Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 26 (2020) 28–34

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

The 1st Mediterranean Conference on Fracture and Structural Integrity, MedFract1

How to apply mitigating actions against critical raw materials issues in mechanical design

P. Ferro*, F. Bonollo

Department of Engineering and Management, University of Padova, Stradella San Nicola 3, 36100 Vicenza (Italy)

Abstract

Circular economy, *sustainability* and *design for environment* are some of the keywords that identify new formidable challenges to be faced in the next years. Raw materials have a dominant role in reaching that goal. Green energy, electric vehicles, communication, etc. depends on raw materials labeled as critical because of their economic importance coupled with high supply risk. For this reason, mitigating actions need to be used in materials selection and design such as material substitution, materials efficiency improvement and recycling. In this work, a method to implement raw materials criticality issues in materials selection for mechanical design is described according to the recent literature. The strategy is based on Ashby's approach and the definition of the alloy criticality index quantifying the criticality per unit of mass of the material.

Keywords: Critical raw materials; material selection; mechanical design

---

1. Introduction

European policies will be framed by the objective of becoming the first climate-neutral continent by 2050 and raw materials (RMs) have a dominant role in reaching that goal. Green energy, electric vehicles, communication, etc. depends on raw materials labeled as critical above all because of their economic importance coupled with their

---

* Corresponding author. Tel.: +39 0444 998769; fax: +39 0444 998888.
E-mail address: paolo.ferro@unipd.it

10.1016/j.prostr.2020.06.005

high supply risk. Therefore, mitigating actions need to be used in materials selection and design. They are: material substitution, materials efficiency improvement and recycling.

Alloys that minimize the environmental impact of a product may suffer of a supply risk because of the presence, inside them, of high mechanical properties inducing alloy critical elements. A multi-objective design approach is thus required that takes into account both the environmental impact reduction and the criticality issues linked to raw materials (P. Ferro et al., 2020).

Unfortunately, the criticality assessment related to raw materials is a very difficult task and there is not a recognized method to reach that goal in literature (Achzet and Helbig, 2013; Blengini et al., 2017). In a recent paper, Hofmann et al. (2018) showed that material scientists seem frequently not concerned with the criticality of raw materials in their work so that they suggested to advance the implementation of the concept of materials criticality in materials research and development.

Today, materials are selected in mechanical design with no integration among performance, supply risks and sustainability requirements. The result is that a great part of industrial world is still unprepared to face the twenty-first century challenges related to a smart use of raw materials. Engineers and designers have, generally speaking, a poor knowledge about materials, but this knowledge is highly lacking when criticality issues about Raw Materials are addressed. This contribution is aimed at describing how to apply mitigating actions against critical raw materials (CRMs) issues in mechanical design.

2. Material selection strategy

Materials selection should accompany all the phases of the design process, from the concept to the details. The consequences of choices made at the concept or embodiment stages may not become apparent until the detail is examined. Iteration, looping back to explore alternatives, is an essential part of the design process. Thus, the materials selection strategy must be systematic and easy to apply. In 2004, Ashby et al. (2004) published a paper dealing with a powerful method to select materials and processes. It consists of four main steps. Starting from the materials universe, design requirements have to be first translated in terms of constraints, free variables and objectives to optimize. All materials are then screened according to constraints and the 'surviving materials' are ranked using the objective. Finally, supporting information is required to select the best material. The method requires a database in which physical, chemical, thermo-mechanical properties are stored for each material.

An interesting concept of the Ashby's method is the definition of the material index that is used to rank the surviving materials. Starting from the objective equation, it is calculated by eliminating the free variable through the constraint equation. For example, if the material that minimizes the mass (m) of a tie rod is to be select, the objective equation is:

$$m = \rho L A \tag{1}$$

where ρ is the material density, L is the length and A is the cross section (free variable) of the component. If the tie rod stiffness (S) is the constraint to take into account,

$$S = EA / L \tag{2}$$

with E = Young's modulus, the free variable is obtained from Eq. (2) and substituted into Eq. (1) obtaining:

$$m = SL^2 \rho / E \tag{3}$$

With fixed values of L and S, the lower the ratio ρ/E, the lower the mass of the tie rod. ρ/E is called material index and it is a function of material proprieties only. Commonly, it is used its inverse expression (say, M = E/ρ) with the aim to optimize the objective equation (Eq. (3)) by maximizing the index M. Now the question is: which is the objective equation used to select materials in a critical raw materials (CRMs) perspective? To answer this question, it is necessary first to quantify the criticality issues of a generic raw material.

