CENTS: Circular Economy Network+ in Transportation Systems

*Linking academic creativity and industry insight to **reduce the environmental burden of transportation systems across their lifecycle***

Rejuvenating Materials for Supporting Circular Economy

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Executive summary

Circular materials are at the core of sustainable transport in a green economy. Improvements to material productivity and reusability can help improve circularity by reducing extraction and enabling efficient fully recyclable vehicles. The quest for such circular materials is often framed as a choice among reuse, renew or recycle materials, which omits maintenance. Indeed, technology adoption for preventive materials therapies are very low and underexplored.

Although the discovery of novel materials can accelerate the transition of a linear into a circular economy, some transport industries are intrinsically reluctant changes. These industries must assure passengers safety and they often rely on years of experience for assuring fitness for purpose. For example, the aerospace industry is typically change-averse and would normally require long terms to adopt novel sustainable materials. Thus, rather than shifting into novel materials, these industries would benefit from applying accepted repairing techniques to heal preventively the potential damage on components.

This work explores the potential of novel "preventive maintenance of materials" and rank various techniques that can be used to extend the structural life of metallic components. We consider scientific data as well as industrial feedback to assess the ecofootprint and feasibility of techniques. The results identify those techniques can have the most circularity impact on transport industry. The findings also support future research in sustainable maintenance techniques.

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Introduction

A sustainable economy is the grand challenge of our century and requires replacing production with sufficiency in terms of economic activity. For instance, a linear economy needs to consider recycling and reuse of their resources to transition into circular models. However, rapid conversion into a circular economy depends on an accelerated pace of change that requires scientific innovation along with updating business practices and preconceptions. This is particularly difficult in risk-adverse applications that may injure humans, such as the transport industry. Catastrophic failure often occur due to the slow growth of fracture and fatigue cracks (Mouritz, 2012). However, these events only occur on rare occasions, which make them difficult to design against and validate. Thus, any approach that aims at improving the circular economy of such industries must take into consideration certification and trust of stakeholders.

Circular materials are one of the primary components of a sustainable economy with greener transport (OECD, 2015; Worrell et al., 2016). Improving material productivity and reusability can help improve circularity by minimizing the extraction of resources and enabling efficient engines in fully recyclable and lighter vehicles. The quest for such circular materials is often driven by novel “reusable, renewable and/or recyclable materials”. However, this quest omits “maintenance”, which corresponds to the circular economy activity with the lowest environmental footprint (Figure 1). Indeed technology readiness or adoption of preventive materials reparability and reuse are very low and underexplored (Raabe et al., 2019).

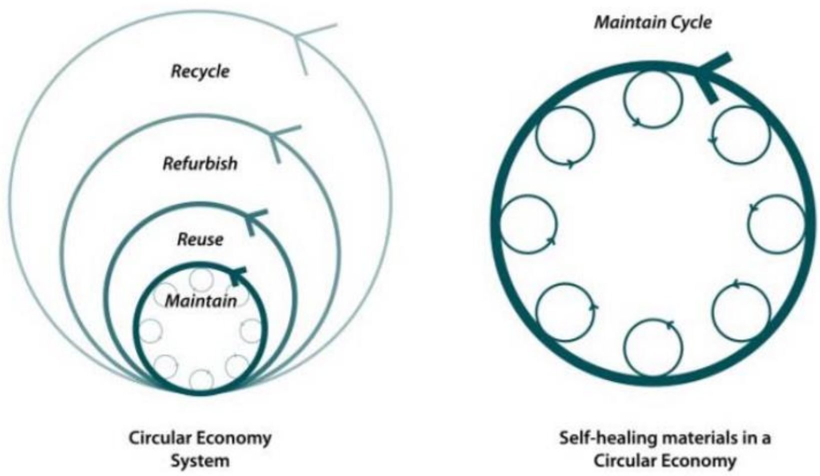


Figure 1: Circular economy system. Maintenance is the activity with the least impact.

An excellent example of a maintenance therapy for metallic materials in the context of structural integrity is the regular polishing of metallic materials. This practice, known for decades, prevents fatigue damage initiation and extends components lives by simply removing the crack embryos. We can also envision other practices related to thermal, mechanical or electrical treatment to hinder crack growth. However, it is unclear which of these practices have lower ecological footprint. To enhance the reusability of engineering components, we propose to maintain the materials during its service life, prior to scheduled repairs for known defects. Hence, in contrast to repairing, maintenance is not intended as an action to reverse known damage but as preventive healing performed at a convenient time that is economically convenient.

This objective of this project are as follows,

- List potential techniques that can be used to regularly to extend the fatigue life of metallic materials,
- Understand the compliance regarding reliability and airworthiness certifications that limit the extension of the fatigue life of airframes components,
- Rank most appropriate techniques and materials with their circularity impact.
- Make recommendations for further research.

The report starts with an introduction to various techniques that can rejuvenate metallic materials, followed by a description of the methodology used for quantifying their circularity. Next, we proceed to present an evaluation of the Eco footprints of materials and techniques by presenting various comparisons and case of studies. We conclude with a discussion and recommendation for future work.

Maintenance of Metallic Materials

The adaption of new circular approaches requires extreme care in applications that risk human lives such as the transport industry. This sector faces regularly failures due to slow growth of cracks under metal fatigue (Mouritz A.P., 2012). Myriads of techniques have been explored for repairing metallic materials and extend components service life. When coupled with appropriate materials design and service practices, periodic treatment of materials has the potential to become a cost-effective strategy for life extension. We start with a taxonomy of repairing treatments, classified in three main categories—coatings, mechanical and thermal— to indicate that a layer of added material, stresses or heat are conveyed into the material.

Coatings

Several efforts (Aouadi et al., 2020; Lim et al., 2019; Yuan et al., 2011) have proposed to deposit thin layers of non-metallic materials (i.e., organic, ceramic) as a means to shield the surface. Treatments such as oil barrier or epoxy coating, were shown to mitigate cracking in metals. For instance, oil-based coatings (Lim et al., 2019) are stable on several metal surfaces and present a good solution for preventive maintenance. However, these coatings have been evaluated under laboratory condition and require further efforts before certification for transport applications. Composite patching is another simple and localized surface treatments to strengthen the cracked member with fibre-reinforced polymers (Emdad and Al-Mahaidi, 2015; Mohammadi et al., 2020; Srilakshmi et al., 2015). This technique has already been commercialized and used widely for repairing cracks in the transport industry (Budhe et al., 2018).

A different approach with significant success has been to overlay a layer of metallic material. For example, laser metal deposition is an efficient technique that deposits metal on the substrate to close superficial damage (Graf et al., 2012; Petrat et al., 2016). This technique is used to repair damage in several engineering materials such as steel and Ti alloys (Capello et al., 2005; Leunda et al., 2011). Several researchers (Zheng et al., 2013a, 2013b) attempted enhancing the atomic mobility and diffusivity by means of electroplating to repair surface cracks in metallic materials. With the depletion of a healing agent at the crack surface, new finer and higher strengths grains are formed in areas with prior damage. This technique has been found efficient in healing cracks in several metals and alloys (Hasegawa et al., 2014; Isern, 2018; Lucci et al., 2008) and has ample potential for preventive maintenance.

Evidently, there are myriads of approaches that have been proposed on the literature. Hence, we proceed with a holistic approach seeking to find generalities that applied to the material deposited along with the demands of the deposition method.

Mechanical

Contrary to coatings, mechanical approaches remove or alter rather than adding material. Traditional mechanical techniques such as grinding (Fhwa, 2013; Nur et al., 2021; Rajemi, 2010; Sinha et al., 2019; Warsi et al., 2015) have been often used to remove material and rejuvenate surfaces. Several companies offer precision grinding for vehicle components such as airframe, landing gear, railways, etc. These companies already meet compliance of the Federal Aviation Administration (FAA) and other safety authorities. Other techniques such as laser shock peening (Kalentics et al., 2019; Sikhamov et al., 2020) and shot peening (Talia and Talia, 1994) have also been widely used to improve the surface properties of metallic materials. However, these techniques are less common in critical components given the uncertainty in the underlying residual stresses.

Metal crack stitching is different type of established mechanical technique used to repair large engineering components such as engine blocks. This approach make use of metallic 'locks' or 'keys' inserted into the base metallic material to bridge areas with damage.

Thermal

Overlay coatings and mechanical techniques are efficient for repairing surface cracks, however, they are not suitable for deep cracks present at the bulk of the material. For such cracks, thermal energy is required at the crack region to heal the crack. High-temperature healing is one of those techniques studied by many researchers (Djugum et al., 2009; Fisher et al., 2018; Gao et al., 2014, 2001; Jung et al., 2009; Qiu et al., 2019; Rohatgi, 2014; Wei et al., 2004). However, this approach has several challenges such as heat cannot be localized to the crack region. Moreover, rising temperature for the whole material can cause material degradation. Another similar approach is called isothermal precipitation (He et al., 2010; Laha et al., 2008; Shinya et al., 2016), but this is limited to precipitation hardened alloys. Laser remelting (Grum and Slabe, 2006) has also been studied to repair cracks. However, this approach is also much efficient and applicable to surface cracks.

Contrary to the above thermal techniques, Electropulsing can localise heat at cracks and heal them leaving a minor effect on the undamaged area (Zhou et al., 2001). Several studies related to Electropulsing have been proposed to heal cracks in medium carbon steel (Yizhou et al., 2004), 1045 steel (Yang et al., 2016; Yizhou et al., 2000), drawing steel (Kumar and Paul, 2020), austenitic stainless steel 316 (Hosoi et al., 2014, 2013, 2012; Tang et al., 2013a, 2013b), austenitic stainless steel 304 (Yu et al., 2016), Mild steel & Constantan (an alloy of copper and nickel) (Y.-M. et al., 2013), titanium alloy (Song et al., 2017). Electropulsing has wide applications for a range of materials, but this has only been tested on lab-scale.

