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Revitalising Metallic Materials: A Path towards a Sustainable Circular Economy

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Abstract: Improving materials' productivity and reusability can advance circularity by reducing extraction and enabling efficient fully recyclable parts and systems. However, the pursuit of circular materials often focuses on the choice among reusing, repairing, or recycling materials, with limited consideration for techniques that can proactively revitalise materials. Consequently, the adoption of preventive material therapies remain relatively scarce and unexplored. This work discusses the potential for revitalising metallic materials with preventive maintenance prior to detectable damage and we identify techniques that can effectively prolong the structural lifespan of metallic components. By analysing the literature and considering the eco-footprint and implementation feasibility within the aerospace sector, this study ranks approaches based on their circularity impact and provides valuable insights to guide future research in the field of materials maintenance.

Keywords: product circularity; circular economy; maintenance

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Citation: Ashraf, F.; Lodh, A.; Pagone, E.; Castelluccio, G.M. Revitalising Metallic Materials: A Path towards a Sustainable Circular Economy. *Sustainability* **2023**, *15*, 11675. https://doi.org/10.3390/su151511675

Academic Editor: Andrea G. Capodaglio

Received: 8 June 2023
Revised: 14 July 2023
Accepted: 24 July 2023
Published: 28 July 2023

1. Introduction

A flourishing circular economy aims to maximise the value and longevity of materials, products, and components. One crucial factor that determines their environmental impact and promotes sustainable consumption is the duration of their life cycle, from production to disposal [1,2]. Extending the lifespan of materials and products can be achieved through maintenance, reuse, refurbishment, and recycling [3]. Significant research has been devoted to business model innovation and design strategies for efficient recycling and remanufacturing. However, there has been comparatively less attention given to approaches that focus on preventive materials maintenance, which has the potential for the lowest impact (Figure 1). Repairing restores functionality after some damage [4–6] while materials maintenance involves treating functional material to extend its lifespan prior to damage. Hence, the challenge is to identify and incorporate material revitalisation strategies into the life cycle of components, from design to decommissioning.

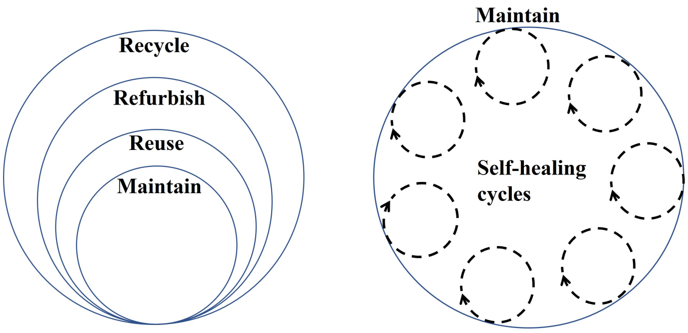


Figure 1. Introduction of self-healing as maintenance procedure in circular economy [7].

Materials revitalisation, maintenance, and circular economy are interrelated concepts that collectively contribute to sustainable resource management and the transition to a more sustainable economic model. While material revitalisation focuses on restoring materials to extend their usability and reduces the demand of raw materials [8], maintenance ensures routine actions to prevent deterioration and ensure optimal performance. Together, these concepts play a critical role in advancing the circular economy by conserving resources, reducing waste, creating economic opportunities, and minimising environmental impact [9]. Incorporating maintenance needs during the design phase can facilitate future maintenance activities and minimise the time and effort requirement. A preventive maintenance plan helps to identify and address materials' ongoing ageing and reduces the need for extensive repairs or replacements. In general, preventive maintenance ensures the enhanced reliability and quality of an asset. For instance, Xia et al. [10] explored an energy-oriented maintenance strategy for a batch production line and demonstrated that the total energy savings with preventive maintenance can be higher than classical maintenance strategies as well as result in reduced failure rate.

Only a few efforts have looked at integrating the design of materials with a comprehensive revitalisation strategy throughout their entire life cycle. One example is self-healing materials [11], which can maintain functionality through their innate ability to repair damage such as crack embryos (see Figure 1). However, designing materials with an intrinsic self-repair capability is challenging and often impractical. Instead of relying on intrinsic self-repair, extrinsic maintenance approaches can be employed to extend the operational life of assets and maximise their economic value. A simple example is the application of painting or polishing surfaces to eliminate or seal potential cracks, thereby prolonging the material's life cycle. To achieve economic efficiency and environmental viability, a sustainable material management strategy [12] must consider materials maintenance during the design phase. In this context, sustainable maintenance has become a new challenge to industries embracing sustainability initiatives. It involves implementing practices and maintenance activities that encourage a harmonious balance among economic, environmental, and social aspects. Going beyond financial concerns like repair expenses and material usage, it also considers environmental factors like minimising greenhouse gas (GHG) emissions. The benefits come directly as incorporating measures such as optimising maintenance schedules to reduce energy consumption, adopting energy-efficient technologies and practices, establishing effective waste management and recycling systems, and considering the life cycle impacts of maintenance activities [13].

The transport sector is of major concern as it is the largest contributor to global GHG emissions, responsible for 27% in 2019 [14], a fraction of which comes from manufacturing materials. In this context, gaining insight into the impact of materials on the environmental footprint can help reduce the CO_2 emissions of the transport sector. Hence, this study evaluates the potential of the revitalisation of key structural alloys in the aerospace sector. We seek to identify the greatest potential for reducing environmental impact [15] by extending metallic materials' lifespan. This paper is organised as follows: the next section presents a comprehensive approach for ranking techniques that can enhance materials' circularity, including the sources for the data and the methodology for the analysis. Following this, we demonstrate the approach with two case studies that focus on identifying the value of revitalising materials. We conclude with a discussion of the implications of our work.