Criticality issues linked to each raw material are quantified by a series of indexes such as the abundance risk (ARL), the sourcing and geopolitical risk (SGR), the environmental country risk (ECR), the normalized supply risk

(NSR), the economic importance (EI) and finally, the recycling drawback index (RDI) (Critical Raw Materials Factsheets, year 2017). In order to use such indicators in design, it is necessary to aggregate them in an overall general indicator for each critical raw material (i) (CI_{CRMi}):

$$CI_{CRM_i} = (k_{ARL}ARL_i + k_{SGR}SGR_i + k_{ECR}ECR_i + k_{NSR}NSR_i + k_{NEI}NEI_i + k_{RDI}RDI_i)/6 \tag{4}$$

In Eq. (4) k is a non-dimensional coefficient which value is in between 0 and 1, according to the seriousness of the corresponding criticality aspect. When all k values are set equal to 1 in Eq. (4), equal seriousness is perceived for all the criticality aspects. The values of the criticality index in Eq. (4) are calculated by using data taken from the literature (Critical Raw Materials Factsheets, year 2017). Table 1 collects the numerical values of each criticality index. It is observed that the high seriousness of the European Union dependence from rare earths is reflected by the highest values of their criticality indicator.

Table 1. Raw materials criticality indexes elaborated starting from values coming from the European Commission evaluations [2]. *LREEs = Light rare earth elements; **HREEs = Heavy rare earth elements.

CRM	ARL	SGR	ECR	NSR	NEI	RDI	CI_{CRM}
Sb	6.15	6.46	7.68	8.78	5.89	3.64	6.43
Ba	2.82	2.59	2.62	3.27	3.97	9.77	4.17
Be	5.00	4.49	6.43	4.90	5.34	10.00	6.03
Bi	7.52	7.18	8.52	7.76	4.93	9.77	7.61
B	4.45	5.04	5.31	6.12	4.25	10.00	5.86
Ce (LREEs*)	3.63	10.00	9.49	10.00	4.93	9.77	7.97
Co	4.05	4.20	3.94	3.27	7.81	10.00	5.55
F	2.68	-	-	2.65	5.75	9.77	-
Ga	4.17	6.88	8.19	2.86	4.38	10.00	6.08
Ge	5.27	6.97	8.33	3.88	4.79	9.55	6.46
Hf	4.97	1.31	2.02	2.65	5.75	9.77	4.41
He	-	-	-	3.27	3.56	9.77	-
In	6.05	3.57	3.97	4.90	4.25	10.00	5.46
Ir	8.45	5.49	6.66	5.71	5.89	6.82	6.50
La (LREEs*)	3.86	8.40	10.00	10.00	4.93	9.77	7.83
Mg	1.08	7.85	9.33	8.16	9.73	7.95	7.35
Natural graphite (carbon)	3.15	6.98	8.33	5.92	3.97	9.32	6.28
Nb	4.15	5.48	6.17	6.33	6.58	9.93	6.44
Pd	7.27	3.11	3.11	3.47	7.67	7.73	5.39
P	2.43	-	-	2.04	6.99	6.14	-
Pt	7.75	3.93	4.71	4.49	6.71	7.50	5.85
Pr	4.49	8.40	10.00	10.00	4.93	7.73	7.59
Rh	8.45	5.49	6.73	5.10	9.04	4.55	6.56
Ru	8.45	5.49	6.73	6.94	4.79	7.50	6.65
Sc	4.11	10.00	9.49	10.00	4.93	9.77	8.05
Si	0.00	5.37	6.36	2.04	5.21	10.00	4.83
Ta	5.15	2.89	3.57	2.04	5.34	9.77	4.79
W	5.35	7.24	8.58	3.67	10.00	0.45	5.88
V	3.37	4.43	5.15	3.27	5.07	0.00	3.55
Y (HREEs**)	3.93	10.00	9.49	10.00	4.93	9.77	8.02

Since CRMs may be contained, in different amounts, in the material composition (say, metallic alloy), the material criticality index can be defined as follows:

$$CI = \sum_{i=1}^{n} CI_{CRM_i} wt\%_{CRM_i} / 100 \tag{5}$$

where n is the number of CRMs in the material chemical composition and $wt\%_{CRMi}$ is the amount of the CRM 'i' measured in weight percent. It is noted that the criticality index (CI) represents an overall criticality value per unit of mass of the material.

3. Application of mitigating actions in mechanical design

3.1. Material efficiency

Once the overall material criticality is assessed (Eq. 5), the objective equation for the material index calculation in the frame of Ashby's method is:

$$\mathrm{m}^* = \mathrm{m} \cdot \mathrm{CI} \tag{6}$$

Since CI defines the criticality per unit of mass of the material, m* quantifies the criticality of the whole component in a CRMs perspective. By using the example described in the introduction, it is easy now to demonstrate that the material index for a rigid and low-criticality tie rod is:

$$\mathrm{M} = \frac{\mathrm{E}}{\rho \cdot \mathrm{CI}} \tag{7}$$

In the so-called Ashby's maps, that are log-log plots showing the position of different materials in the space defined by two materials properties (or combination of them) (Fig. 1), Eq. (7) is a series of parallel straight lines of slope 1 (index lines). As M value increases, the index line moves toward the top left corner of the map. Materials on the left of the index line (search area) are of interest. By increasing the M value the search area narrows and selects the materials that optimize the objective (Ferro and Bonollo, 2019). This approach can be easily extended to design for recycling (Ferro and Bonollo, 2019), material substitution (P. Ferro et al., 2020) as well as design for environment in a CRMs perspective (P. Ferro et al., 2020).

