig. 2. In this setup, the disc sample is mounted horizontally and rotated by an electrical motor. The pin is held vertically by a pin holder, applying normal loads on the disc through dead weights. The PoD test rig is enclosed in a clean sealed chamber, ensuring that

the counted and captured airborne particles are all emitted from the brake wear process. Room air is pumped through a HEPA filter (class H13 EN 1822 with a particle collection efficiency of 99.95%) by a unidirectional fan. In such a way, the air flowing into the clean chamber is particle-free. The air is well mixed inside the chamber due to the complex volume of the PoD tribometer and subsequently transports the generated airborne particles to the air outlet.

A TSI® optical particle sizer (OPS) Model 3330 is set at the outlet to measure the PNC and size distribution in the particle size range 0.3–10  $\mu\text{m}$ . A DEKATI® PM10 impactor is used to collect generated airborne particles on three particle sizes, i.e. PM10, PM2.5 and PM1, for microscopic observation. The coefficient of friction (CoF) in the pin-disc contact is indirectly evaluated by measuring the tangential force with a HBM® Z6FC3/20 kg load cell. The pin and disc mass losses due to wear are measured with a Sartorius® ME614S analytical balance. The cross-sectional microstructure of the pins, collected with PM10 impactor airborne particles and worn surfaces of the tested samples, both pins and discs, are observed with scanning electron microscope (SEM, Jeol – IT300LV) equipped with an energy dispersive X-ray spectroscopy, EDXS (Bruker Quantax EDS with XFlash 1050 detector).

The tested coating is laser-cladded onto a cast iron substrate using a stainless steel powder (Höganäs Rockit 401). A commercial GCI brake rotor material, with hardness of about 20 HRC, is used as a reference for comparing the tribological and particle emission performances. The laser-cladded material and GCI rotor are manufactured into disc sample blanks ( $\varnothing 100$  mm 6 mm) to fit into the PoD tribometer. A commercial low metallic, copper containing, brake pad material is used to manufacture the cylinder-like pin specimens ( $\varnothing 10$  mm 20 mm) to test as the counterpart. Chemical composition obtained with EDXS analysis and surface condition of the laser-cladded coating, GCI rotor and brake pad are listed in Table 1.

**Fig. 2** Schematic of the PoD tribometer inside a clean sealed chamber with airborne particle sampling instruments [20]



**Table 1** Chemical composition and surface condition of the tested materials

	Element (wt%)										Surface condition
	C	Cr	Ni	Mo	Si	Mn	Fe	Cu	O	Other	
Laser cladding overlay, Rockit 401	0.13	18	2.5	0.5	–	–	Bal	–	–	–	$R_a=0.25\text{ }\mu\text{m}$
GCI rotor	3.8	–	–	–	1.8	0.65	Bal	–	–	–	$R_a=0.31\text{ }\mu\text{m}$
Brake pad-pin	N/A	1.5	–	–	3.7	–	13.1	12.1	30.9	Bal	Scorched

## 2.3 Life Cycle Assessment

The life cycle assessment (LCA) methodology according to the ISO 14040:2006 standard [21] is used to analyse the environmental impact of the disc brake rotors. The method includes four steps: goal and scope definition, inventory analysis, impact assessment and interpretation [22].

The aim in this streamlined LCA study is to compare the standard manufacturing process of disc brake rotors, from casting raw materials with the following two different scenarios:

1. Standard cast iron rotor using remelted scrap GCI rotor material
2. Reused cast iron rotor refurbished with laser-cladded stainless steel based powder mix

The LCA program used in this study is the Eco Audit Tool, included in the material selection tool CES EduPack from Granta Design [23], containing a database with around 4000 materials. In this framework, the impacts analysed are energy consumption and CO<sub>2</sub> footprint. A cradle-to-grave perspective is used including the following parts of the life cycle: material, manufacture, transport and disposal. Transports included are truck transports from rotor manufacturer to surface treatment workshop and, eventually, to car manufacturer. The disc use stage is not included, whereas also a part of a future life cycle is included, presented as an end-of-life potential. This is the potential gain/loss of impact

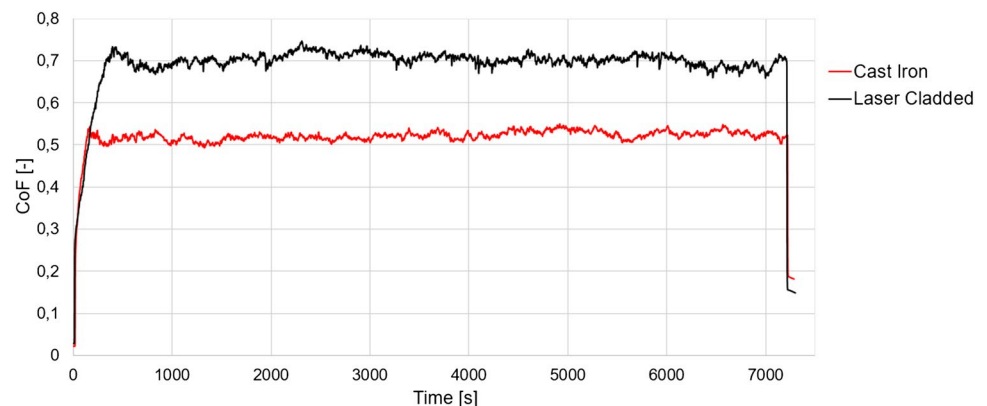
depending on the disposal procedure. The disposal for all scenarios is recycling, although the amount of recycled material differs depending on the manufacturing method. After casting of the rotor, a further surface finishing treatment is usually conducted by coarse and, eventually, fine grinding. This corresponds to 45% of material removal. Thereby the disposal of this material is also included in the recycling calculations.