The taxonomy of these techniques is summarised in Figure 1. This is not an extensive description of all techniques, but a simplified review which aims at identifying gaps in knowledge and opportunities to enhance circularity. Next, we aim to consider all these techniques and evaluate them in terms of their environmental footprints and applicability in the transport sector.

Mechanisms	Technique
Coatings	Microcapsule-thickened oil barrier coatings Epoxy materials with epoxy/mercaptan system Laser metal deposition Composite Overlay Electroplating
Mechanical	Metal crack stitching Grinding Peening Vee and Weld
Thermal	Heat treatment Electro pulsing treatment Eddy current treatment Laser melting
Prognosis reassessment	Conservative assessment supported by more evidences

Figure 1 Taxonomy of maintenance techniques

Methodology

To evaluate the sustainability, feasibility, and applicability of these techniques, we conducted some interviews with colleagues and transport experts to evaluated the potential attributes that should be considered to fully explore the objective of this project. Following discussions, we list the potential indicators required to rank the techniques, and these include,

- Ecofootprints of techniques,
- The extent of life extension of material/part using proposed techniques,
- Prior industry experience in related techniques,
- Feasibility regarding implementation of techniques,
- Possibility of onsite/offsite maintenance,
- Limitations and challenges regarding these techniques,
- Feedback regarding the industrial preferences

The nature of potential indicators demonstrated the need for data to assess ecofootprints of techniques as well as the practical feedback from the industry. Both datasets are essential to rank techniques in the initial phase of this project and to reflect future efforts required to overcome challenges and develop top-ranked techniques for preventive maintenance.

Regarding the sustainable aspect of healing techniques, we first explored which metallic material are worth treating by comparing their production energy demands, CO_2 emissions, cost, and recycling potential. The data related to these parameters is accessed for different materials from Granta EduPack 2021: Level 3 Eco Design (Limited, 2009). In addition, the material circularity index (MCI) that represents a circular value of a material or a process is also quantified using a dynamic modelling tool proposed by Ellen Macarthur Foundation ("Material circularity indicator," n.d.). For the analysis of materials, we selected representative metal alloys widely used in the transport sector: Al 7075-T6, Ni

Superalloys, Ti-6Al-4V, low carbon steel, and Austenitic stainless steel. The results for these materials should be taken as representative for a whole class with similar composition and properties.

The data related to the feasibility and applicability of maintenance techniques is collected from industrial expects using surveys and interviews. The survey consisted of 8 questions and was designed to be completed in 15 minutes. The details of the survey including format and questions are mentioned in Appendix A. The survey was made available online through social media platforms such ResearchGate, LinkedIn, etc. Due to the specific nature of the survey, experts' feedback was essential. For this purpose, we also filled the survey using live interviews with several industry experts. The following section will highlight the ecofootprints of maintenance techniques as well as the industrial feedback on the applicability of these techniques.

Analysis of Materials Maintenance Techniques

Eco Footprints of Materials

By relying on the Granta Software (CES EduPack, 2009), Figure 2 compares the energy requirement, CO_2 emission, and cost of producing different metallic materials as a function of the yield strength. The results demonstrate that resources and emissions have a direct non-linear relation with the material strength. For example, steels have comparatively lower strength, require less energy, and cost, and emits lower CO_2 compared to other materials. Hence, these results would prioritise treating high strength-high value materials such as Ti and Ni alloys to mitigate CO_2 emission and energy consumption.

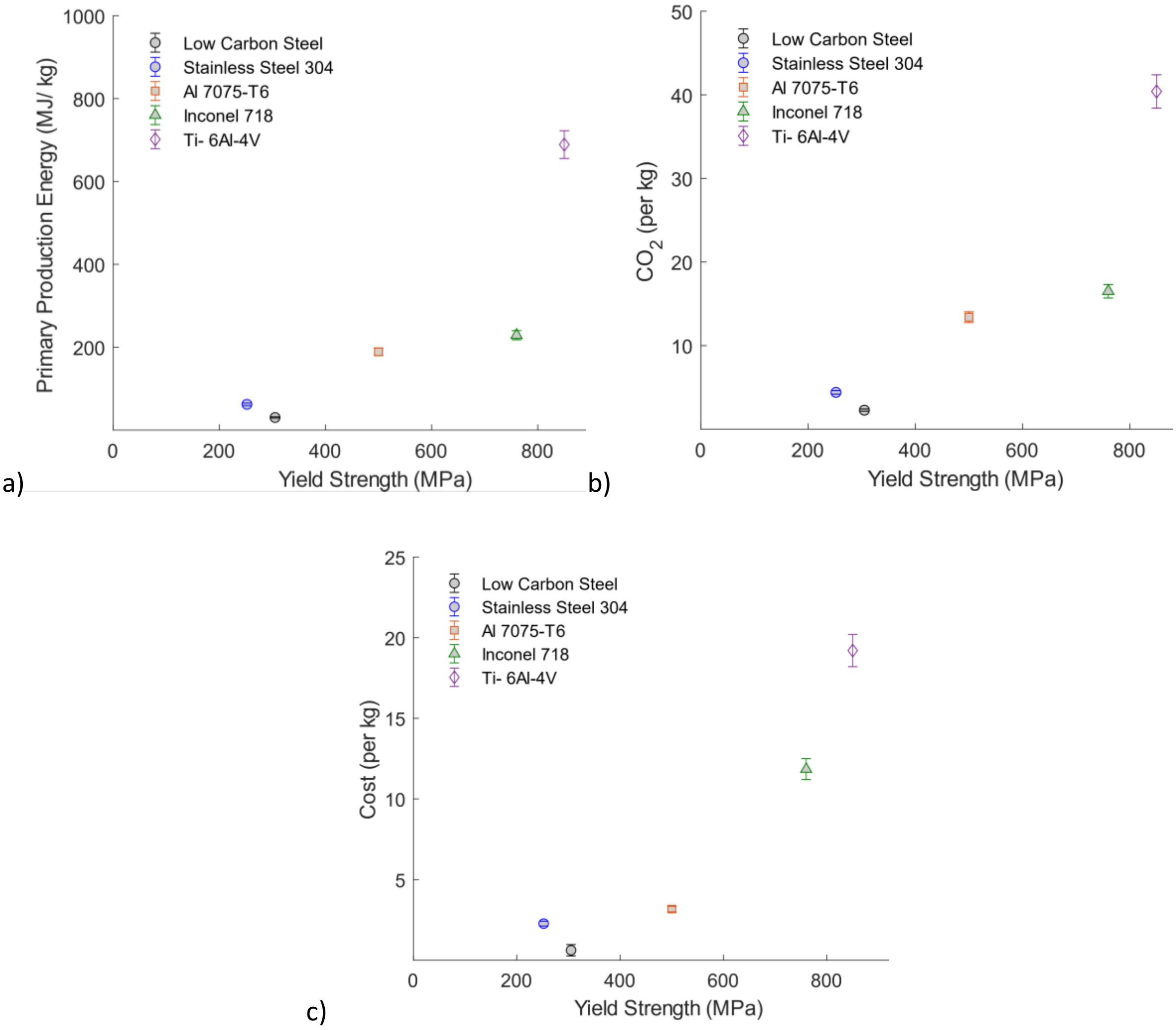


Figure 2 a) Primary production energy requirement b) CO_2 emission c) Cost to produce 1 kg of materials as a function of yield strength

Recycling potential of Materials

When considering the circularity of a material we should evaluate not only the footprint to produce a part, but the potential impact of recycling. Figure 3 presents the energy requirements to recycle per kg of different materials and CO_2 emission during the recycling process, which are 4-8 times lower than for the primary production (Figure 2a). Again, relying of Ti and Ni alloys has the higher environmental burden, which suggest that extending the life of these materials would provide the most benefits to the eco footprint.

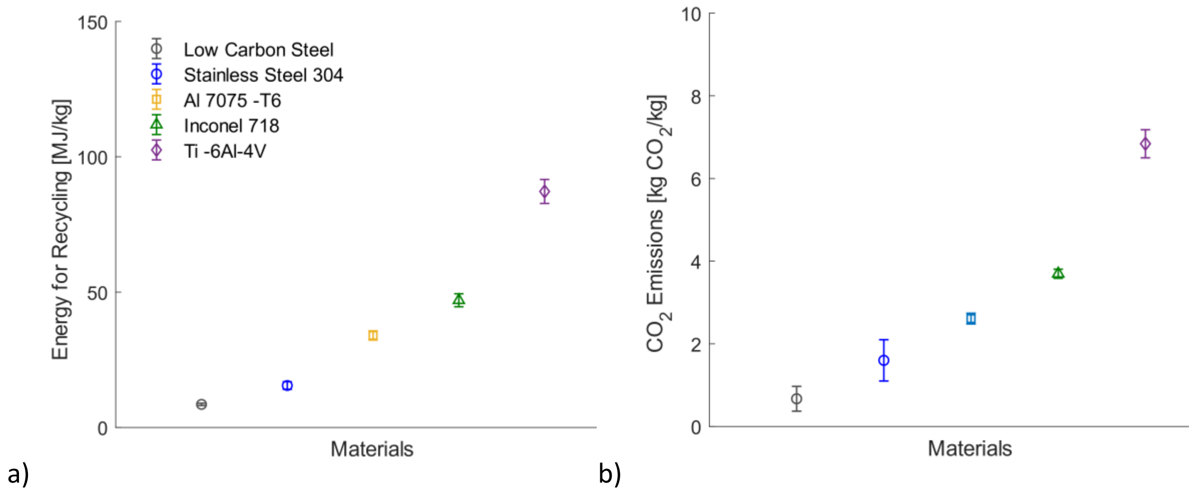


Figure 3 a) Energy requirement b) CO_2 emission for recycling per kg of material

Case study 1

Thus far we have compared the energy required to produce materials and CO_2 emissions per kg of materials. However, actual impact will depend on the characteristics of the component such as the volume, density, function, etc. Therefore, to better understand the eco footprints of materials, we present a simple case of study that consists of a beam (Figure 4) that can carry 10 kN load and is made of different materials. To carry the same load within the elastic regime, different materials require different dimensions. Hence, we calculated the required volume using the load and yield strength assuming unit diameter and length. The mass of each material is then calculated using the densities and volume of the beam as shown in Table 1.

