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Material selection for high temperature applications

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Abstract In this paper several materials have been evaluated in order to select the best suitable alloy for the production of a gas turbine transition piece. These components are exposed to complex thermal stresses and different damages, each of them requiring particular characteristics of the material. The procedure described takes into account the variability of requirements with some parameters, in particular temperature and service time. Due to the high value of temperature and the constraint of ductility, the choice of material has been limited to superalloys and stainless steels. A comparison between several alloys has been carried out on the basis of constraints and requirements previously determined. Using a suitable objective function, the method allows ranking materials in order to find the alloy which maximize component's performance.

Keywords Material selection · High temperature materials · Transition piece · Superalloys

1 Introduction

In the selection of materials several studies have been performed [1, 2] in order to determine a property, or a combination of properties, which specify the role of materials in component performance. The choice of materials is carried out using specific, measurable characteristics that are identified by customers as necessary for their satisfaction. According to terminology of Six Sigma approach, these requirements are called Critical to Quality (CTQs) [3], and they define in this case a set of attributes required for a material in a specific application.

The final choice is performed on the basis of a suitable function which combines different requirements in multi-goal problems. The step from CTQs to analytical relations useful for the target function is critical and this phase of the work is often underestimated.

For high temperature applications it is often very difficult to perform a comparison among materials and to select the best one for a specific application, because the components are subjected to different damage causes (fatigue, creep, oxidation, etc.) and balancing contrasting characteristics is frequently required. Moreover, the design values often are not clearly defined, depending on material properties. A significant example is the service temperature, which depends on many parameters, such as thermal conductivity, type of cooling, thermal exchange coefficients, etc.; some of these parameters are specific properties of the particular material considered. In order to overcome this problem, a range of design values has been considered in this work, taking the variations of material properties into account and allowing an objective evaluation for the choice of the best material.

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2 Procedure

A selection procedure has been proposed in this paper in which the variability of the requirements on some parameters (e.g., temperature and service time) is considered. This procedure has been applied to the transition piece of a gas turbine.

Considering the high temperature value on the component, only superalloys and stainless steels have been considered. Twenty-two different materials have been selected. Their properties have been retrieved both by databases or leaflets, available online, of the main superalloys industries—like Special Metals™ and Haynes Int.™—and in the technical literature [4]. Availability and reliability of data are fundamental for the correct application of this method.

On the basis of the average temperature in working conditions, four different temperature values have been chosen: 850 °C, 900 °C, 950 °C and 1000 °C. For every CTQ, the material characteristics have been compared and, for each value of temperature, specific indices have been defined which balance strength and design values. Then these indices have been combined in a single parameter (as percentage of that corresponding to the material with maximum value). The parameters thus identified take the variation of material properties with temperature into account.

Often it was not been possible to find all the material data or, when found, they frequently did not correspond to temperatures above mentioned. Missing information was evaluated by numerical regression and fitting of available data. The indices have been combined using the weight factors defined with CTQs and finally the materials have been sorted and the best one for the transition piece application identified.

2.1 CTQs and constraints

The first step is the definition of constraints and CTQs: constraints are non-negotiable characteristics which define the field of material selection, CTQs are combinations of material properties that must be maximized in order to optimize the performance.

To identify these requirements, people which have an active part in both production and use of the component—designers, manufacturing managers and clients—have been consulted. By means of interviews, suitable information has been obtained and specific material characteristics have been identified. In the answers each material property is coupled to a coefficient that indicates its relative importance.

Table 1 Materials constraints

Number	Constraint
1	ductile
2	melting point greater then 900 °C
3	weldable
4	available in sheet
5	workable by plastic deformation
6	machinable

Table 2 Materials CTQs and CTQ weights

Number	CTQ	CTQ weight
1	thermal stress	5.1
2	cost	2.7
3	creep strength	9.7
4	LCF strength	9.5
5	HCF strength	3.5
6	oxidation resistance	5.8
7	yield strength	4.2

From the information collected, constraints and CTQs have been identified [5]. The weight factors have been evaluated on the basis of both frequency and relative importance in the obtained answers.

Constraints and CTQs thus obtained are reported in Tables 1 and 2, respectively. Most of the constraints derive from the fact that it is not possible to modify the actual manufacturing process. In order to increase the performance of the component, it is very important to maximize the material resistance to all damage mechanisms acting on the component. Material cost frequently is the most important factor in material selection. In this work it was not considered as a fundamental parameter, because for this specific application it varies between 5% and 15% of the total component cost; therefore, the cost increase of the raw material can be neglected thanks to the benefit of a much longer achievable service.