## 3 Results

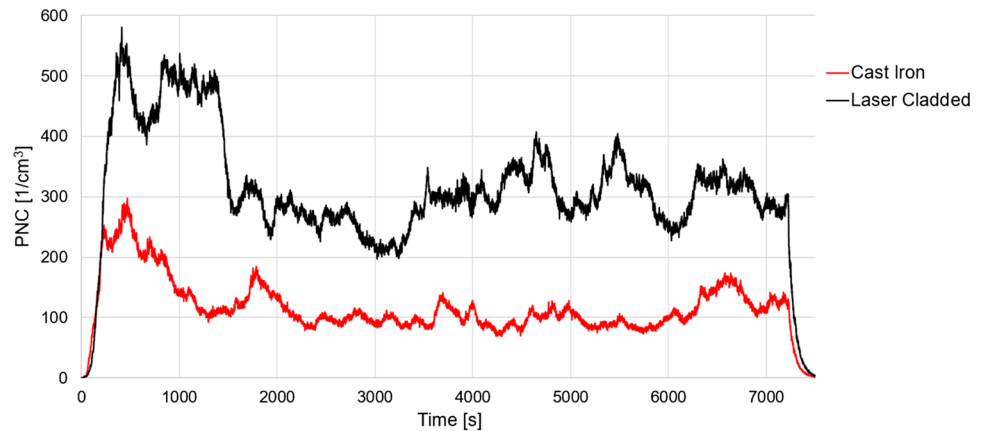
### 3.1 Tribological and Emission Issues

Typical graphs of the CoF and PNC for the GCI and laser-cladded GCI discs are shown in Fig. 3 and 4, respectively. Table 2 presents the mean and standard deviation for the measured CoF and PNC after running-in (i.e. between 2000 and 7200 s), and the wear of the discs and pins in terms of weight loss for the tested GCI and laser-cladded GCI discs. It can be noted that the CoF is higher for the test couples using laser-cladded rather than GCI rotors, and the same is applicable to the pin and disc wear and number concentration. In Fig. 5, the typical mean particle size distributions for the GCI and the laser-cladded GCI rotors as measured by the OPS after running-in are presented. Both conditions show a maximum in the size range from 0.4 to 0.6  $\mu\text{m}$ .

Figure 6 shows the SEM micrographs of the wear tracks on the GCI (Fig. 6a and b) and laser-cladded GCI (Fig. 6c

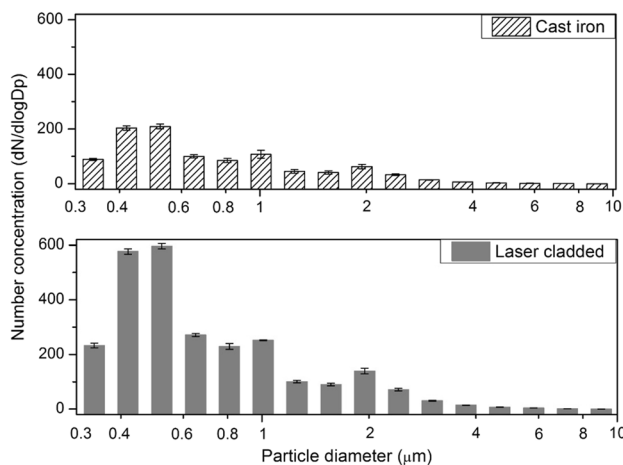
**Fig. 3** Characteristic CoF curves registered on testing the pins against the cast iron and laser-cladded discs

**Fig. 4** Characteristic PNC curves as registered in the cast iron and laser-cladded discs tests



**Table 2** Mean and standard deviation of the weight loss of the pins and discs, CoF and PNC for the two disc conditions

Disc type	Pin loss [mg]	Disc loss [mg]	CoF	PNC (1/cm <sup>3</sup> )
Cast iron	62 ± 2	58 ± 8	0.52 ± 0.01	130 ± 54
Laser-cladded	83 ± 6	105 ± 8	0.72 ± 0.01	299 ± 45



**Fig. 5** Mean normalized particle size distribution after running-in as measured by the OPS

and d) discs, at low and high magnification, after PoD tests. The tested discs show wear tracks with both relatively shallow and wide scars, due to plasticity-dominated wear, as well as narrow and sharp scars, due to abrasion. Material transfer is obvious (see the arrows), with patches of transferred material from the pin to the disc, which partially cover the wear track. From a comparison between the two disc surface conditions, i.e. laser-cladded and uncoated GCI, it turns out that this coverage is more pronounced in case of the cast iron disc. In fact, referring to