2. Methods

Our analysis explores the circularity of alloys that are representative of the most common metallic materials used in the aerospace industry: AA7075-T6, Inconel 718, Ti-6Al-4V, low carbon steel, and Austenitic stainless steel (AISI304). Our criteria to evaluate recyclability and maintenance potential relies on estimating primary and secondary production impact from energy consumption, CO_2 emission, and cost per kg. These indicators were estimated for each material from the existing literature [16–20]. Additional data regarding material properties were obtained from Cambridge Engineering Selector (CES) EduPack software (version 22.2.2.0) of Granta Design Limited (Level 3 Eco Design) along with literature information regarding processes. For comparing the consumption and CO_2 emission of processes, we ranked the materials' required resources based on their yield strength in two case studies.

In addition, we developed a taxonomy of techniques (Table 1) from a non-extensive number of mainstream maintenance strategies available in the literature based on the revitalisation source of energy. The energy consumption linked to the application of various techniques was utilised as a performance indicator to assess the environmental impact and rank various processes.

Table 1. Categorisation of material maintenance techniques based on mechanisms.

Mechanisms	Techniques
Coatings	Microcapsule-thickened oil barrier coatings [21] Epoxy materials with epoxy/mercaptan system [22] Laser metal deposition [23] Composite overlay [24] Electroplating [25,26]
Mechanical	Metal crack stitching [27] Grinding [28–31] Peening [32–34] Vee and Weld [35]
Thermal	Heat treatment [36,37] Electropulsing treatment [38,39] Eddy current treatment [40] Laser melting [41–43]

We also employed the Material Circularity Indicator (MCI) protocol for material-based assessment. MCI is developed by the Ellen MacArthur Foundation (EMF) and Granta Design to measure the extent to which linear flow can be minimised as well as the usage intensity of a product compared to the industry average product [44]. MCI does not consider the environmental and socio-economic risks of the analysed systems; hence, further indicators like C2C, Circular Economy Toolkit, and Circular Economy Indicator Prototype have been proposed. Following the definition, the MCI is a function of linear flow index (LFI) and utility (X), as shown schematically in Figure 2.

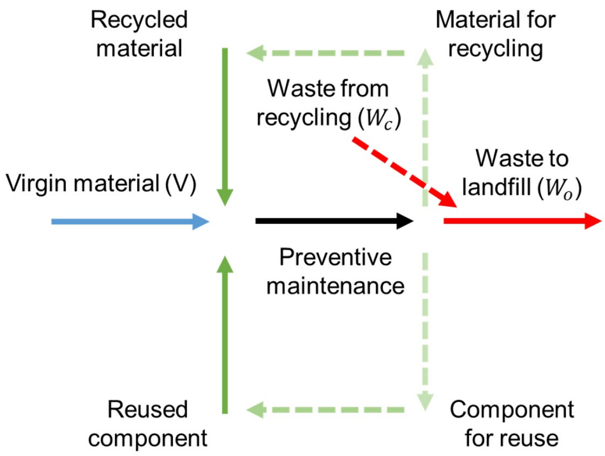


Figure 2. Graphical representation of material flow during the usage.

Using this material flow in Figure 2, the LFI can be calculated as,

$$LFI = \frac{(V + W)}{2M} \quad (1)$$

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 the product with respect to the average industrial product,

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

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 Equations (1) and (2) [44] as

$$MCI = 1 - LFI \cdot F(X) \tag{3}$$

Since we aim to preventively treat the metallic materials to extend their lives, no recycling and reuse are assumed for each technique while calculating the MCI and it solely depends on the utility or life extension potential of each technique.

Finally, the coupled output of energy–sensitivity of different techniques and MCI was verified by Multiple-Criteria Decision Analysis (MCDA) [45]. MCDA is a valuable technique to objectively rank a number of discrete alternatives on the basis of criteria (or indicators) that are not directly comparable and have a contrasting impact. In recent decades, various MCDA methods have been developed, offering tailored characteristics to meet different needs (e.g., quantitative vs. qualitative criteria, deterministic vs. stochastic vs. fuzzy uncertainty, non-compensatory vs. compensatory models) [45,46]. MCDA methods are particularly helpful in decision-making because they provide a single, unambiguous ranking based on an objective (i.e., algorithmic) consolidation method. Therefore, manufacturers may benefit from ranking material maintenance techniques which are evaluated with sustainability indicators from various sources (i.e., embodied energy and MCI). In fact, although a higher MCI determines a better environmental sustainability performance from the material-flow standpoint, a higher embodied energy has a negative impact on environmental sustainability and gives a measure of the energy flows involved.

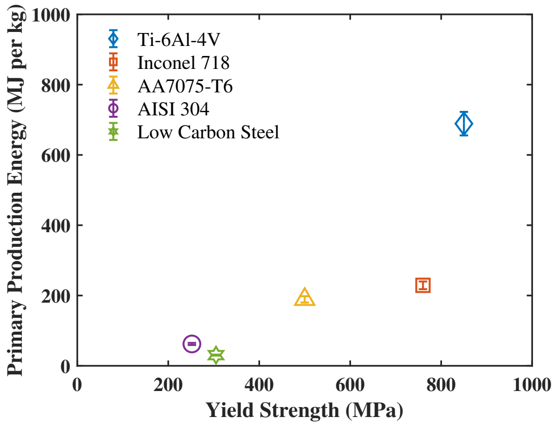
3. Results

Next, we present the environmental footprint analysis for the materials of interest, and we demonstrate the concepts with two case studies that represent engineering components.