3 Selection and comparison of materials

The transition piece considered is now produced with Nimonic 263, a nickel based superalloy. Its tensile

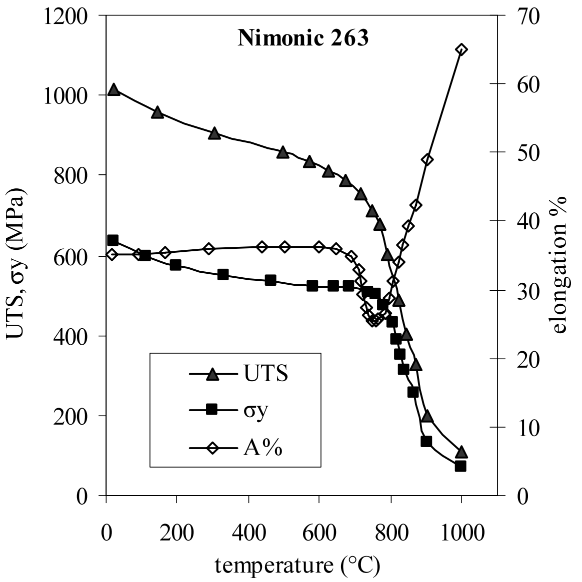

Fig. 1 Ultimate tensile strength (*UTS*), yield strength (σ_y) and elongation (A) of Nimonic 263

properties are reported in Fig. 1, in which one can easily observe that alloy properties decay very quickly above 850 °C (owing to the solution of γ' hardening phase), namely in the range of temperatures considered for the material selection.

A large set of materials, which satisfied the constraints, has been considered in this work. All these materials are shown in Table 3 and in particular they are: 3 stainless steel, 2 iron based alloys, 2 cobalt based superalloys and 15 nickel based superalloys.

It must be noted that Udimet 700 superalloy has been considered because it is recently available in sheet form and thus compatible with the involved constraints, but its data are relative to cast material because they are the only available at the moment. During the analysis of the results this aspect must be considered.

3.1 Creep comparison

The creep strength is the most important CTQ and the comparison has been done with Larson-Miller parameter (*PLM*), defined as follows:

$$PLM = T \cdot [C + \text{Log}(t)] \quad (1)$$

where T is the temperature in kelvin, t is the time in hours and C is a constant of the material, assumed

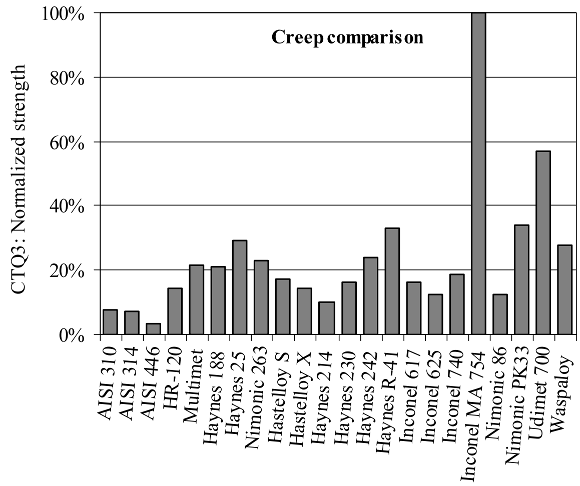

Fig. 2 Normalized creep index

in this work to be equal to 20 for all the superalloys analysed. The Larson-Miller parameter has been chosen because it allows the master curve to be used for the comparison and not the stress-time curves which are temperature dependent [6].

For PLM in design conditions, the value of 29000 has been evaluated from service time and design temperature and the comparison has been done using the stress (CR) related to this value. In some cases it has been necessary to extrapolate the master curve with an exponential function in order to find the required value; in this case the fitting coefficient was always greater then 0.9.

The CR values, obtained for all materials, have been summarized in Fig. 2, where they are normalized to the best material. The worst alloys are the three stainless steels, while the best is Inconel MA 754, an ODS (oxide dispersion strengthened) nickel based superalloy.

3.2 Low cycle fatigue comparison

The second CTQ that has been analysed is the material behavior to Low Cycle Fatigue (LCF). LCF data are very difficult to find in the technical literature and available information on the selected materials is very limited.