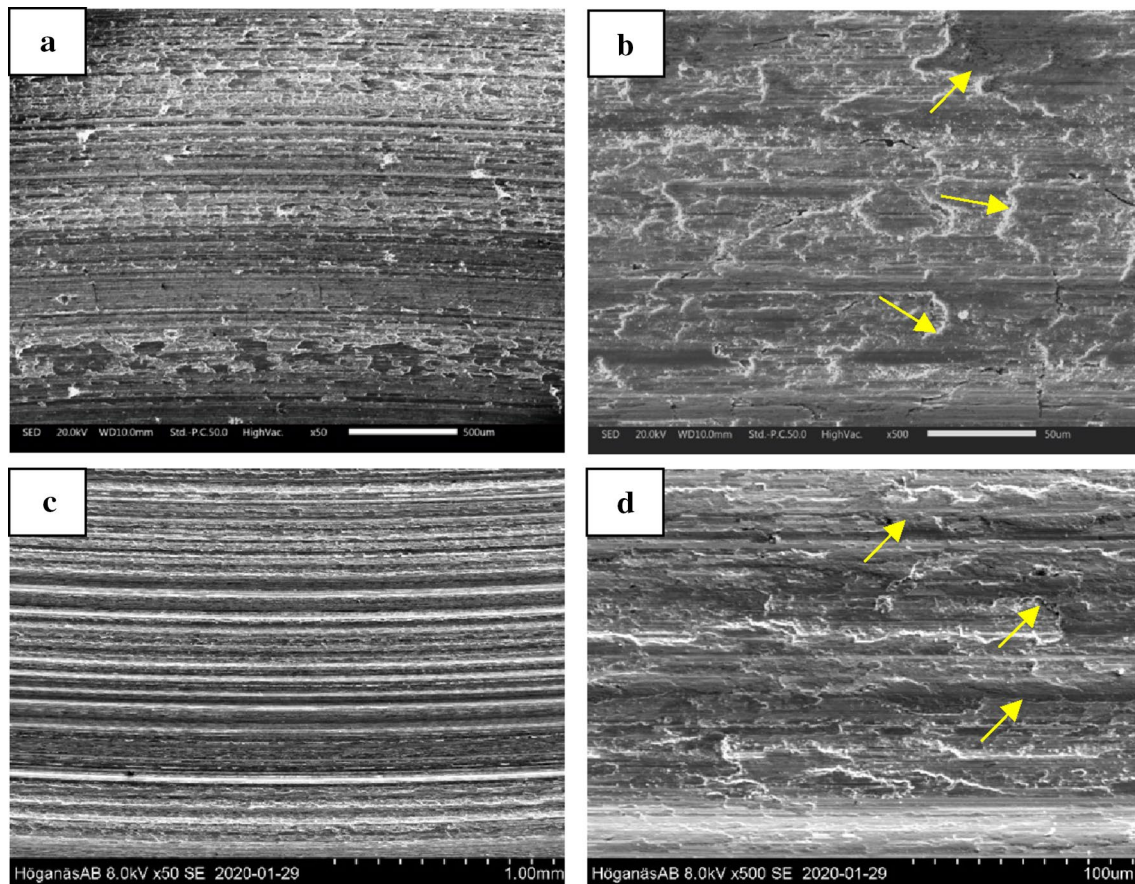
Fig. 6c, the ploughing effect deriving from the abrasive contribution to the overall tribological interaction is not so evident on this substrate disc as it is on the laser-cladded surface. The higher magnification micrographs of the disc surfaces (Fig. 6b and d) better show the more extensive material transfer from the friction material onto the disc surface.

The EDXS maps of the disc surface confirm the presence of transferred layers on the disc surface and also the lower coverage of the laser-cladded disc (see Fig. 7), as shown by those maps referring to the disc substrate element, mainly, like chromium and iron. In the relevant map for the laser-cladded sample, a larger fraction of the disc surface, than in case of the cast iron sample, results to be free from patches of friction material transfer layer, from which the oxygen, aluminium and sulphur X-ray signals are emitted.

Figures 8 and 9 show the SEM observations on the pins' worn surface, top and cross-sectional view, respectively. For both cast iron (a) and laser-cladded (b) conditions, a typical friction layer morphology is noticed, featuring primary plateaus, mainly constituted by the coarse iron fibres present in the friction materials, promoting the piling up and densification of wear debris, to form the so-called secondary plateaus.

The elemental compositions of the secondary plateaus obtained upon testing the pins against GCI and laser-cladded discs, as obtained from EDXS analysis, are listed in Table 3. The carbon content was not included in the evaluation. The results suggest the presence of elements from the laser-cladded coating, such Cr and Ni, in the secondary plateaus of the respective sample. It is also noticed the larger amount of Cu in the secondary plateaus of the pin tested using the laser-cladded rather than cast iron discs. The relatively higher concentration of copper, associated with a lower presence of iron, and chromium, from the laser-cladded layer, indicates that a low fraction of wear debris from the disc enter the secondary plateaus. This is not so in case of GCI discs, whose wear debris contribute more significantly to the building up of the secondary plateaus. In this case, a higher iron





**Fig. 6** SEM micrographs, acquired at two different magnifications, of the wear track on the GCI disc (**a** and **b**) and laser-cladded GCI disc (**c** and **d**). The arrows highlighted the transferred materials