3.1. Recycling Potential of Materials

Figure 3 compares primary production energy (Figure 3a, CO_2 emission (Figure 3b, and cost per kg (Figure 3c) for various metallic materials. This analysis demonstrates that resources and emissions have a non-linear and non-trivial relation with material strength. For example, low carbon steel or AISI304 have comparatively lower strength and require less energy with lower costs and CO_2 compared to other materials. Hence, these results suggest that the maintenance of high-strength materials such as Ti and Ni alloys should be prioritised to mitigate CO_2 emission and energy consumption.

Figure 4 highlights that the energy requirements and CO_2 emissions associated with recycling the mentioned alloys per kg of weight are considerably lower (four to eight times lower) compared to primary production. This finding aligns with the understanding that recycling plays a crucial role in reducing the environmental burden associated with material production. However, the data also suggest that recycling Ti and Ni alloys has a higher environmental burden compared to the other alloys. This indicates that extending the lifespan of these alloys through practices such as maintenance, repair, and refurbishment may provide more significant benefits to the eco-footprint than solely relying on recycling. By increasing the lifespan of Ti and Ni alloys, the need for recycling can be reduced; hence, less energy consumption and CO_2 emissions associated with the recycling processes. This finding underscores the importance of implementing sustainable maintenance practices to maximise the lifespan and value of these alloys, leading to improved environmental outcomes.



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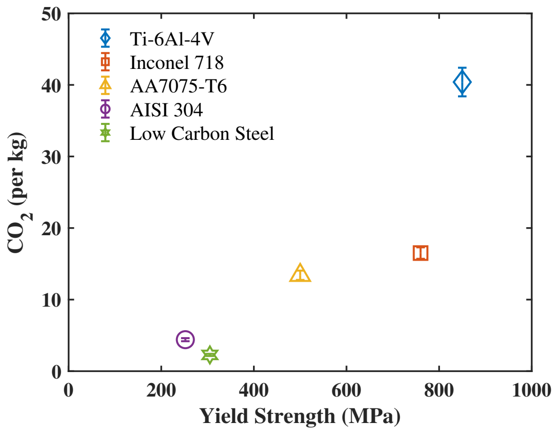

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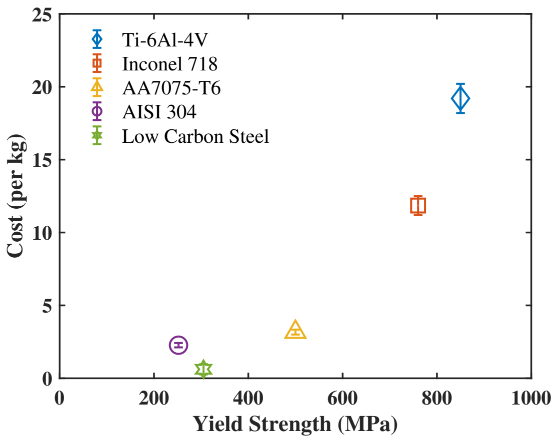

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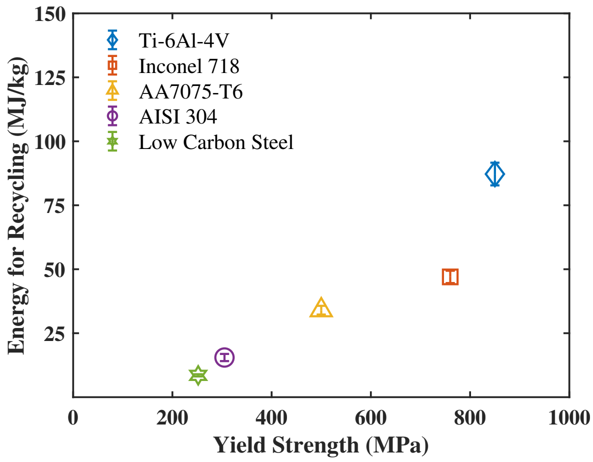
Figure 3. (**a**) Primary production energy requirement; (**b**) CO_2 emission; (**c**) Cost to produce 1 kg of materials as a function of yield strength. The comparison indicates the importance of maintenance for Ti and Ni alloys.



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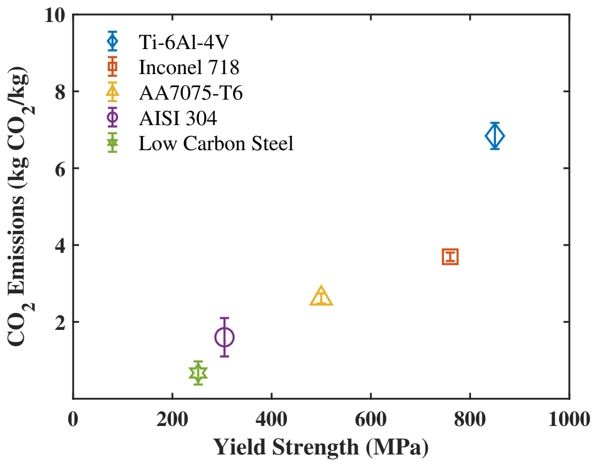

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Figure 4. (**a**) Energy requirement; (**b**) CO_2 emission associated with recycling of different materials. Environmental consequences related to secondary production follow a similar trend as primary production.

Overall, Figures 3 and 4 indicate that suitable strategies of maintenance should be applied to achieve the maximised environmental benefits and eco-footprints for Ti and Ni alloys. However, when considering load-bearing applications, it is important to recognise that different component weights are required to support similar loads. To make the comparison uniform, we designed a case study wherein a cantilever beam carries a 10 kN load (see Figure 5).