Figure 5 compares the production energy requirement, CO_2 emission, and cost of materials as a function of yield strength. Also, the blue bars correspond to the mass on the right hand axis. Since Ti alloy and Ni superalloys have higher yield strengths than the rest, they require lower volume to carry 10kN load. Hence, their energy requirement, CO_2 emission, and cost are much closer, but still higher, than for the other materials. Notably, stainless steel is within a factor of two with Ti, compared to a factor of ten in Figure 2. Hence, high strength metallic materials used in transport seems to have a higher production energy and CO_2 emission footprint, and extending their lives should be prioritised. However, we recommend individual assessment of components to identify the potential of each case.

Table 1 Materials data to design a beam carrying 10kN load

Materials	Yield strength [MPa]	Volume [m^3] X 10^{-5}	Density [kg/m^3] X 10^3	Mass [kg]
Low carbon steel	305	3.28	7.85	0.26
Stainless steel 304	252	3.97	8.00	0.32
Al 7075 -T6	500	2.00	2.80	0.06
Inconel 718	760	1.32	8.22	0.11
Ti-6Al-4V	850	1.18	4.41	0.05

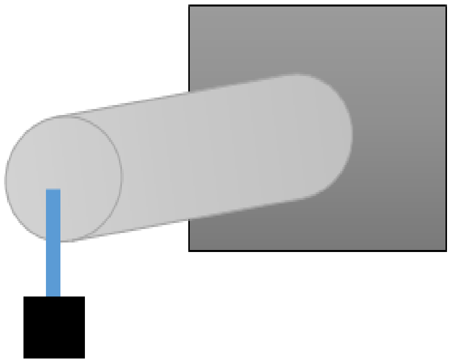


Figure 4 Case of study with a cantilever beam carries 10 kN load.

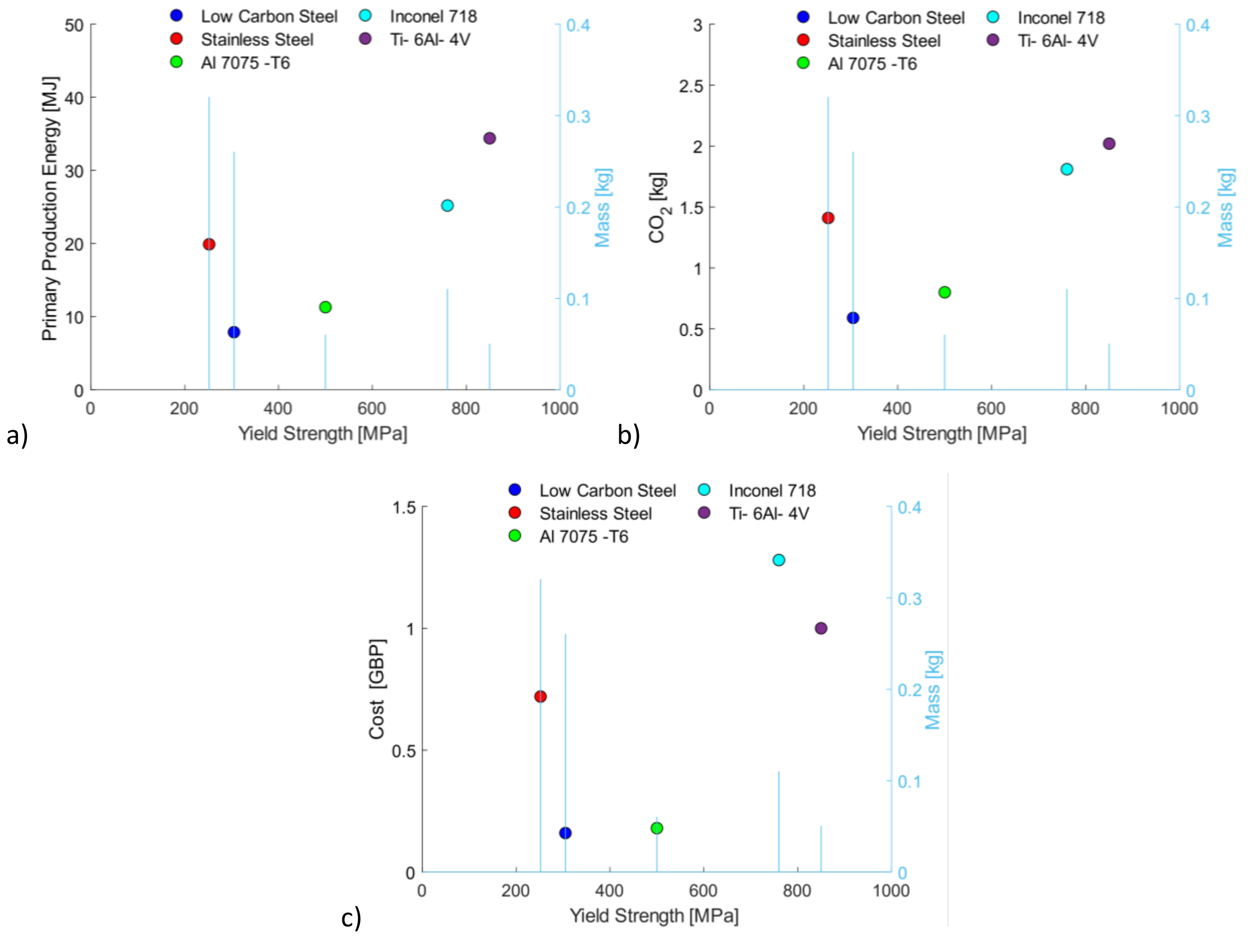


Figure 5 a) Primary production energy requirement b) CO_2 emissions and c) Cost of different materials for carrying 10kN load. The blue bars show the mass of each material corresponding to right hand axis.

Eco footprints of techniques

We now consider the primary resources required to perform the techniques in Figure 1, including process energy and material consumption.

Coatings

As explained before, various coatings technologies have been used to repair materials. Laser metal deposition and electroplating require process energy in addition to the filler material to perform the maintenance. Other coatings such as oil coatings and composite patching require only the material. However, these coatings are not energy free, since energy is required to produce the materials used in the coating.

Figure 6 compares estimations of the energy consumed during laser metal deposition and electroplating process calculated from the literature (Graf et al., 2012; Hasegawa et al., 2014; Isern, 2018; Liu et al., 2019). The results show that electroplating consumes roughly twice the energy as compared to the laser metal deposition process. Interestingly, laser deposition of Ti-6Al-4V requires less energy as compared to stainless steel 304. This might occur due to the fact that, for the same deposited volume, Ti-6Al-4V requires less mass and less time provided at similar feed rate. Furthermore, the specific energy consumption for laser processes is not significant. From a process energy consumption standpoint, laser metal deposition seems to be more sustainable than electrodeposition techniques. Note however, that both techniques have limitations in the materials and conditions in which they can be applied.

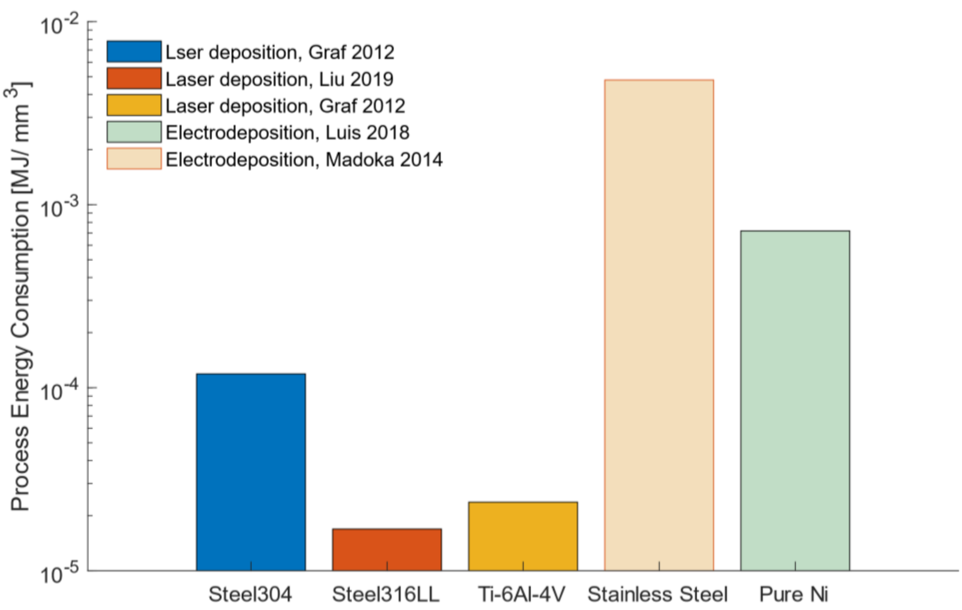


Figure 6 Comparison of process energy consumption between laser metal deposition and electrodeposition. The energy is normalised by volume of specimen treated by the laser process.