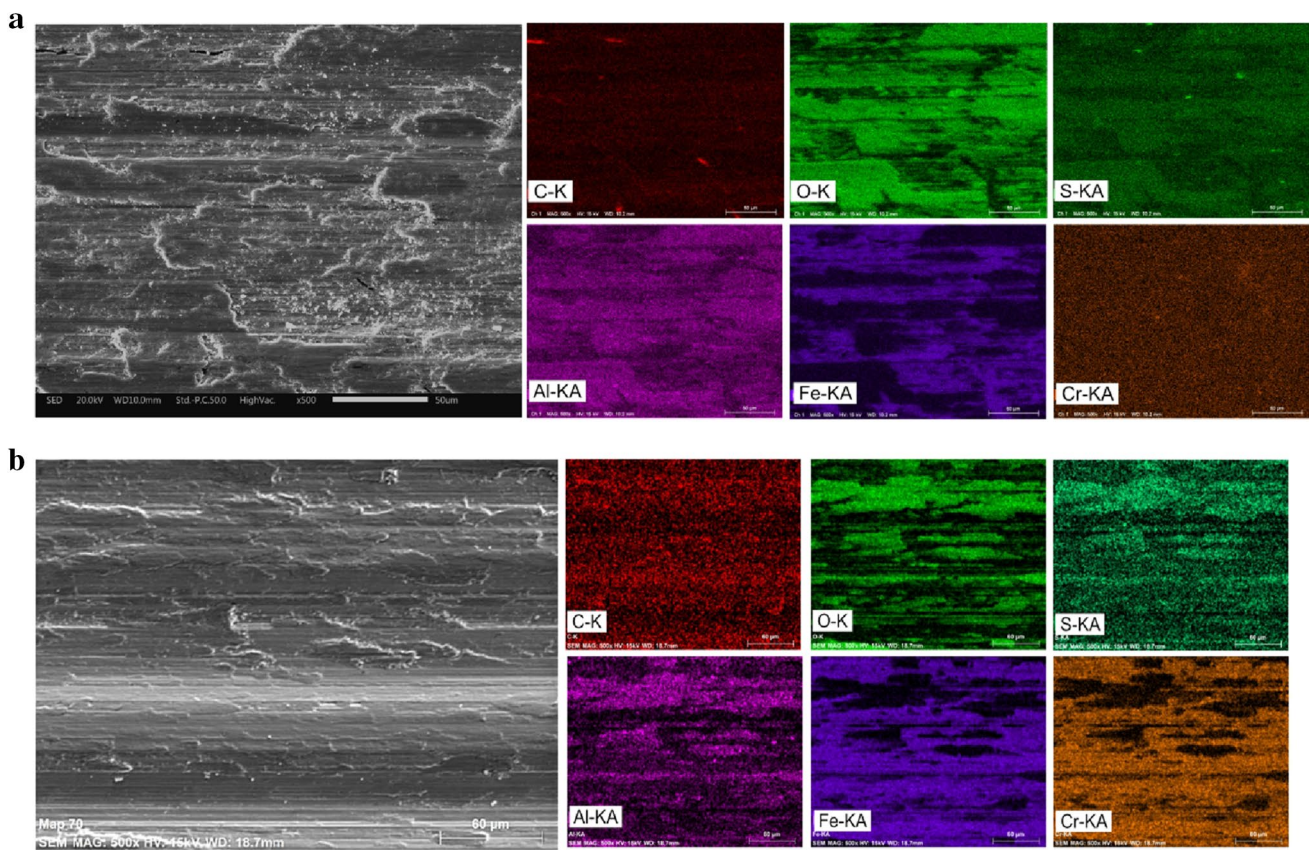
concentration is measured, in association with a lower copper content, see Table 3.

The PoD tests conducted in both conditions, i.e. using GCI and laser-cladded discs, produce debris rather heterogeneous in size and morphology, see Figs. 10 and 11, showing coarse plate-shaped and small rounded particles. The presence of plate-shaped particles can be ascribed to the fragmentation and detachment of the friction layer that forms during the tests on the pin surface.

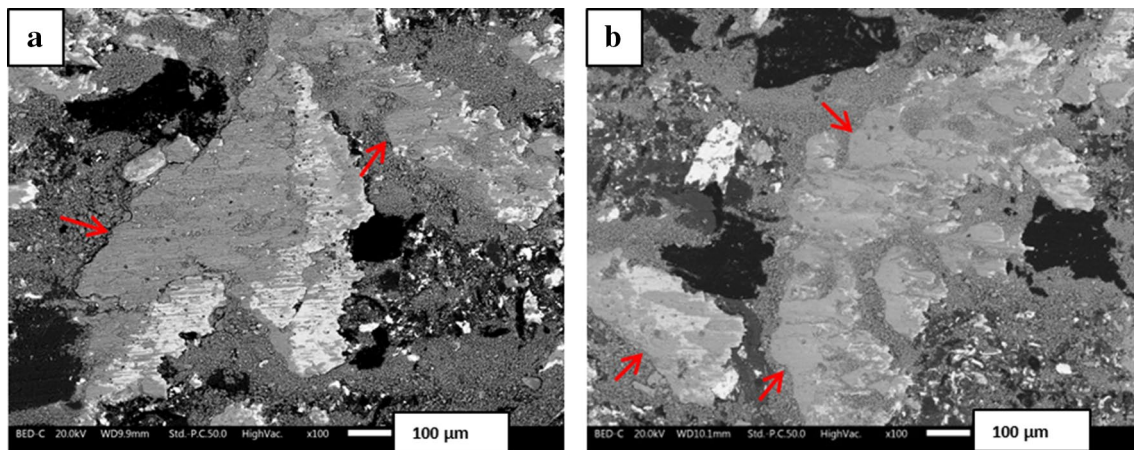
The elemental composition of the airborne particles is given in Table 4, without considering the carbon content. The compositional data confirm that the main contributions to the airborne wear debris, are a mix of fragments from the wearing out of the pin and oxidative wear of the disc. This latter contribution can be inferred from the high concentration of iron, present as oxide, which turns out to be the majority element in the collected airborne fragments, irrespective of the relevant aerodynamic diameters, i.e.  $PM_{10}$ ,  $PM_{2.5}$ , or  $PM_1$ . This is so also for the wear tests involving the laser-cladded discs. Iron in the airborne particles mainly comes from the coating, as demonstrated by the joint presence of chromium. Interesting to note the lower

concentration of copper in the airborne particles, as compared to its concentration in the pristine friction material, see Table 1, and in the secondary plateaus forming on the pin surface during the PoD tests, see Table 3. This confirms the role of copper [24–26], in formation of the friction layers on the mating surfaces. Moreover, it can be concluded that copper is preferentially emitted from the tribological system as large, non-airborne fragments coming from the disruption of the friction layer itself.