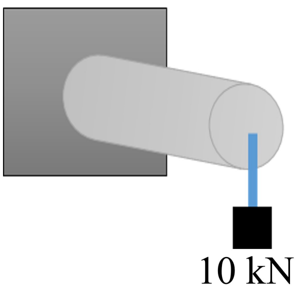


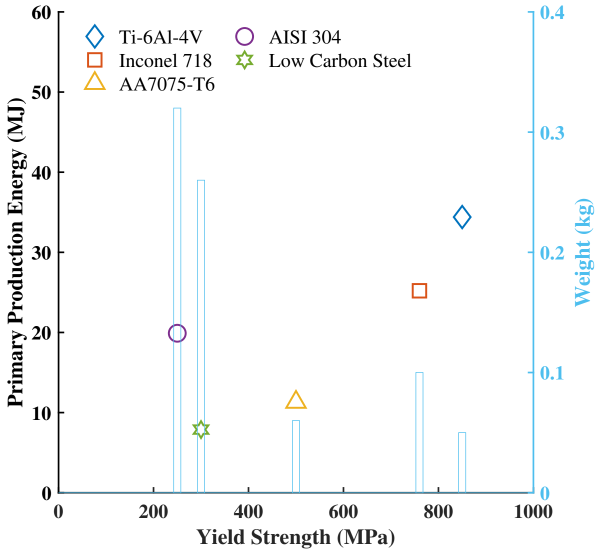
Figure 5. A cantilever beam assumed in the first case study carrying 10 kN load. The beam was assumed to be made of different alloys, as shown in Table 2.

Assuming different materials and unit thickness for the beam, the weight requirement was calculated using yield strength and density data (Table 2).

Table 2. Materials' data to design a beam carrying 10 kN load.

Material	Yield Stress (MPa)	Volume ($\times 10^{-5}$ m^3)	Density ($\times 10^3$ kg/mm^3)	Weight (kg)
Low Carbon Steel	300	3.30	7.90	0.25
AISI304	252	4.00	8.00	0.30
AA7075-T6	500	2.00	2.80	0.06
Inconel 718	760	1.35	8.25	0.10
Ti-6Al-4V	850	1.20	4.40	0.05

In Figure 6, the production energy requirement, CO_2 emission, and cost of materials are evaluated based on the calculated weights, as a function of yield strength. The data indicate that high-strength alloys such as Inconel 718 and Ti-6Al-4V result in lower weight or volume of material required compared to the other alloys. However, they still exhibit higher energy requirements and carbon footprint.



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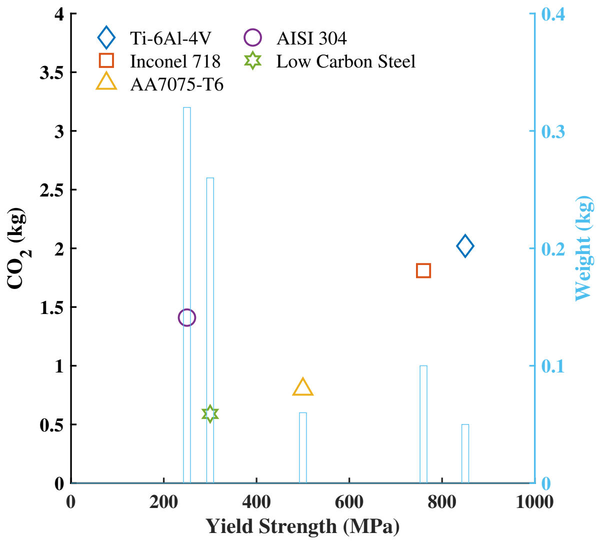

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Figure 6. *Cont.*

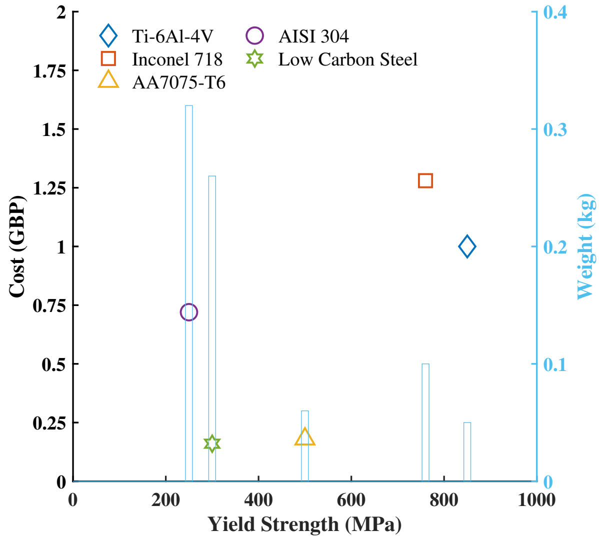

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Figure 6. (**a**) Primary production energy requirement; (**b**) CO_2 emission; (**c**) Cost of different materials for carrying 10 kN load. Blue bars indicate weight of materials required for case study one, as detailed in Table 2.

This comparison supports a similar outcome: proper maintenance strategies should be employed for high-value alloys like Ni and Ti alloys to minimise costs and mitigate the environmental footprint. Comparing the low-carbon steel and aluminium alloy, they have similar carbon footprints or costs. However, considering the higher yield strength of the aluminium alloy, it requires less material for a given application. Taking into account both factors, the aluminium alloys seem to minimise resource consumption and CO_2 emissions, making them a potentially more sustainable choice.

3.2. Environmental Footprint of Maintenance Techniques

Manufacturers may benefit from understanding the best strategies to integrate maintenance strategies to achieve sustainability and circularity goals. Hence, following our taxonomy of techniques (Table 1), we proceed to estimate the energy requirement and CO_2 emissions for various processes.