Mechanical

Grinding and peening are mechanical techniques widely used to treat surface defects. These techniques primarily use electrical energy to perform the maintenance. However, material is also involved especially in grinding like the grinding wheel consumption, waste of removed material. Since material consumption is relatively smaller compared to energy in a unit process, we only considered energy consumed during grinding process. Figure 7 estimates the energy required per unit volume of material removed for grinding different metallic materials (Nur et al., 2021; Rajemi, 2010; Sinha et al., 2019; Warsi et al., 2015). The energy on the y-axis in Figure 7 is normalized by the volume of material removed. The result shows that aluminium alloys require less energy as compared to other metals. The results can be verified by relating the required energy to the hardness of the material. For instance, Ti alloy and Ni superalloy are harder than Al alloy and stainless steel. Thereby, the former requires more energy for grinding. Figure 7 also shows that process energy is also sensitive to the milling machine. For instance, the Takisawa milling machine consumes more energy than the MHP latte for grinding Ti-6Al-4V. This result highlights that future research should also explore sustainable machining processes.

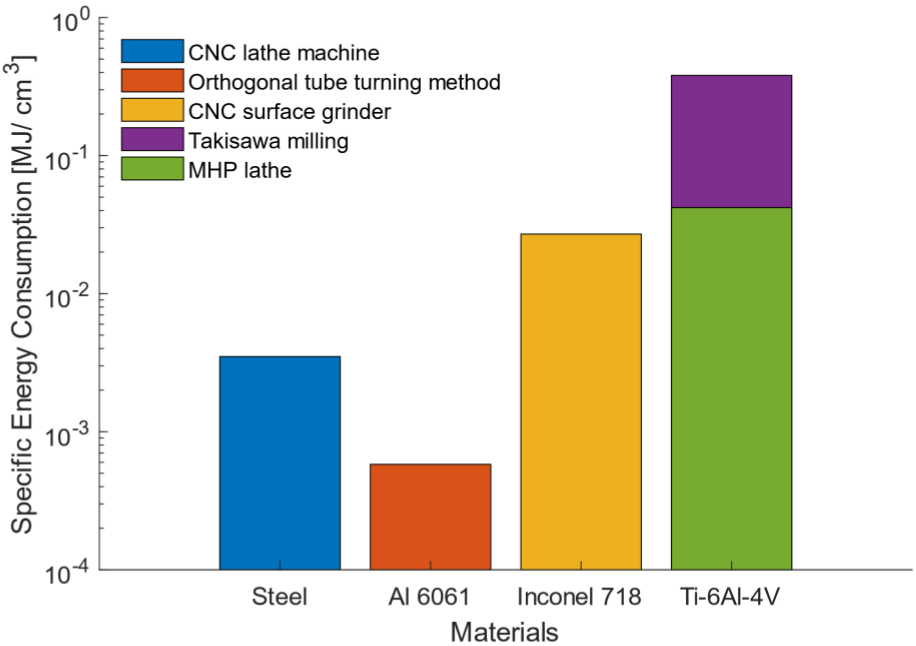


Figure 7 Estimation of the specific energy consumption during the grinding process for different materials

Figure 8 further compared energy consumed per area unit during laser shock peening and shot peening processes. Since these techniques are used to treat surfaces, the energy is normalized by the treated surface area. The results show that energy consumption in the shot peening process is much higher as compared to the laser shock peening process (Ding et al., 2014).

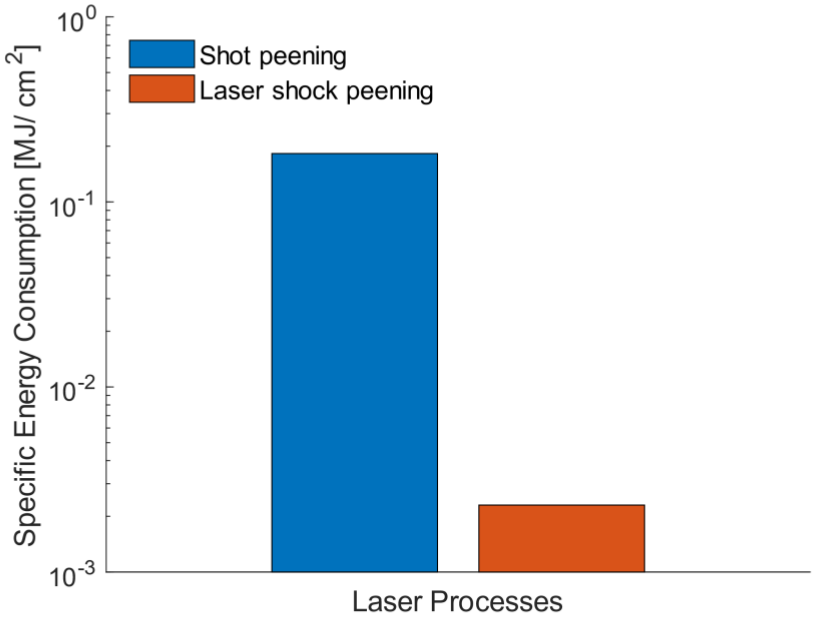


Figure 8 Energy consumption comparison between laser shock peening and shot peening process. The energy on the y-axis is normalized by surface area.

Thermal

For processes in which energy transfer relies on heat, we compared the energy consumption for several techniques such as electropulsing and laser remelting. Figure 9 shows that electric treatment consumes less energy per unit volume as compared to the laser melting process. The data in Figure 9 is calculated using literature (Grum and Slabe, 2006; Andre Temmler et al., 2015; A. Temmler et al., 2015).

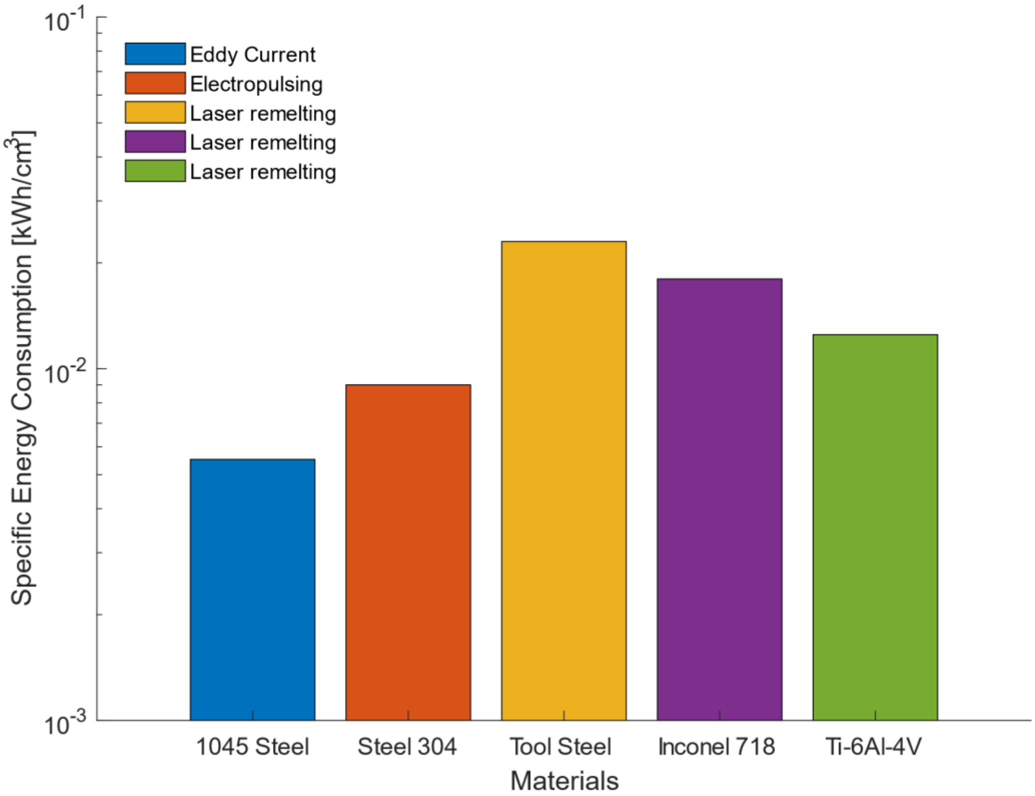


Figure 9 Comparison of energy consumption between different thermal processes for different materials

Figure 10 shows the average energy consumption in a day in the heat treatment industry. The results show that an average of 1200 kWh energy is consumed per hour for heat-treating the materials (Källén, 2012), which is a significant amount of energy. In terms of specific energy per amount of material, the energy consumption in the plant is 2.93 kWh/ kg (Källén, 2012).