The analyses of the wear products indicate that the higher CoF observed with laser-cladded discs, see Fig. 3, is to be ascribed to the interplay of abrasive and adhesive wear, being this latter particularly important for average surface roughness  $R_a$  below  $1\ \mu\text{m}$ , as it is in the present case, see Fig. 1. The reduced amount of transfer layer observed on the surface of the laser-cladded disc after the tribological tests is coherent with this picture, since owing to a larger contact area that can be there between the pin and the disc itself. In the tribological couple involving GCI disc, a lower CoF can be related to the lower shear strength at the interface between the two mating surfaces, considering the larger coverage of the disc surfaces by the friction material from



**Fig. 7** SEM/EDXS analysis of the wear track of the **a** cast iron and, **b** laser-cladded test disc The SEM micrograph shows a detail of a wear track on the laser-cladded layer and the corresponding X-ray maps



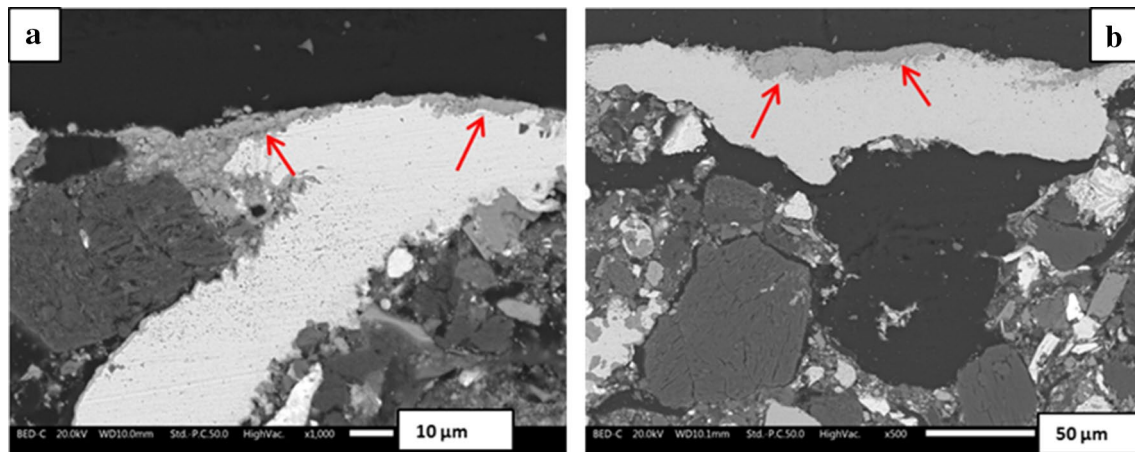
**Fig. 8** SEM micrographs showing the top view of the worn surfaces of the pins at the end of the PoD tests using: **a** GCI, **b** laser-cladded discs. The arrows indicate a portion of the secondary plateaus in the friction layer for each one of the samples

the pin. Another important indication regards the scarce tendency of the wear debris from the laser-cladded layer to enter the friction layer, this contributing to the higher airborne emission, see Fig. 5, particularly in the ultrafine range, i.e. particles with an aerodynamic diameter below 1 µm.

### 3.2 Life Cycle Assessment of the Proposed Reuse Approach

In Tables 5 and 6, the result of the streamlined LCA analysis is presented. Here at first, the comparison between standard





**Fig. 9** SEM micrographs showing the cross-sectional view of the pins at the end of the PoD tests using: **a** cast iron, **b** laser-cladded discs. The arrows indicate regions of the secondary plateaus present in the relevant friction layers

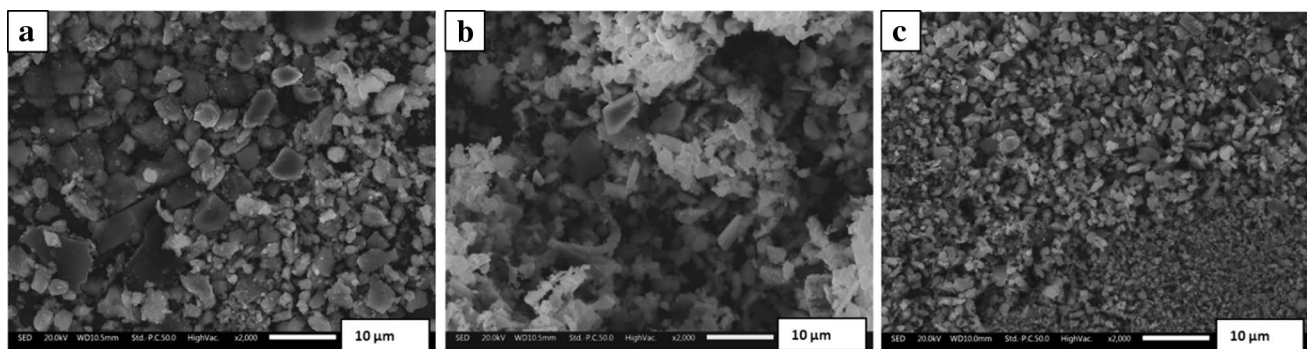
**Table 3** Elemental compositions of the secondary plateau forming on the worn surfaces of the pin samples

	Cast iron	Laser cladding
O	$9.8 \pm 0.1$	$9.8 \pm 0.5$
Mg	$2.7 \pm 0.3$	$2.1 \pm 0.1$
Al	$2.6 \pm 0.4$	$2.0 \pm 0.2$
Si	$2.8 \pm 0.8$	$1.3 \pm 0.1$
S	$2.6 \pm 0.2$	$2.1 \pm 0.1$
Ca	$1.7 \pm 0.3$	$1.4 \pm 0.1$
Cr	$1.2 \pm 0.1$	$9.0 \pm 1.8$
Fe	$50.9 \pm 1.5$	$36.2 \pm 0.8$
Ni	—	$0.8 \pm 0.3$
Cu	$13.3 \pm 0.1$	$26.0 \pm 3.2$
Zn	$7.3 \pm 0.2$	$5.3 \pm 0.5$
Sn	$4.6 \pm 0.6$	$3.9 \pm 0.1$

disc and remelted disc shows a clear decrease in both CO<sub>2</sub> footprint and energy consumption with around 23% in total. By remelting the disc, less raw material extraction is needed and thereby recourses are saved.