3.2.1. Coating Techniques

Coatings play a crucial role in material management by enhancing the properties and lifespan of materials. Understanding the performance requirements, a suitable coating technique should be evaluated by cost-effectiveness, compatibility, and environmental impact. Amongst the various maintenance or repair techniques mentioned in Table 1, energy input is an essential component for achieving the desired deposition and coating quality for laser metal deposition and electrodeposition. On the other hand, composite patching or barrier coatings do not need additional energy beyond the mechanical action of applying the coating. To understand the energy intensity of the processes, Figure 7 compares the energy consumed during the laser metal deposition and electrodeposition calculated from the literature [23,25,26,41]. 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 AISI304, which could be due to the lesser material and time requirement. The energy consumption for laser processes is not significant. Hence, the choice of laser metal deposition and laser plating should be different from other coatings based on process energy consumption.

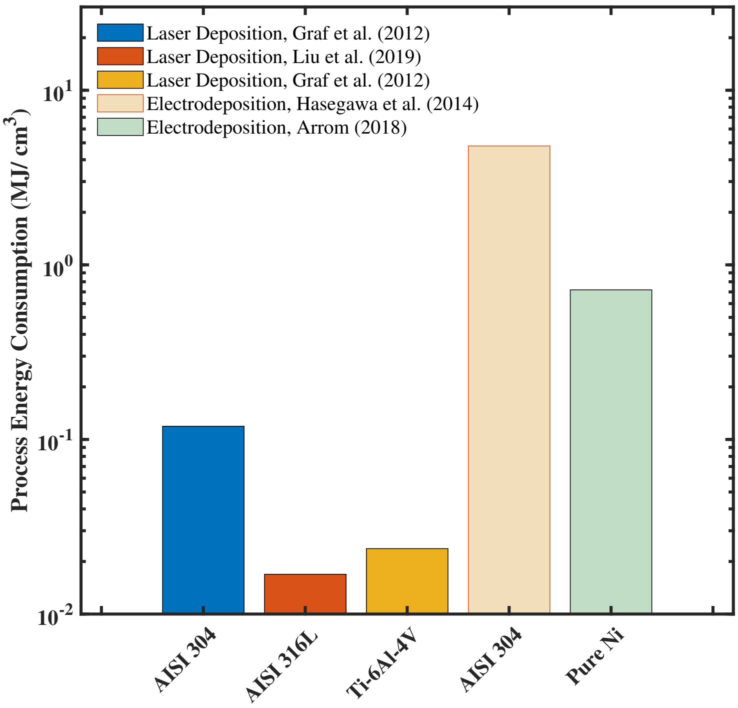


Figure 7. Comparison of process energy consumption between laser metal deposition and electrodeposition. The energy is normalised by the volume of the specimen. (The mentioned references are Graf et al. (2012) [41], Liu et al. (2019) [23], Hasegawa et al. (2014) [26], Arrom (2018) [25]).

Since all the techniques do not involve process energy, a fair comparison should consider the energy invested in the processing as well as in the production of raw materials needed for the coating. Hence, we assessed the energy required for material production for coatings and carbon footprint and compared the impact of different approaches. This was performed using a case study assuming a one-metre-long beam as a substrate to which different coatings are applied, as shown in Figure 8.

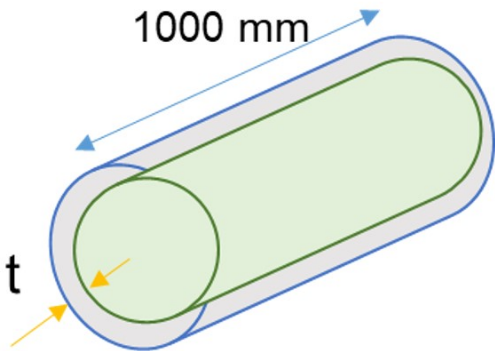


Figure 8. One-metre-long load-carrying beam considered to evaluate eco-footprints of different coatings. Here, "t" relates to the thickness of coatings from various techniques.

The thicknesses of different coatings are considered following literature recommendations and are shown in Table 3. For each material corresponding to the coating techniques, the deposited mass for lower and upper thickness values is calculated using the density of the material and volume, as shown in Table 4.

Figure 9a reflects that production energy is more important to consider compared to process energy during the selection of technology for specific maintenance. Though oil barrier coating, epoxy coating, and composite patching do not require significant energy during the application stage, they need more material; hence, they have higher energy requirements due to the higher thickness compared to other techniques. From the application and material requirement point of view, electrodeposition and laser deposition emerge as energy-friendly solutions. However, the choice of techniques is material-sensitive, as can be seen from Figure 9b. Electrodeposition of Ti-6Al-4V is costly, both economically and environmentally, as compared to AISI304.

Table 3. Different coating thicknesses needed for various techniques.

Technique	Thickness (mm)
Laser deposition	0.06–0.125
Electrodeposition	0.05–0.1
Oil and epoxy coating	1.5–3
Composite patching	0.17 (3–6 layers)

Table 4. Amount of material needed for different coating techniques.

Material	Technique	Amount Needed for Lower Thickness Values ($\times 10^{-5}$ kg)	Amount Needed for Upper Thickness Values ($\times 10^{-4}$ kg)
AISI304	Laser deposition	9	4
AA7075-T6	Laser deposition	3.2	1.5
Inconel 718	Laser deposition	9.5	4
Ti-6Al-4V	Laser deposition	5	2.2
AISI316L	Electrodeposition	7	3
Graphene	Oil barrier coating	1300	540
Epoxy	Epoxy coating	1400	570
carbon fibre	Composite patching	590	240

From the carbon emission footprint and cost viewpoints, the results show the trend presented for primary energy production techniques.Hence, our analysis suggests that oil barrier coatings and composite overlay are the worst ones among those shown in Figure 10, and that greater consideration should be given to utilising electrodeposition or laser metal deposition techniques for the revitalisation of alloys.