In order to determine the LCF behavior of materials several methods have been used which provide the Manson-Coffin curve starting from tensile data. In particular they are: Original Universal Slopes Method

Table 3 List of selected materials with their composition

Alloy	Base element	Composition
AISI 310	Fe	0.25C, 25Cr, 21Ni, 2Mn, 1.5Si
AISI 314	Fe	0, 25C, 25Cr, 21Ni, 2Mn, 2.5Si
AISI 446	Fe	0, 2C, 26Cr, 1.5Mn, 1Si
HR-120	Fe	37Ni, 25Cr, 3Co, 2.5Mo, 2.5W, 0.7Nb, 0.7Mn, 0.6Si
Multimet	Fe	21Cr, 20Ni, 20Co, 3Mo, 2.5W, 1.5Mn, 1Nb + Ta, 1Si
Haynes 188	Co	22Ni, 22Cr, 14W, 3Fe, 1.25Mn, 0.35Si, 0.03La
Haynes 25	Co	20Cr, 10Ni, 15W, 3Fe, 1.5Mn, 0.4Si
Nimonic 263	Ni	20Cr, 20Co, 6Mo, 2Ti, 0.7Fe, 0.6Al, 0.6Mn, 0.4Si, 0.2Cu
Hastelloy-S	Ni	16Cr, 15Mo, 3Fe, 2Co, 1W, 0.5Si, 0.4Al, 0.3Cu, 0.05La
Hastelloy-X	Ni	22Cr, 19Fe, 9Mo, 1.5Co, 1Si, 1Mn, 0.7W
Haynes 214	Ni	16Cr, 4.5Al, 3Fe, 0.5Mn, 0.2Si, 0.1Zr, 0.01Y
Haynes 230	Ni	22Cr, 14W, 5Co, 3Fe, 2Mo, 0.5Mn, 0.4Si, 0.3Al, 0.02La
Haynes 242	Ni	25Mo, 8Cr, 2.5Co, 2Fe, 0.8Mn, 0.8Si, 0.5Al, 0.5Cu
Haynes R-41	Ni	19Cr, 11Co, 10Mo, 5Fe, 3.1Ti, 1.5Al, 0.5Si, 0.1Mn
Inconel 617	Ni	22Cr, 13Co, 9Mo, 3Fe, 1.2Al, 1Si, 1Mn, 0.6Ti, 0.5Cu
Inconel 625	Ni	22Cr, 13Co, 9Mo, 5Fe, 4Nb, 1Co, 0.5Si, 0.4Al, 0.4Ti
Inconel 740	Ni	25Cr, 20Co, 2Nb, 1.8Ti, 0.9Al, 0.7Fe, 0.5Mo, 0.5Si
Inconel MA 754	Ni	20Cr, 1Fe, 0.6Y, 0.5Ti, 0.3Al
Nimonic 86	Ni	25Cr, 10Mo, 0.03Ce
Nimonic PK 33	Ni	18Cr, 14Co, 7Mo, 2Ti, 2Al, 1Fe, 0.5Si, 0.2Cu, 0.06Zr
Udimet 700	Ni	17Co, 15Cr, 5Mo, 4Al, 3.5Ti, 0.5Fe
Waspaloy	Ni	19Cr, 13.5Co, 4.3Mo, 3Ti, 2Fe, 1.5Al, 0.15Si, 0.05Zr

[7], Modified Universal Slopes Method [8], Uniform Material Law [9] and Modified Mitchell Method [10]. Comparing the results obtained with some available experimental curves, the best fit has been obtained employing the Universal Material Law method. This method has been used for all materials to perform LCF comparison.

The comparison has been carried out referring to a "LCF" index, defined for each material as follows:

$$LCF_m = (\Delta\varepsilon_{m1} - \Delta\varepsilon_1) + (\Delta\varepsilon_{m2} - \Delta\varepsilon_2) + (\Delta\varepsilon_{m3} - \Delta\varepsilon_3) + (\Delta\varepsilon_{m4} - \Delta\varepsilon_4). \quad (2)$$

To evaluate this index some design values are used and in particular the required number of cycles (250) with the associated strain range values at the different temperatures considered, which are: $\Delta\varepsilon_1 = 0.604\%$ at 850 °C, $\Delta\varepsilon_2 = 0.435\%$ at 900 °C, $\Delta\varepsilon_3 = 0.265\%$ at 950 °C, $\Delta\varepsilon_4 = 0.085\%$ at 1000 °C. In (2) $\Delta\varepsilon_{m1} - \Delta\varepsilon_{m4}$ are the values (for material m) of the strain ranges corresponding to 250 cycles at the four selected temperatures. If a term in brackets is negative, the index LCF is set equal to zero. The obtained results have been normalized and shown in Fig. 3.