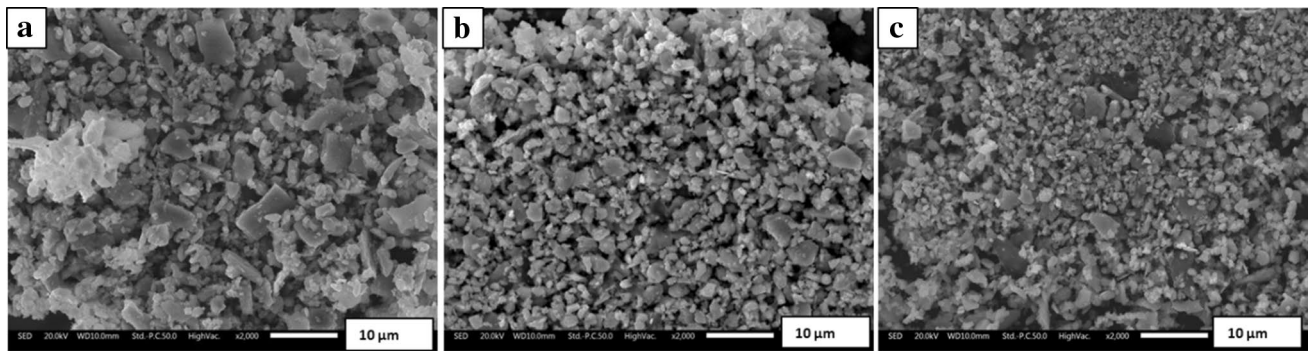
Then comparing reuse of the disc adding laser-cladded disc with standard disc, here the savings are even larger with 56% for CO<sub>2</sub> footprint and 61% in energy consumption. This is explained by less resources needed for both material extraction and manufacturing of the disc.

Studying the end-of-life potential of the discs, all three scenarios show possible savings of energy and CO<sub>2</sub> footprint for the following life cycle, indicated by the negative sign. The higher absolute end-of-life potential value for the laser-cladded disc is connected to the reuse of the disc. Reuse compared to recycling is preferred if possible from an environmental point of view, because of less processing resulting in both decreased energy consumption and CO<sub>2</sub> footprint. Therefore reuse is higher in ranking compared to recycling in the waste management hierarchy, in accordance to EUs Waste Framework Directive, Directive 2008/98/EC on waste.



**Fig. 10** SEM micrographs of the airborne particles PM10 (a), PM2.5 (b) and PM1 (c), collected during PoD tests involving cast iron disc





**Fig. 11** SEM micrographs of the airborne particles PM10 (a), PM2.5 (b) and PM1 (c), collected during PoD tests involving laser-cladded discs

**Table 4** EDXS evaluated elemental composition of airborne particles obtained from the PoD tests

	GCI			Laser-cladded		
	PM10	PM2.5	PM1	PM10	PM2.5	PM1
O	$7.3 \pm 1.6$	$12.6 \pm 0.9$	$8.5 \pm 2.2$	$6.0 \pm 2.2$	$5.1 \pm 2.9$	$10.6 \pm 3.0$
Mg	$2.5 \pm 0.2$	$3.2 \pm 0.5$	$2.3 \pm 0.5$	$1.5 \pm 0.6$	$1.2 \pm 0.5$	$2.4 \pm 0.6$
Al	$2.6 \pm 0.4$	$3.5 \pm 0.1$	$3.1 \pm 0.3$	$2.3 \pm 0.4$	$2.2 \pm 0.0$	$2-3 \pm 0.6$
Si	$2.4 \pm 0.3$	$3.5 \pm 0.5$	$3.4 \pm 0.3$	$1.8 \pm 0.5$	$1.2 \pm 0.2$	$2.0 \pm 0.4$
S	$2.4 \pm 0.1$	$2.5 \pm 0.3$	$2.5 \pm 0.1$	$1.9 \pm 0.6$	$2.2 \pm 0.7$	$2.0 \pm 0.2$
K	$0.1 \pm 0.0$	$0.2 \pm 0.0$	$0.2 \pm 0.1$	—	—	—
Ca	$1.4 \pm 0.1$	$1.7 \pm 0.2$	$2.0 \pm 0.2$	$1.5 \pm 0.4$	$1.3 \pm 0.1$	$1.2 \pm 0.1$
Cr	$0.9 \pm 0.1$	$0.9 \pm 0.1$	$1.0 \pm 0.2$	$13.4 \pm 2.6$	$11.8 \pm 0.2$	$10.9 \pm 0.4$
Mn	$0.2 \pm 0.1$	—	—	—	—	—
Fe	$63.7 \pm 1.5$	$56.2 \pm 1.6$	$61.2 \pm 1.9$	$57.0 \pm 1.7$	$59.4 \pm 3.1$	$54.0 \pm 1.9$
Ni	—	—	—	$0.4 \pm 0.1$	$1.2 \pm 0.3$	$1.4 \pm 0.1$
Cu	$6.4 \pm 0.9$	$6.4 \pm 0.2$	$6.6 \pm 0.3$	$6.1 \pm 1.2$	$5.5 \pm 0.1$	$5.1 \pm 0.3$
Zn	$5.7 \pm 0.3$	$5.6 \pm 0.5$	$5.4 \pm 0.1$	$4.9 \pm 0.3$	$5.0 \pm 0.2$	$5.2 \pm 0.3$
Sn	$4.0 \pm 0.3$	$3.8 \pm 0.1$	$3.9 \pm 0.2$	$3.4 \pm 0.3$	$3.7 \pm 0.6$	$2.8 \pm 0.4$