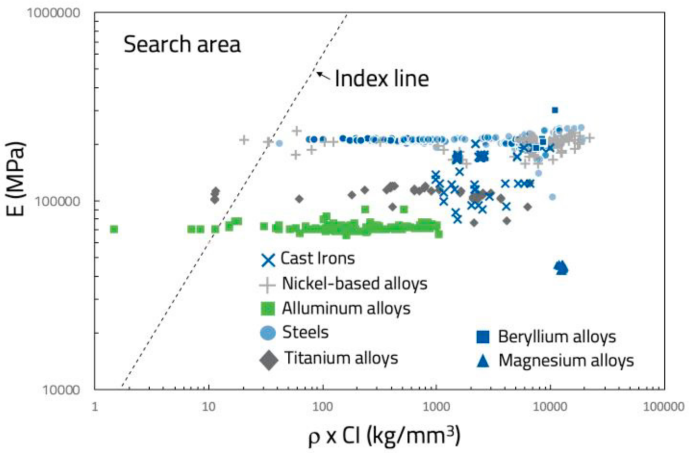

Fig. 1. Metallic materials map for material selection in a CRMs perspective

3.2. Recycling

By taking into account recycling as a mitigating action to reduce the CRMs related issues, the objective equation (m*) takes now the following form (Eq. 8):

$$m^* = (1-\chi_a)\cdot m \tag{8}$$

where m is the mass of the component to be produced and (1-χ_a) is an index quantifying the criticality in terms of EOL-RIR per the unit of mass of the alloy itself:

$$\chi_a = \sum_{i=1}^{n}\left(\frac{(EOL-RIR_i)\%}{100}\right)\frac{wt\%_i}{100} \tag{9}$$

In Eq. (9) n is the number of elements in the alloy chemical composition, wt%$_i$ is the amount of element ‘i’ contained in the alloy and measured in weight percent and EOL-RIR$_i$ is the end-of-life recycling input rate of the CRM ‘i’ defined as the ‘input of secondary material to the European Union (EU) from old scrap to the total input of material (primary and secondary)’. Furthermore, the EOL-RIR of non-critical elements is assumed equal to 100%.

Since χ_a quantifies the total EOL-RIR per unit of mass of the alloy, the objective equation m* measures the criticality associated to the critical raw materials EOL-RIR per unit of function (to be minimized). The minimization of m* is aimed at limiting the amount of CRMs having the lowest EOL-RIR values required to produce a specified component. For example, if now the constraint equation for the tie rod carrying a tensile force F without failure is:

$$\frac{F}{A} \le \sigma_y \tag{10}$$

where σ_y is the yield stress of the alloy, it is easy to demonstrate that the material index to maximize is:

$$M = \frac{\sigma_y}{(1-\chi_a)\rho} \tag{11}$$

The materials map to use in this case is shown in Fig. 2.

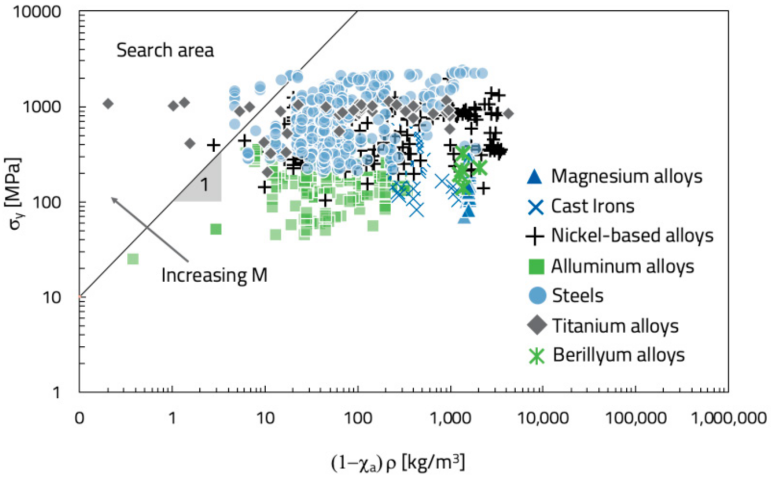

Fig. 2. Ashby’s map for alloy selection in a CRMs recycling perspective.