3.2.2. Mechanical Treatments

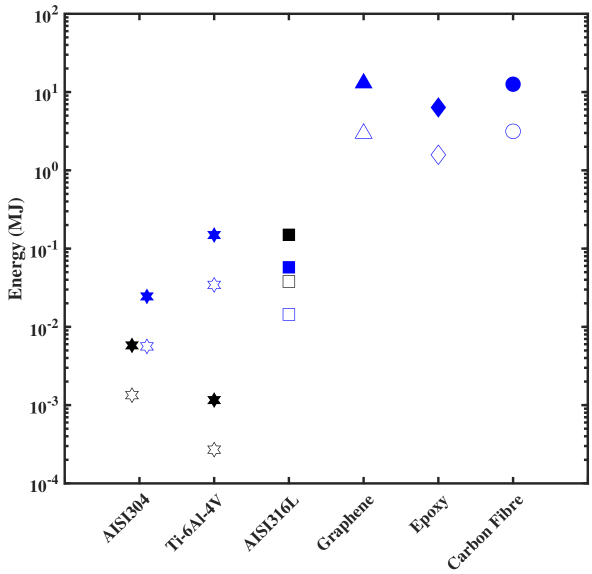
Grinding, machining, and peening are mature techniques to treat surface defects and they carry negligible material consumption compared to energy demands. Figure 11 overviews the energies consumed by different methods and materials [29–31,47], which correlates to the hardness of the material. For instance, Ti-6Al-4V and Inconel 718 are harder than AA7075 and AISI304, so the former requires more energy for grinding. Figure 11 also shows that process energy is sensitive to the milling machine. For instance, the Takisawa milling machine consumes more energy than the MHP lathe for grinding Ti-6Al-4V, which highlights the potential for improving sustainable machining processes.

3.2.3. Thermal Treatments

Regarding processes that seek changes in temperatures, Figure 12 compares the energy consumption by different techniques without considering the heat dissipated into the environment due to limited literature data [42,43]. Figure 12 shows that electric circulation methods consume less energy per unit volume as compared to the laser melting process. Overall, thermal and mechanical energy requirements are closely related.

3.3. Analysis of Material Circularity Index (MCI) and Multiple-Criteria Decision Analysis (MCDA)

Different techniques have fairly comparable MCIs in the range from 0.63 to 0.85, as shown in Table 5. However, the conclusion is not definitive since this does not account for environmental impacts.



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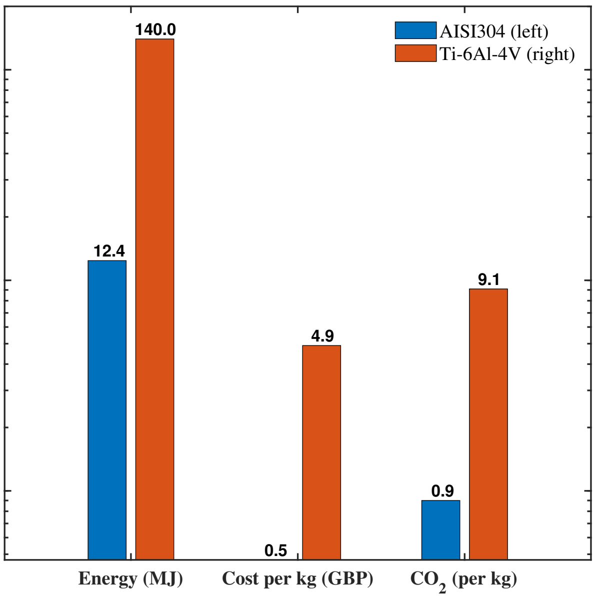

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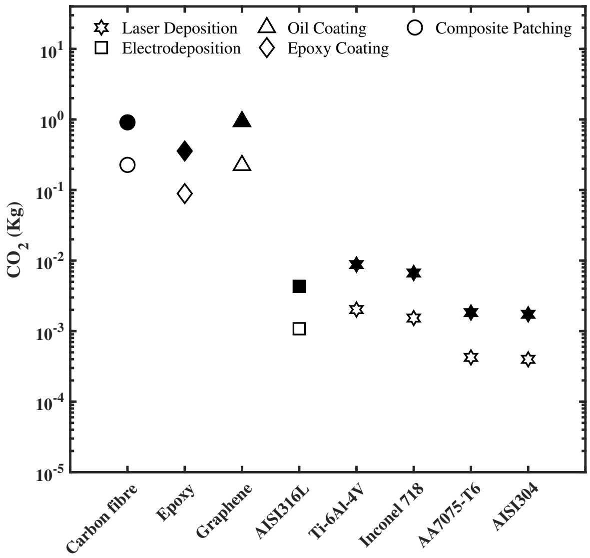
Figure 9. (**a**) Comparison of energy consumption for different techniques considering same repair. Black symbols show energy required range for application of coating while blue symbols denote the material production energy requirement. Filled and open symbols suggest upper and lower bound thicknesses, respectively, as shown in Table 2. AISI304 and Ti-6Al-4V are associated with laser deposition (shown as star), while AISI316L, Graphene, Epoxy, and Carbon fibre are related to electrodeposition (shown as square), Oil barrier coating (shown as triangle), Epoxy coating (shown as diamond), and Composite patching (shown as circle), respectively. (**b**) Comparison of ecofootprint of Ti-6Al-4V and AISI304.