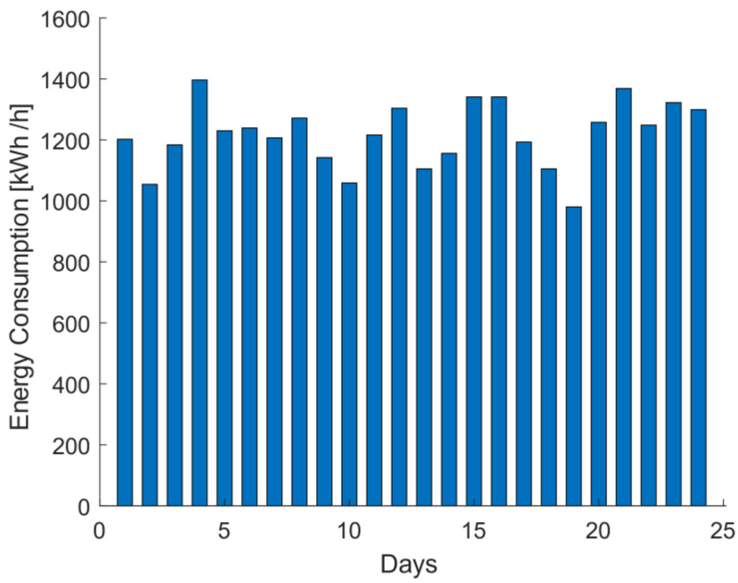
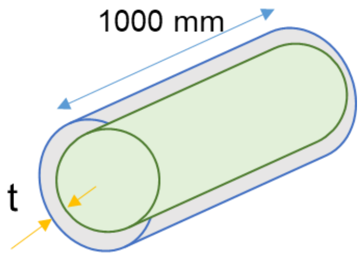


Figure 10 The energy consumption during an average day in the heat treatment plant in Sweden (Källén, 2012)

Case study 2

We now assess the energy required by each technique to identify the most eco-friendly coating. For this purpose, we considered a second case of study assuming a 1m long cylindrical beam shown in Figure 11. The thicknesses of different coatings are considered following literature recommendations. For each material corresponding to the coating technique, the deposited mass for lower and upper thickness value is calculated using the density of the material and layer thickness as shown in Figure 11.



Technique	thickness [mm]
Laser metal deposition (Liu et al., 2019)	0.06 – 0.125
Electro deposition (Isern, 2018)	0.05 - 0.1
Oil and epoxy coating (Talbert, 2013)	1.5 -3
Composite patching (Emdad and Al-Mahaidi, 2015)	0.17 (3- 6 layers)

Figure 11 Reference beam as a component to evaluate eco footprints of different coatings

Table 2 Materials data for different coating techniques

Material	Mass @lower bound thickness 'kg'	Mass @upper bound thickness 'kg'
Stainless steel 304	9.0×10^{-5}	3.9×10^{-4}
Al 7075-T6	3.2×10^{-5}	1.4×10^{-4}
Inconel 718	9.3×10^{-5}	4.0×10^{-4}
Ti-6Al-4V	5.0×10^{-5}	2.2×10^{-4}
Stainless steel 316L	7.0×10^{-5}	2.8×10^{-4}
Oil barrier coating	1.3×10^{-2}	5.4×10^{-2}
Epoxy coating	1.4×10^{-2}	5.7×10^{-2}
Composite overlay	5.9×10^{-3}	2.4×10^{-2}

Figure 12 summarises the energy consumption of all the techniques using the second case of study in Figure 11. For techniques that require both material and processing energy, data related to production energy of material is computed from Figure 2 (a) while the process energy is calculated by scaling the data in Figure 6, Figure 8, and Figure 9. For this purpose, we estimated the surface area and volume required for mechanical and thermal treatment respectively by considering penetration depth of 1mm. The area and volume are used along with the data in Figure 8 and Figure 9 to estimate the process energy.

Since the thickness of oil barrier coating, epoxy coating, and composite overlay is larger, they contain more material and require high energy. In terms of application, laser metal deposition and electrodeposition provide a more energy-friendly solution. The comparison with Figure 6 shows that material production energy is more important to be considered compared to process energy during the selection of technique for specific maintenance. Thus, the results in Figure 6 do not represent the dominant total energy required in the technique for this component.

Overall, the results in Figure 12 demonstrate that laser metal deposition and electrodeposition consume overall less energy as compared to other coating, mechanical and thermal techniques, even when considering the footprint of the added material. We note however that this analysis changes for the specific volume/area/strength, and it should be considered on a case-by-case.

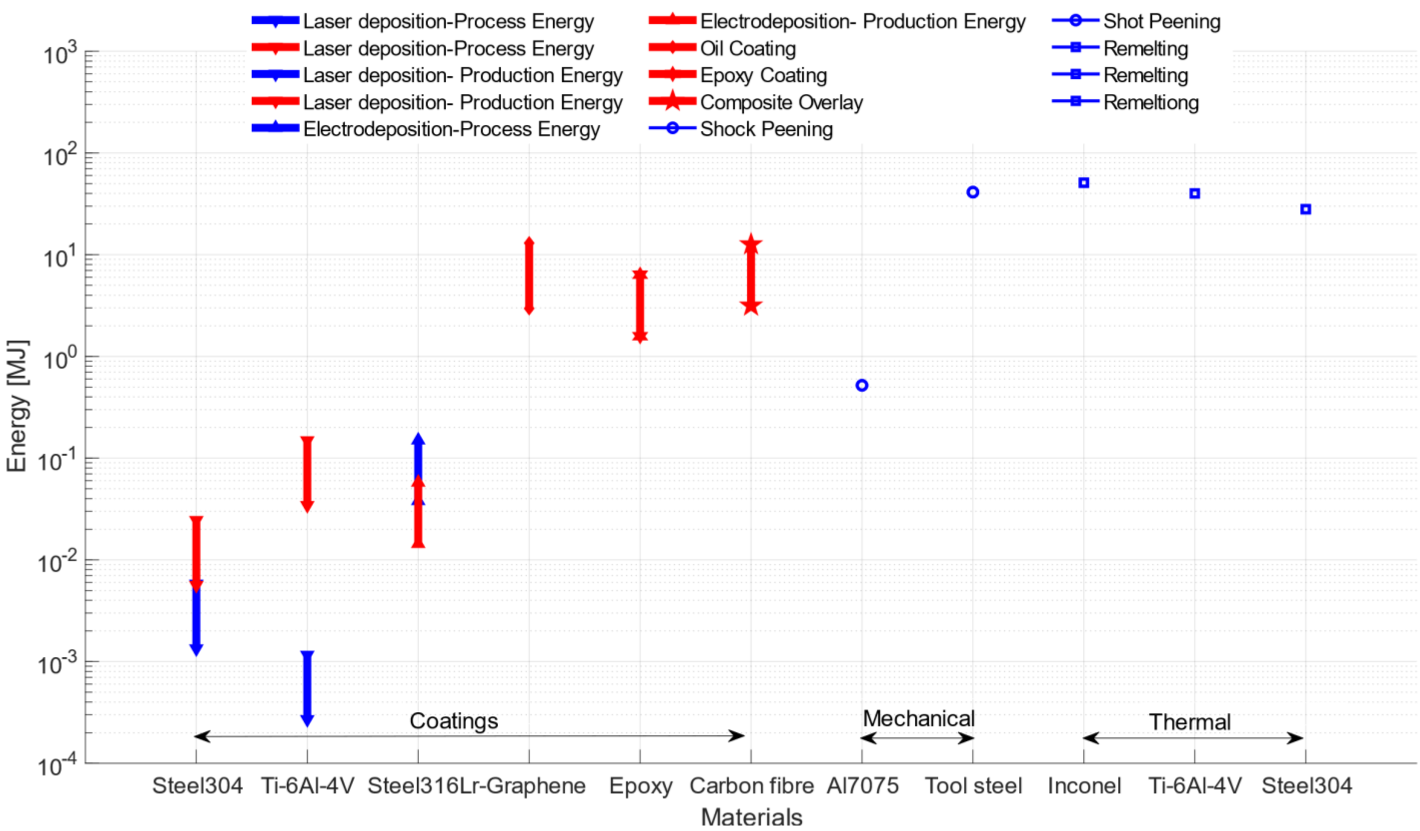
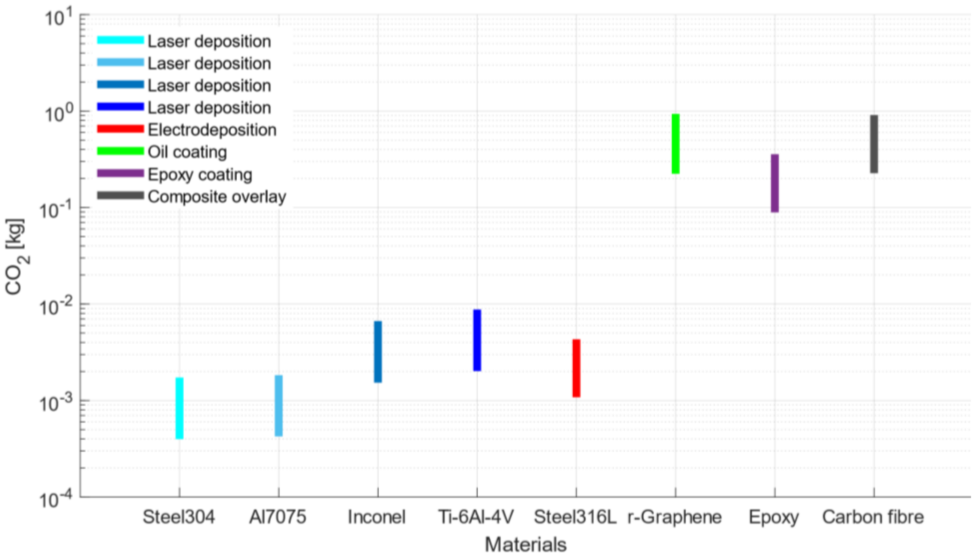
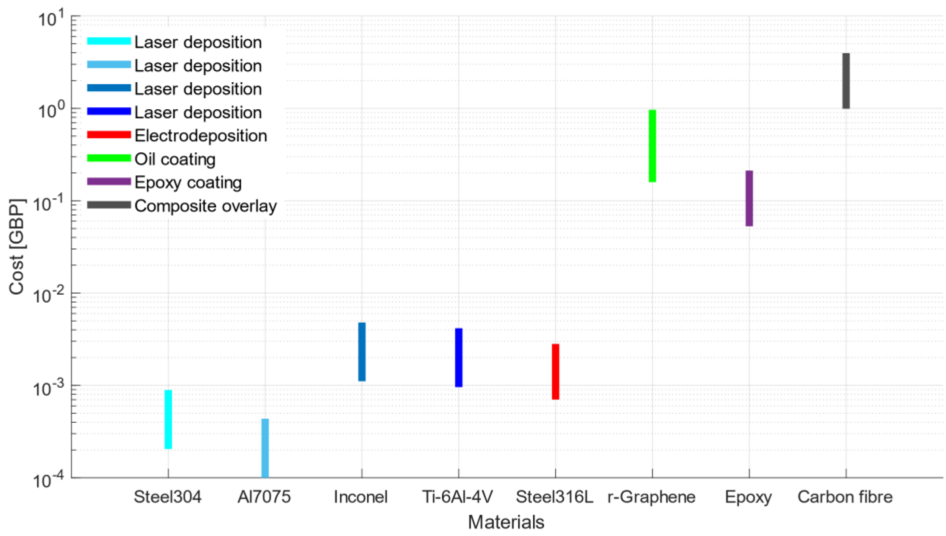