3.3. Material substitution

For material substitution purpose in a CRMs perspective, it is required to reduce the component criticality while maintaining, or even increasing, at the same time the actual component performance. If the constraint equation is given by the tie rod stiffness (Eq. 2) and the component performance is the mass, it is convenient to minimize the material index, $M_m = \rho/E$. On the other hand, in order to reduce the component criticality, the material index will be the inverse of Eq. 7. If M_m^* and M^* are now the material indexes of the actual material to be substituted, it is useful to plot the relative values of the material indexes, as shown in Fig. 3.

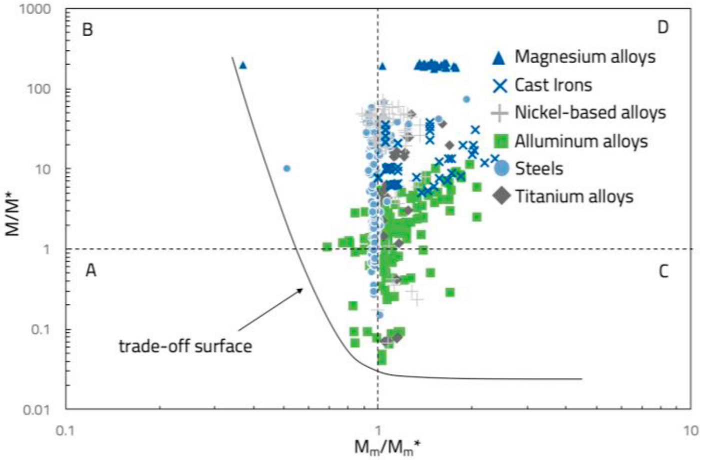

Fig. 3. Trade-off diagram for material substitution in a CRMs perspective.

By taking the steel SA212 (normalized) as the actual material to be substituted, and identified by the coordinates (1,1) in Fig. 3, it is easy to guess that the best alternative material lays near the trade-off surface in quadrant A, as it reduces both the mass, m, and the criticality issue, m*. In all cases, the materials selection needs to take into account the top three or five materials since supporting information and design verification are required before reaching the final choice. For instance, a limit in the free variable values cold result in the impossibility to select the material number one in the top five materials.

4. Conclusions

The 21st century challenges related to a new economy that respects the environment and resources can be tackled by an excellent knowledge of materials and even the acquisition of new skills that allow engineers and designers to apply mitigating actions against resource and energy consumption. In this scenario, a systematic strategy to select materials in a critical raw materials perspective was developed. The proposed strategy is based on the material criticality index definition that in turn allows defining an objective equation for the material index calculation following the Ashby's procedure. The method is particularly suitable for the application of mitigating actions against CRMs intensive use (recycling, substitution, material efficiency).

Acknowledgements

This work is part of the results of the European project called 'Design of Components in a Critical Raw Materials Perspective' (DERMAP, KAVA project # 17205). Authors want to thank EIT RawMaterials for the financial support and all the Project Partners (SWEREA SWEECAST AB, Mondragon University, AGH University, EURECAT, Enginsoft, Fonderie Zanardi) for their contribute to the project development.

References

Achzet, B., Helbig, C. How to evaluate raw material supply risks -an overview. Resources Policy 38 (2013) 435–447

Ashby, M.F., Bréchet, Y.J.M, Cebon, D., Salvo, L. Selection strategies for materials and processes. Materials & Design, Vol 25, Issue 1, 2004, 51-67

Blengini, G. A., Nuss, P., Dewulf, J., Nita, V., Peirò, L. T., Legaz, B.V., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Maercke, A.V., Solar, S., Grohol, M., Ciupagea. C. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. Resources Policy 53 (2017) 12–19

Critical Raw Materials Factsheets. Study on the review of the list of Critical Raw Materials, (year 2017) (ISBN 978-92-79-72119-9, doi: 10.2873/398823)

Ferro, P., Bonollo, F. & Cruz, S.A. Alloy Substitution in a Critical Raw Materials Perspective. Frattura ed Integrità Strutturale, 51 (2020) 81-91.

Ferro, P., Bonollo, F. & Cruz, S.A. Product design from an environmental and critical raw materials perspective, 2020 International Journal of Sustainable Engineering, DOI: 10.1080/19397038.2020.1719445

Ferro, P., Bonollo, F. Design for Recycling in a Critical Raw Materials Perspective. Recycling 2019, 4, 44; doi:10.3390/recycling4040044

Ferro, P., Bonollo, F. Materials selection in a critical raw materials perspective. Materials and Design 177 (2019) 107848

Hofmann, M., Hofmann, H., Hagelüken, C., Hool, A. Critical raw materials: A perspective from the materials science community. Sustainable Materials and Technologies 17 (2018) e00074