**Table 5** CO<sub>2</sub> footprint comparing standard disc with remelted and laser-cladded ones

	CO <sub>2</sub> footprint (kg)				Total	End-of-life potential
	Material	Manufacturing	Transport	Disposal		
Standard disc	20.8	20.3	2.3	0.4	43.8	— 8.6
Remelted disc	10.6	20.3	2.4	0.4	33.7	— 8.6
Laser-cladded disc	9.4	7.4	1.9	0.4	19.1	— 17.3

**Table 6** Energy consumption comparing standard disc with remelted and laser-cladded ones

	Energy (MJ)				Total	End-of-life potential
	Material	Manufacturing	Transport	Disposal		
Standard disc	273.1	275.2	34.1	5.0	587.4	— 112.6
Remelted disc	138.8	275.2	34.1	5.0	453.1	— 112.6
Laser-cladded disc	179.7	16.3	27.2	5.6	228.2	— 138.3

## 4 Discussion

The present research has demonstrated the potential of a laser cladding based approach in the reuse of brake discs, as clearly assessed by the results from the streamlined LCA. The main improvement of the value chain resides in the manufacturing phase. Laser cladding with stainless steel powders provided more than 50% savings in both energy consumption and CO<sub>2</sub> footprint respectively, compared with standard disc. By adding a new surface layer, as investigated herewith, the disc can be used over and over, by repeating the surface treatment several times, thus prolonging the disc lifetime. Then the perspective is changed, from linear to circular, for the next life cycle and the end-of-life potential can be included in the calculations. Closing the loop results in 80% savings in energy consumption and 90% in CO<sub>2</sub> footprint decrease.

Moreover, comparing standard disc with recycling of disc in the LCA model, an important decrease in energy consumption and CO<sub>2</sub> footprint using 100% recycled material during the material extraction phase can be inferred. This can be compared with results from the ECOPADS project, in which a similar study using the streamlined LCA method was carried out for brake pads [27, 28], in view of possible recycling strategies. By recycling brake pads 40% in energy savings and 30% in CO<sub>2</sub> footprint savings were estimated.

The tribological performances indicate the importance of refining the surface conditions of the coated rotors, with a mechanical rectifying treatment which should follow the deposition. This post-processing step is meant to tune the rotor surface roughness in order to reduce the CoF and, consequently, the emission rate of wear particles. These two parameters turn out to be definitely worse when using a laser-cladded rather than a cast iron disc. On the other hand, an excessive smoothness of the rectified laser-cladded disc surface seems to enhance the adhesive wear contributions, through the increase of the CoF. Still concerning the laser-cladded coating, another issue to consider is its composition. It should be optimized so to have a positive contribution to the formation of an effective friction layer, in terms of brake performances and PM emission. In this regard, the low tribo-oxidation tendency of the coating used in the present study can be taken as an additional reason for the relatively higher PM emission rate, as compared to the GCI uncoated disc. Indeed, the fragments produced by adhesive wear detachment from the coating surface, enter in a comparatively lower fraction the friction layer, while become directly airborne. The brake pad material in this study is of low metallic type with the composition developed many years ago to suit GCI brake disc rotors. As the test results suggest, laser-cladded

stainless steel coating should need a more suitable brake pad material composition to lower the friction coefficient and improve formation of the low-shear friction layer. A first idea might be to consider different amount and type of solid lubricants but also metallic, iron partition. However, it is for sure a more complex task.

The improvement of the emission behaviour of the reused disc would trigger the investigation of environmental effects using a full LCA approach, including particulate emissions and health effects. Eventually, for a complete assessment of the proposed technology the use phase is of interest, since the life length might be different with the added laser cladding coating. In the EU project Lowbrasy, [29], a full life cycle LCA study was carried out, comparing two disc brakes. The aim was to compare a new low PM emission disc brake and a reference disc brake over the complete life cycle. The use phase was assessed with different number of spare parts for both disc and brake pads as well as differences in weight. Worth mentioning here is that the new disc was thermally spray coated with a carbide-based powder. Moreover, the material mix of the two brake pads was different. The result showed that the new disc brake had limited environmental advantages, partly explained by the increased resource use for coating of the new disc.

## 5 Conclusions

In the present study, the potential of reusing brake discs has been demonstrated as concerns the energy and environmental impacts, as indicated from the LCA results. The proposed approach can be regarded as a realistic alternative to electric-arc furnace remelting and landfill disposal of these components at the end of their life.

The tribological results have shown the critical aspects to be solved, concerning the selection of a coating material, and development of a more suitable brake pad material to contribute to the formation of stable friction layers, lower friction coefficient and lower PM emission rate. Surface finishing, through a post-processing mechanical finishing treatment, is another important aspect of the proposed approach. An optimum surface finishing is of course paramount, to be tailored as a satisfactory trade-off between abrasive and adhesive wear relevant to an optimal duration of the useful lifetime of the components.

**Acknowledgements** This research has been carried out within the EIT Raw Materials projects: ECOPADS (Eliminating Copper from brake PADS & recycling—no. 17182) and ECODISCS (Environmentally Compatible reuse of brake DISCS – no. 18391). Part of the SEM analysis has been performed at Höganäs AB, which is gratefully acknowledged.