Figure 12 Comparison of energy consumption for different techniques considering same repair.

Figure 13 further compares the CO_2 emissions and cost from various coating solutions applied to the second case of study. The results present the same trend as the primary production energy, which highlights oil coatings and composite overlay emit more CO_2 emission and are more expensive solutions. Although it is not currently possible to perform a similar comparison of CO_2 emission for all techniques due to a lack of data, the analysis of coatings leads us to believe that CO_2 emissions roughly follows the same energy consumption trends in Figure 12.



a)



b)

Figure 13 a) CO_2 emission and b) Cost of different coatings on a substrate shown in Figure 11.

Material Circularity Index (MCI)

The material circularity indicator (MCI) measures the extent to which linear flow can be minimized and the usage intensity of a product compared to the industry average product. Following the definition, the MCI is a function of linear flow index (LFI) and utility (X). Figure 14 shows the schematic of material flow. Using this material flow in Figure 14, LFI can be calculated as,

$$LFI = \frac{V+W}{2M} \tag{1}$$

Where M is the mass of the product, W is the total unrecoverable waste, and V is the virgin feedstock. On the other hand, utility determines the lifetime and usage intensity of product with respect to the average industrial product,

$$X = (\frac{L}{L_{av}})(\frac{U}{U_{av}}) \quad (2)$$

Where $\frac{L}{L_{av}}$ accounts for the increase or decrease in the waste stream in a life span (L) of the product compared to industrial average life (L_{av}) and $\frac{U}{U_{av}}$ reflects the use of the product compared to average industrial usage.

The MCI now can be defined considering Equation (1) and (2) as,

$$MCI = 1 - LFI \,.\, F(X) \quad (3)$$

The utility function should have the form $\frac{a}{X}$ for some constant a (Goddin et al., n.d.). The value of a is set to be 0.9 considering the MCI =0.1 for a fully linear product (LFI=1) whose utility equals to industrial average (X=1) (Goddin et al., n.d.).

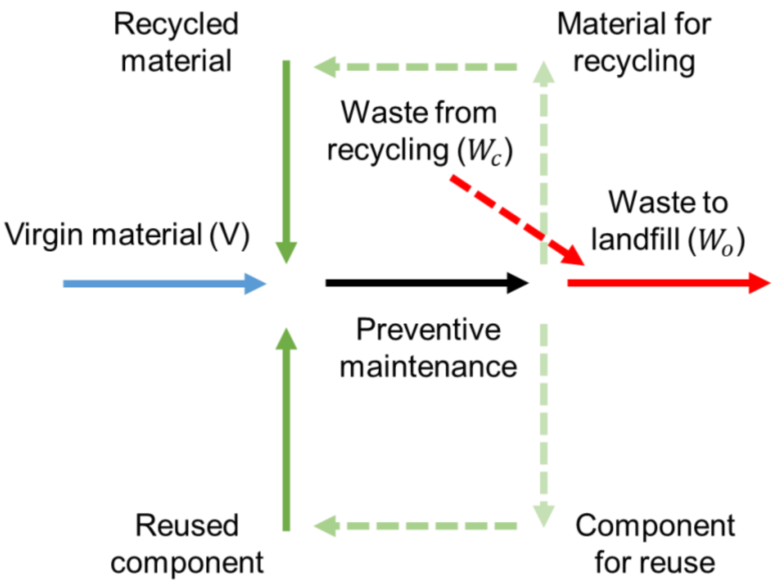


Figure 14 Graphical representation of a material flow

Table 3 shows the MCI of different techniques computed using a dynamic modelling tool ("Material circularity indicator," n.d.). Since we aim to preventively treat the materials, no recycling and reuse are assumed for each technique while calculating the MCI. However, in this case, the MCI solely depends on the utility or life extension potential of each technique. The results present all technologies have fairly comparable MCIs in the range of 0.63 to 0.85.

Table 3 Material circularity index of different techniques

Techniques		MCI	Comments
Coating	Oil barrier coating	0.72- 0.77	No recycling/ reused, 60-80% life extension
	Composite Overlay	0.65	No recycling/ reused, Each patch increases life by 30%
	Electro deposition	0.67 - 0.77	No recycling/ reused,
	Laser metal deposition	0.77	
Mechanical	Grinding	0.77	No recycling/ reused, 90 -95% life extensions
	Metal crack stitching	0.84	50% recycling/ & 95% life extension
	Peening	0.76	No recycling/ reused 95% life extension
Thermal	Heat treatment	0.75- 0.77	No recycling/ reused, 90 -95% life extensions
	Laser melting	0.77	No recycling/ reused 95% life extension
	Electric current	0.63 - 0.75	No recycling/ reused 20- 80 % life extension

Industry Feedback

In addition to the theoretical examination of techniques, we also considered the feedback from the industry regarding the applicability, feasibility, and preferences in applying healing techniques. Figure 15 shows the feedback from industry experts, most from the aerospace sector, regarding their experience of these techniques. Mechanical techniques are common practice in some transport industries and many participants have reported experience in these techniques. On the other hand, around 75% of participants mentioned their experience in thermal techniques followed by coating techniques, which have 40% usage in the industry.

Table 4 presents the industry experience for repairing components using multiple techniques. The feedback reveals that the proposed techniques have a larger scope in terms of applicability. However, the adherent limitations and challenges associated with these techniques will be recorded separately. Following current practices, coatings are being used for several components including the entire airframe, landing gear, wing, aircraft nose repair, eroded and rusted parts, and rivets. Whereas mechanical techniques are used for repairing turbine blades, landing gears, primary airframe parts, engine blocks, hydraulic cylinders, to remove material and crack blunting. Thermal techniques are being utilized for heat treatment to remove residual stresses and reconditioning materials. Additionally, it is also being used for creating specialized tools and military main rotors. Overall, the numerous components that are regularly repaired with several techniques suggests good potential for the adoption materials maintenance practices.

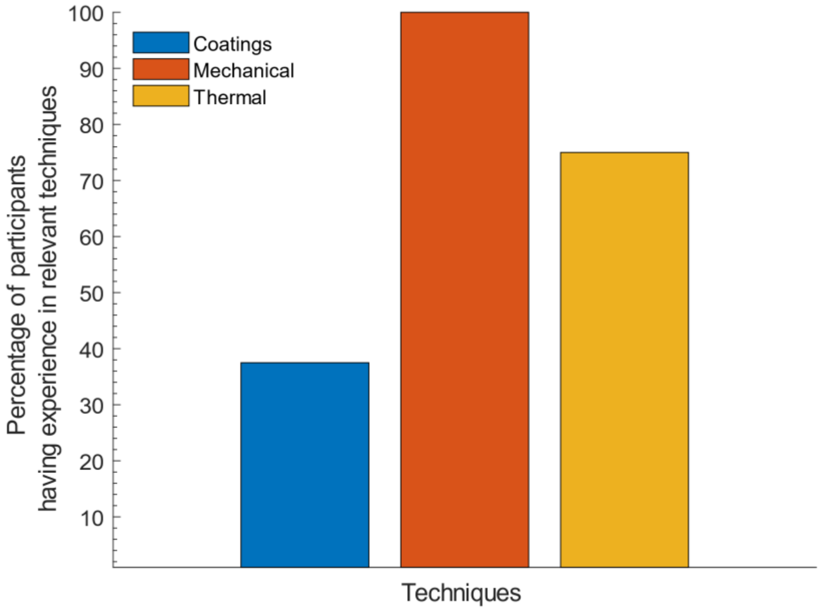


Figure 15 Industry experience in different techniques

Table 4 Examples of components that can repaired with different techniques.