Two common and suitable MCDA methods have been selected to rank the alternatives: the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [45] and COmplex PRoportional ASsessment (COPRAS) [48]. As an example, we conducted the analysis for Ti-6Al-4V considering different techniques. We used MCI and embodied energy as the criteria to rank the techniques. An average MCI for each family of techniques is obtained from Table 5, i.e., a value of 0.721 for surface coating, 0.79 for mechanical, and 0.74 for thermal processes. Embodied energies (or the production energy) for different processes were obtained from the literature, as shown in Section 3.2.



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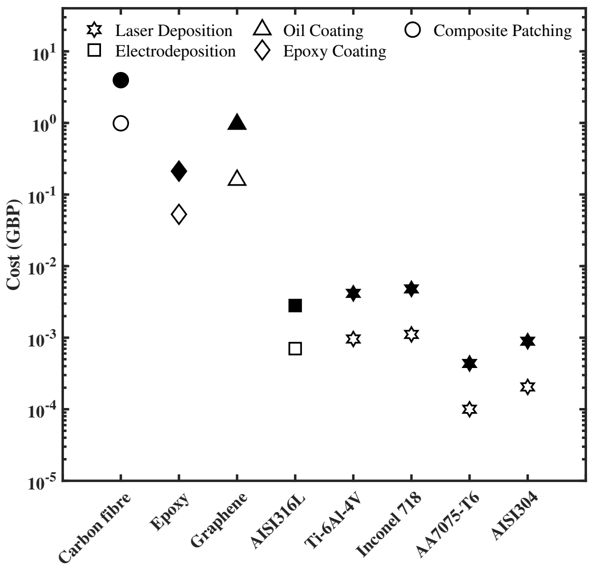

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Figure 10. (**a**) CO_2 emission and (**b**) cost of different coatings on a substrate composed of different materials. Filled and open symbols suggest upper and lower bound thicknesses, respectively, as shown in Table 2.

The consolidated scores of both MCDA methods rank the surface coating technique as the best option (by a small margin) in comparison to thermal approaches (Figure 13). Mechanical techniques are clearly ranked last in terms of environmental sustainability. It is interesting to note that the COPRAS ranking is more evident, whereas the TOPSIS score of the first two options appears very close. One typical approach to amplify the difference between options (and make the results more readable) is weighing the importance of individual criteria using their entropy of information [45]. However, as illustrated in this case, the use of another MCDA method (equally suitable for the problem, like COPRAS) can provide clarity without resorting to entropy weighting.

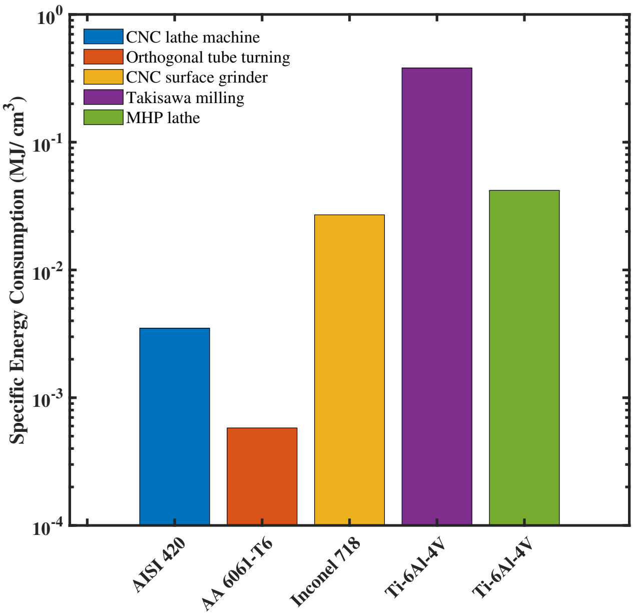

Figure 11. Specific energy consumption during the grinding process for different materials.

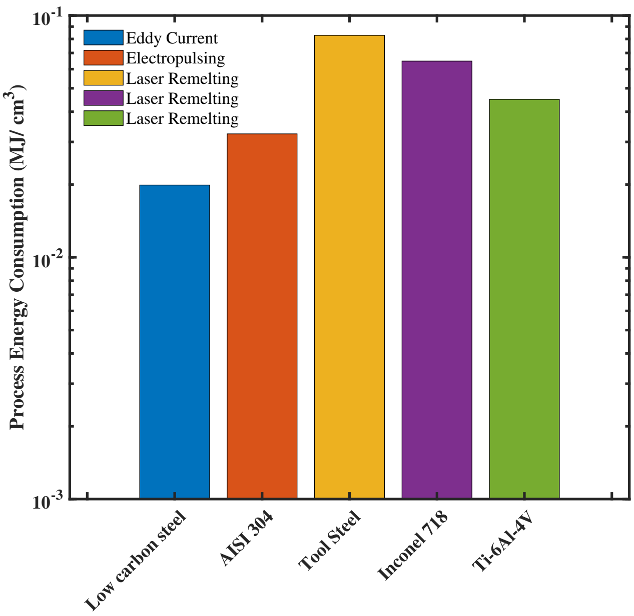

Figure 12. Comparison of energy consumption between different thermal processes for different materials.

Table 5. Material circularity index of different techniques.