**Funding** Open access funding provided by Royal Institute of Technology.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Maluf, O., Angeloni, M., Milan, M., Spinelli, T., Filho, W.: Development of materials for automotive disc brakes. *Minerva* **4–2**, 149–158 (2007)
- Grigoratos, T.: Brake wear particle emissions: a review. *Environ. Sci. Pollut. Res.* **22**, 2491–2504 (2015)
- Hak, C., Larssen, S., Randall, S., Guerreiro, C., Denby, B., Horálek, J.: Traffic and air quality contribution of traffic to urban air quality in European Cities. European Topic Centre on Air and Climate Change Mitigation, Technical Paper 2009/12 (2012)
- European Commission. Directive 2008/50/EC on ambient air quality and cleaner air for Europe. Off J Eur Union (2008)
- Perricone, G., Matějka, V., Alemani, M., Valota, G., Bonfanti, A., Ciotti, A., Olofsson, U., Söderberg, A., Wahlström, J., Nosko, O., Straffelini, G., Gialanella, S., Metinoz, I.: A concept for reducing PM10 emissions for car brakes by 50%. *Wear* **396**, 135–145 (2018)
- Wahlström, J., Lyu, Y., Matejka, V., Söderberg, A.: A pin-on-disc tribometer study of disc brake contact pairs with respect to wear and airborne particle emissions. *Wear* **384–385**, 124–130 (2017)
- Federici, M., Menapace, C., Moscatelli, A., Gialanella, S., Straffelini, G.: Effect of roughness on the wear behavior of HVOF coatings dry sliding against a friction material. *Wear* **368–369**, 326–334 (2016)
- Federici, M., Menapace, C., Moscatelli, A., Gialanella, S., Straffelini, G.: Pin-on-disc study of a friction material dry sliding against HVOF coated discs at room temperature and 300 °C. *Tribol. Int.* **115**, 89–99 (2017)
- Demir, A., Samur, R., Kiliçaslan, I.: Investigation of the coatings applied onto brake discs on disc-brake pad pair. *Metalurgija* **48**, 161–166 (2009)
- Guney, B., Mutlu, İ., Kuçuksarıyidiz, H.: The effect of flame spray coating on the tribological properties of brake disc. *J. Polytech.* **23**, 755–761 (2020)
- Stanford, M.K., Jain, V.K.: Friction and wear characteristics of hard coatings. *Wear* **251**, 990–996 (2001)
- Lyu, Y., Wahlström, J., Tu, M., Olofsson, U.: A friction, wear and emission tribometer study of non-asbestos organic pins sliding against alsic mmc discs. *Tribol. Ind.* **40**, 274–282 (2018)
- Djafri, M., Bouchetara, M., Busch, C., Weber, S.: Effects of humidity and corrosion on the tribological behaviour of the brake disc materials. *Wear* **321**, 8–15 (2014)
- Toyserkani, E., Khajepour, A., Corbin, S.: *Laser Cladding*. CRC Press, Boca Raton, FL (2005)
- Davis, J.R. (ed.): *Surface Engineering for Corrosion and Wear Resistance*. ASM Int, Materials Park, OH (2001)
- Dizdar, S., Lyu, Y., Lampa, C., Olofsson, U.: Grey cast iron brake discs laser clad with nickel-tungsten carbide—friction, wear and airborne wear particle emission. *Atmosphere* **11**(6), 621, 2–14 (2020)
- European commission. Critical raw materials. Available at [https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical\\_en](https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en). Search in 03/11/2020.
- European committee for standardization – CEN. EN 14700 Welding consumables—welding consumables for hard facing. Brussels (2014)
- Olofsson, U., Olander, L., Jansson, A.: A study of airborne wear particles generated from a sliding contact. *J. Tribol.* **131**(4), 1–4 (2009)
- Nosko, O., Olofsson, U.: Effective density of airborne wear particles from car brake materials. *J. Aerosol Sci.* **107**, 94–106 (2017)
- ISO. ISO 14040:2006. Environmental management: life cycle assessment, principles and framework. International Organization for Standardization, Geneva (2006a)
- ISO. ISO 14044:2006. Environmental management—life cycle assessment—requirements and guidelines. Brussels (2006b)
- Ashby, M., Coulter, P., Ball, N., Bream, C.: The CES EduPack Eco Audit Tool—a white paper. Granta Material Inspiration, version 1.3, 1–18 (2009)
- Barros, L., Poletto, J., Neis, P., Ferreira, N.F., Pereira, C.: Influence of copper on automotive brake performance. *Wear* **426–427**, 741–749 (2019)
- Kumar, M., Bijwe, J.: Non-asbestos organic (NAO) friction composites: role of copper; its shape and amount. *Wear* **270**, 269–280 (2011)
- Nogueira, A.P.G., Bagolan, P., Leonardi, M., Gialanella, S., Straffelini, G.: The role of scorching treatment on the wear and emission of friction materials with and without copper. *Wear* **460–461**, 1–9 (2020)
- Jijie, M., Åström, A.H., Olofsson, U., Lyu, Y., Leonardi, M., Wahlström, J.: Eco Design of Brake Pads with Recycled Friction Materials. *Eurobrake-2019*, Dresden (2019)
- Lyu, Y., Ma, J., Åström, A.H., Wahlström, J., Olofsson, U.: Recycling of worn out brake pads—impact on tribology and environment. *Sci. Rep.* (2020). <https://doi.org/10.1038/s41598-020-65265-w>
- Gradin, K.T., Åström, A.H.: Comparative life cycle assessment of car disc brake systems—case study results and method discussion about comparative LCAs. *Int. J. Life Cycle Assess.* **25**, 350–362 (2019)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.