Techniques	Components
Coating	▪ Entire airframe, rivets, and landing gear in particular ▪ Rust pipes ▪ Wing, structure prone to erosion, Parts that suffer friction ▪ Aircraft nose repair
Mechanical	▪ Bearing surfaces in the landing gear ▪ Hammer Peening is used to Insert turbine blade into its rotor ▪ Blunting of cracks, rivets, removal of material ▪ Rough surfaces ▪ Mainly hammer peening to prevent crack initiation, ▪ Primary airframe part under tensile load, fuselage frames, wings ▪ Internal aircraft parts that do not require aerodynamic performance ▪ Engine blocks, and hydraulic cylinders
Thermal	▪ Heat Treatment is used to release residual stresses from shafts ▪ Reconditioning a material using heat treatment ▪ Mainly Al alloys e.g., Al-Cu (series 2 and series 7) to prevent cracking and make the part more durable. ▪ Eddy current is used in checking for minor cracks on the metal surfaces and undercarriage parts ▪ HSS tools, specialized tooling, military main rotor head assemblies

Figure 16 shows the industry response to the implementation difficulty of different techniques. Overall results based on higher values showed that coatings and mechanical have medium to the high difficulty level in terms of implementation. Whereas thermal technique would be either easy or difficult to implement subject to the defect, component, and specific technique.

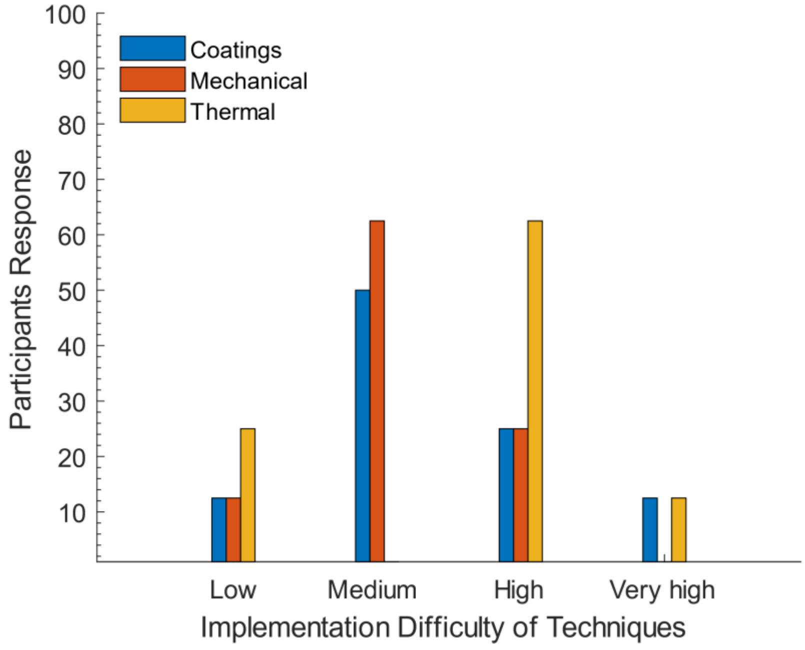


Figure 16 Industry feedback on the implementation difficulty of techniques

Figure 17 provides a rough estimate of maintenance cost for different techniques suggested by several industrial experts. The 80% of results showed that mechanical techniques require a medium level of maintenance cost. On the other hand, mechanical and thermal involve medium to the very level of cost subject to specific maintenance.

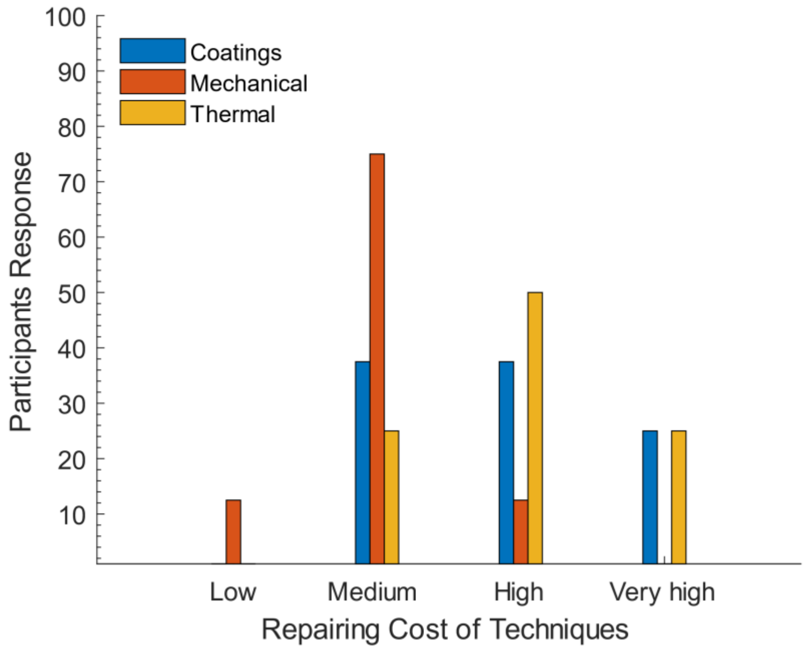


Figure 17 Participant's feedback on the maintenance cost of techniques

Figure 18 highlights the recommendation made by industrial experts regarding preventive maintenance and frequent inspections. About 68% of experts support that preventive maintenance is a better solution than frequent inspections. However, 16% of experts justified frequent inspection or recommend both strategies.

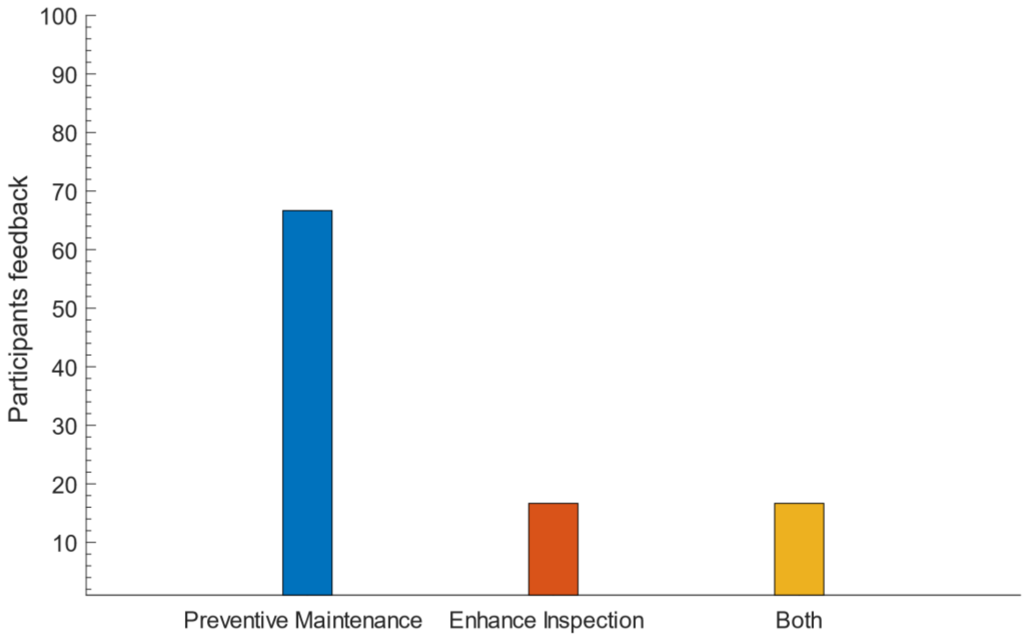


Figure 18 Participant’s recommendation on the choice of maintenance operations

Regarding the industrial feedback related to the feasibility score for application of different techniques, 67% participants suggested that coatings can be done onsite on assembled parts. On the other hand, mechanical and thermal techniques got 50% and 16% vote respectively for their applicability to repair assembled parts onsite. However, 80-90% participant agreed that coatings, mechanical, and thermal techniques can be applied to dissembled part offsite if the underlying challenges related to particular techniques can be fixed.

Table 5 further lists some limitations and challenges associated with maintenance techniques reported by industry experts. Certifying the techniques is an important and common concern for the aerospace industry. However, multiple other issues have been highlighted that need consideration. Based on overall feedback, material and coatings are preferable options to thermal techniques. Because it's difficult to develop an effective process for thermal techniques. Additionally, localizing the thermal energy and scaling up from local region to bigger with an oven is a grand challenge.

Table 5 Limitation and challenges related to techniques suggested by participants

Techniques	Limitations	Challenges
Coating	▪ Non-accessible surface ▪ Bonding strength ▪ Time and cost if damage location is unknown ▪ Extension to the entire part might require disassembling ▪ Leakage and surface finishing ▪ Certifying issue ▪ Good agreement with the recurring party, recurring cost ▪ Equipment	▪ Chemical compatibility, fire hazard ▪ **Electropulsing**@ Disassembling the part could be challenging ▪ **Paint**@ Containment and localized application ▪ Training personal to prepare the surface, the manipulating coating is risk ▪ Justify the cost of having it onsite
Mechanical	▪ Access issue, repeating the process on primary critical components ▪ Time for grinding and polishing big components ▪ Material selection ▪ Investment on mains ▪ Noise pollution, space requirement, engineering hygiene	▪ How much and where you could use it ▪ Change of design might require consideration with this technique ▪ Number of repairs in years ▪ Health and safety, vibration monitoring
Thermal	▪ Temperature: under 100 probably fine, certifying issue ▪ Size: could be challenging for big components, time and cost ▪ Disassembling the part ▪ Might involve high energy ▪ Certifying issue ▪ Investment on mains	▪ Location-specific ▪ **Electric current**@ Dispersion of electric current ▪ **Heat treatment** @Scale up from local region to bigger without having an oven ▪ **Melting**@ Development of an effective process is difficult. Additionally, difficult to construct part and tool

Finally, Figure 19 ranks the industrial preferences in terms of considering maintenance techniques. Interestingly, 60% of experts choose "supporting net-zero target" as their 1st or 2nd preference. On the other hand, cost and degree of life extension are mostly selected as 2nd or 3rd preferences. Whereas 60% of participants gave the third preference to lenient certification. Healing operation time is chosen mostly in 3 and 4 places. In summary, cost, degree of life extension and reduction emissions are the main preferences of industries following by certification issues and healing time of techniques.