Techniques		MCI	Life Extension
Coating	Oil barrier coating	0.72–0.77	60–80%
	Composite patching	0.65	30% with each patch
	Electrodeposition	0.67–0.77	40–60%
	Laser metal deposition	0.77	90–95%
Mechanical	Grinding	0.77	90–95%
	Crack stitching	0.84	95%
	Peening	0.76	95%
Thermal	Heat treatment	0.75–0.77	90–95%
	Laser melting	0.77	95%
	Electric current	0.63–0.75	20–80%

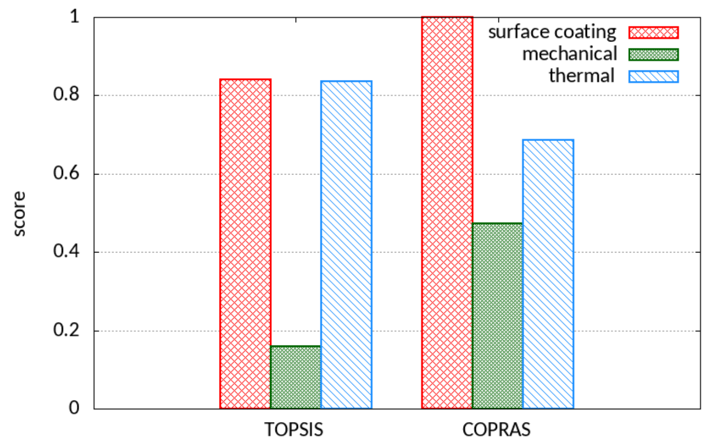

Figure 13. Consolidated environmental sustainability Multiple-Criteria Decision Analysis (MCDA) score, comprising embodied energy and the Material Circularity Index, of competing material revitalisation techniques for Ti-6Al-4V. Both MCDA methods (i.e., TOPSIS and COPRAS) agree on ranking surface coating as the best option.

4. Discussion

Our analysis compared the environmental impact of materials and revitalisation processes as a means to promote a sustainable circular economy. The analysis of pristine materials production demonstrated that high-strength metallic materials along with composite fibre have the highest effect on the environment. Hence, healing approaches applied to them without adding mass can effectively reduce extraction needs and promote longer use. For example, mechanical or thermal processes do not normally require additional material but they come at an energy cost. Overall, the present work suggests that coating technologies emerge as the greener technique for extending materials' lifespan at a minimum impact, which was also suggested by others [49]. Coatings has been considered for aesthetic and protection purposes in various materials for a long time. Yet their value in terms of increasing material circularity by revitalising products has not been clearly identified.

The concept of circular economy is directly related to the materials' efficiency, which is dependent on optimised utility embodied in materials and products during the life cycle. Manufacturers follow their own standards of material efficiency and circularity, which are normally independent of the maintenance of operators. However, we selected techniques that are well-established in aerospace applications and already in use to repair damage rather than to extend life preventively. For example, mechanical treatments can be of easier implementation than thermal approaches, while coating applications are often easy and scalable on-site. This is supported by similar MCI values for different processes, which suggests that the MCI alone cannot indicate material maintenance strategy. Further knowledge or information is needed alongside the MCI to develop a hierarchical maintenance strategy. This includes operator knowledge of the materials' behaviour, the feasibility of implementation of different techniques, the possibility in on-site/off-site conditions, etc. However, the development and certification of revitalisation approaches are in their infancy, and they should address strategies to avoid disassembly for on-site application as well as up-scaling strategies aligned with Net Zero.

MCDA is a valuable tool to consolidate conflicting characteristics of alternative revitalising techniques (like cost, quality, environmental sustainability, and productivity) and rank them objectively. The illustrative example based on Ti-6Al-4V shows the usefulness of MCDA in complex, real-world scenarios with conflicting criteria that can also be considered within a specific area (e.g., within the mentioned areas of environmental sustainability, cost, quality, and productivity). Furthermore, different decision-maker preferences can be mapped, providing a broad picture of the decision-making space [50].

Finally, one important consideration is that we focused on materials and techniques that are well-established and can have a short-term impact. Nevertheless, we envision the design of novel materials associated with revitalisation therapies tuned to specific applications. For example, metallic materials can be designed at a metastable state such that electropulse cycles localise the energy around damaged areas and reconfigure the local properties to extend life.

5. Conclusions

This work explored a preventive maintenance perspective applied to extend the lifespan of metallic materials. The rationale to justify preventive maintenance of components depends on multiple characteristics such as cost of maintenance, size and morphology of defects, availability of replacement, etc. A hierarchy of alloys was proposed to decide between repair and recycling operations. The case studies revealed that high-strength materials (e.g., Ti-alloys) have a higher environmental footprint and should be given priority for revitalising. Also, existing maintenance techniques were evaluated based on their environmental footprints and feasibility of application in the transportation sector. An illustrative application of MCDA to objectively rank material revitalisation approaches in terms of environmental sustainability for Ti-6Al-4V has been conducted. This study shows that surface coating is the preferable option, followed by thermal processes. Based on current practice and theoretical data, coating techniques present a sustainable solution for preventive maintenance. We also specify the direction for future work to nurture preventive maintenance by highlighting challenges related to other potential techniques.

Author Contributions: Conceptualisation, A.L. and G.M.C.; methodology, G.M.C. and F.A.; software, F.A.; validation, F.A. and E.P.; formal analysis, F.A. and E.P.; investigation, F.A.; resources, F.A.; data curation, F.A. and A.L.; writing—original draft preparation, A.L.; writing—review and editing, G.M.C., F.A. and E.P.; visualisation, A.L. and F.A.; supervision, G.M.C.; project administration, G.M.C.; funding acquisition, G.M.C. and A.L. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by Circular Economy Network+ in Transportation Systems (CENTS) as a feasibility study. CENTS is an EPSRC-funded research network for the sustainable transport community.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors express their gratitude to Mark Jolly, Cranfield University for his suggestions and mentoring during the project.

Conflicts of Interest: The authors declare no conflicts of interest.

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2023-07-28

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MDPI

Ashraf F, Lodh A, Pagone E, Castelluccio GM. (2023) Revitalising metallic materials: a path towards a sustainable circular economy, Sustainability, Volume 15, Issue 15, July 2023, Article Number 11675

https://doi.org/10.3390/su151511675