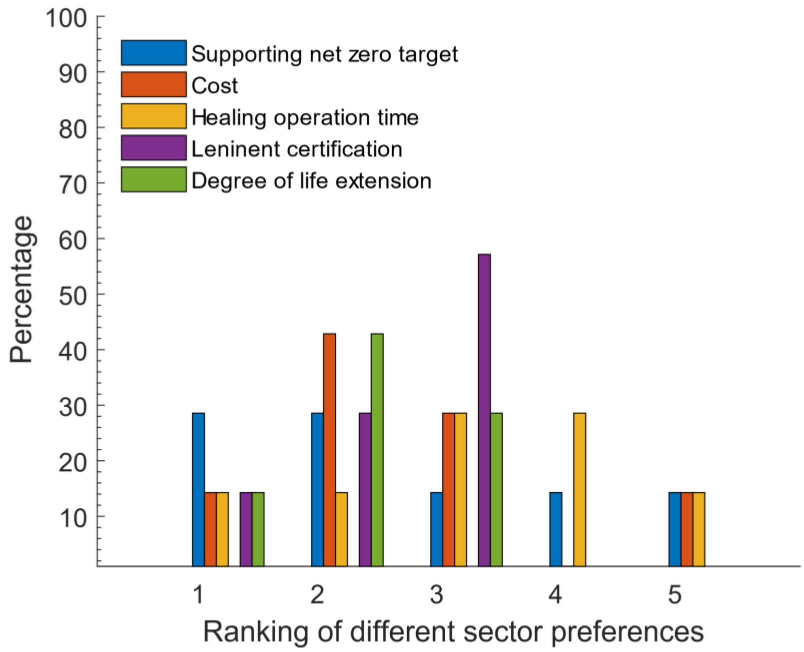


Figure 19 Different sector preferences regarding the ranking of important issues. 1- most important, 5- least important.

Discussion

This study explores the potential of maintenance techniques applied to regular rejuvenation of metallic materials. We evaluated the environmental footprints and feasibility with focus on the transport industry. Firstly, we estimated the energy demand and CO_2 emission of various materials to identify which alloys have the most impact on the environment. Figure 2 shows that Ni superalloys and Ti alloys have three times more primary production energy consumption and CO_2 emission as compared to Al alloys and Austenitic steels. A second criterion that gives priority to those alloys is related to the criticality of raw materials[1].

The rational to justify preventive treatment of a components depends on multiples characteristics such as cost of maintenance, size, shape , availability of replacement, etc. We presented two cases of study to demonstrate that, although Ti alloy requires less material to holda load compared to other materials, it still has a higher energy requirement and $C0_2$ emissions. Even though multiple factors can affect the comparison, the results seem to suggest that high strength material can have higher environmental footprint and should be given priority.

Regarding the environmental performance of maintenance techniques, we firstly considered technologies that apply a thing coat of new material, deform mechanically or heat the base material. The results demonstrate that some localized coatings (such as laser metal deposition and electroplating but not composite patching) are greener than other coating techniques. However, if we analysed the production of materials for coatings , then Ti alloys and composite fibre have a more adverse effect on the environment compared to other materials.

Contrary to coatings, mechanical techniques do not typically require the addition of material to the treated component. However, these processes consume energy to perform the operation which,

[1] https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

compared the energy demands of manufacturing raw materials, are not too high. In addition, green energy from renewable resources can minimise the impact of these technologies.

Similarly, thermal techniques do not require material addition to the repaired component. However, these techniques require high temperatures which can lead to higher energy consumption when the bulk of the component is heated. Some techniques such as Electropulsing have the ability to localise heat around damaged areas and mitigate the overall energy consumption. However, the applicability of these techniques is difficult and there is no prior experience from industries, which hampers their applicability.

In terms of circularity, our analysis suggests that mechanical techniques tend to have marginally better material circularity indicator, but all technologies have a similar level of MCIs. Hence, material and energy consumptions are the primary footprint indicators.

The feedback from our industrial partners suggests that many of these techniques are being currently used to repair existing damage rather than for preventive maintenance. In terms of implementation of techniques, most participants suggested that mechanical and coating are easy to implement compared to thermal. Similarly, the majority reported that mechanical is relatively cheaper than other techniques while coatings have the advantage that it can be done on assembled parts on site.

In terms of limitations and challenges reported by industrial experts, mechanical is less of a concern given their ample dissemination and extended industrial experience. Contrarily, coatings and thermal techniques require the development of process and certification.

Recommendation for future work

Our research suggests that the development of coating technologies for high strength materials can have the most beneficial impacts to extend the lives of components. The ecological footprint of organic coatings is higher than that for metals, so we recommend advancing techniques such as electrodeposition and laser deposition. One particular challenge is to simplify the application of the technique such that their cost is low enough to treat large areas regularly. In this sense, the development of portable and user-friendly techniques can accelerate the adoption of the technique.

In addition to advancing accessibility, coating compositions and microstructures should be further explored to maximise circularity. Extending the life of high-strength metallic materials with low strength metallic coatings aimed at shielding the environmental seems to provide the lowest ecological footprint. In this sense, further research should explore coating that can applied to components after some service and without any special surface preparation. These efforts should also focus on the standardisation of these coating technologies, such that their healing effects are accrued on longer inspection periods.

Another underdeveloped technologies are those related to the localization of heat. Increasing the temperature of a component can have healing properties. However, heating the bulk of the component sometimes is unfeasible, impractical or uneconomic. Hence, techniques with heat localisation, such as electropulsing, can be effective, especially when they are integrated into the design of the alloy.

Finally, we envision maintenance of materials can be integrated as part of the design concept of a new vehicle. Indeed, materials maintenance should be conceived as part of novel holistic design strategies that includes provision for novel materials, component degradation assessment and system through-life management. Akin to changing the oil of an engine or cleaning of a vehicle, we envision that easy and flexible materials maintenance strategies with demonstrated life extension can be adopted by industries.

Conclusions

This work explored a novel concept of preventive maintenance to extend the fatigue life of metallic materials. We evaluated existing maintenance techniques based on their environmental footprints and feasibility of application in the aerospace industry. Based on current practice in the transport industry and scientific data, we identified the techniques that can extend materials lives, at low ecological impact. We also specify the direction for future work to nurture preventive maintenance by highlighting challenges related to other potential techniques.

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Appendix A: Questionnaire shared with industrial partners

Question 1: Do have any prior experience of repairing materials using these techniques?

	Yes	No	Suggestions
Coating - Oil barrier coating - Composite Overlay - Electro deposition - Laser metal deposition	☐	☐	
Mechanical - Grinding - Metal crack stitching - Hammer peening	☐	☐	
Thermal - Heat treatment - Laser shock peening - Laser melting - Melting - Electric current	☐	☐	

Question 2: Could you please suggest components that can be repaired using these techniques?

	Component example	Suggestions
Coating - Oil barrier coating - Composite Overlay - Electro deposition - Laser metal deposition		
Mechanical - Grinding - Metal crack stitching - Hammer peening		
Thermal - Heat treatment - Laser shock peening - Laser melting - Melting - Electric current		

Question 3: How would you rank the implementation difficulty of these techniques?

	Low	Medium	High	Very high	Suggestions (Optional)
Coating - Oil barrier coating - Composite Overlay - Electro deposition - Laser metal deposition	☐	☐	☐	☐	
Mechanical - Grinding - Metal crack stitching - Hammer peening	☐	☐	☐	☐	
Thermal - Heat treatment - Laser shock peening - Laser melting - Melting - Electric current	☐	☐	☐	☐	

Question 4: Could you please rank the repairing cost for these techniques?

	Low	Medium	High	Very high	Suggestions (Optional)
Coating - Oil barrier coating - Composite Overlay - Electro deposition - Laser metal deposition	☐	☐	☐	☐	
Mechanical - Grinding - Metal crack stitching - Hammer peening	☐	☐	☐	☐	
Thermal - Heat treatment - Laser shock peening - Laser melting - Melting - Electric current	☐	☐	☐	☐	

Question 5: What seems better strategy: treat materials preventively or enhance inspection?

Question 6: Could you please score the feasibility of carrying out these techniques between 1 and 10 (1=less likely & 10=most likely)?

	Assembled part: Onsite	Disassembled part: Offsite	Suggestions (optional)
Coating - Oil barrier coating - Composite Overlay - Electro deposition - Laser metal deposition			
Mechanical - Grinding - Metal crack stitching - Hammer peening			
Thermal - Heat treatment - Laser shock peening - Laser melting - Melting - Electric current			

Question 7: Could you please highlight limitations and challenges in carrying out these techniques?

	Limitation	Challenges
Coating - Oil barrier coating - Composite Overlay - Electro deposition - Laser metal deposition		
Mechanical - Grinding - Metal crack stitching - Hammer peening		
Thermal - Heat treatment - Laser shock peening - Laser melting - Melting - Electric current		

Question 8: Finally, please rank your sector preferences (1=most important, 5=less important).

	Preference
Supporting net zero target	
Cost	
Healing operation time	
Lenient certification	
Degree of life extension	