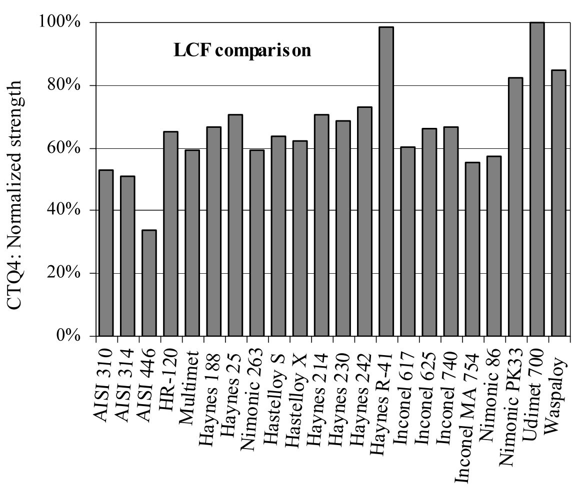

Fig. 3 Normalized LCF index

3.3 Oxidation comparison

Data reported in Haynes Int.™ brochures have been considered for the oxidation resistance; they are only available for 1000 hours and at 980 °C. In the test, samples were exposed to air flowing in a tube furnace. Following the exposure, thinning and average depth of oxidation penetration were determined. Oxidation is expressed by the sum (S_m) of these two quantities, measured in μm.

The inverse of S_m has been assumed as the oxidation strength parameter (OR) for the selected material.

$$OR_m = 1/S_m. \tag{3}$$

Then the OR values have been normalized in comparison to the maximum value of the same parameter. The results are shown in Fig. 4.

3.4 Thermal stress comparison

An important factor is the product between the Young modulus (E) and the coefficient of thermal expansion (α), which results to be directly correlated to the stress induced by thermal gradients. A lower value of this parameter, at the same temperature, implies a lower level of thermal stress on the material. For each alloy the corresponding index (TS) has been calculated as follows:

$$(TS)_m = 1/(E_{m1}\alpha_{m1} + E_{m2}\alpha_{m2} + E_{m3}\alpha_{m3} + E_{m4}\alpha_{m4}) \tag{4}$$

where 1, 2, 3 and 4 represent the four values of selected temperatures. Then, this index has been normalized to his maximum value and is shown in Fig. 5.

For AISI 446 stainless steel it can be noted that the high value of this parameter is due to its very low Young modulus at elevated temperature.

3.5 Yield strength comparison

In this section, the yield strength values of the materials have been compared, with reference to minimal design values for this property, in particular: $\sigma_{y1} = 100$ MPa at 850 °C, $\sigma_{y2} = 90$ MPa at 900 °C, $\sigma_{y3} = 70$ MPa at 950 °C, $\sigma_{y4} = 40$ MPa at 1000 °C.

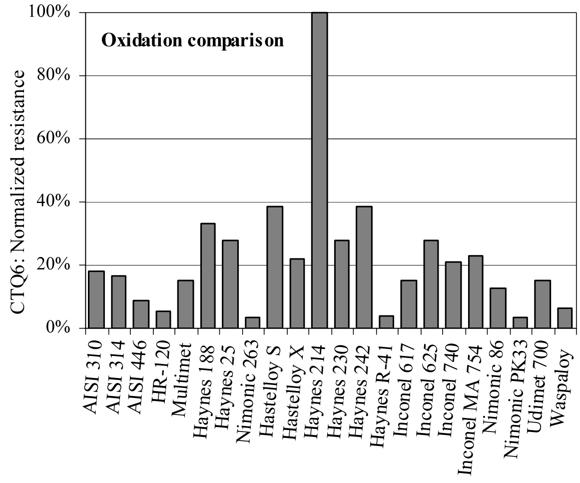

Fig. 4 Normalized oxidation index

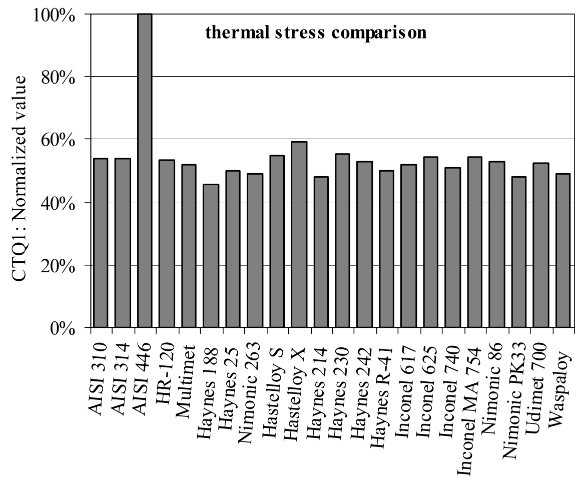

Fig. 5 Comparison of thermal stress index

The YS index has been used for the comparison, calculated as follows:

$$YS_m = (\sigma_{ym1} - \sigma_{y1}) + (\sigma_{ym2} - \sigma_{y2}) + (\sigma_{ym3} - \sigma_{y3}) + (\sigma_{ym4} - \sigma_{y4}) \tag{5}$$

where σ_{ym1}–σ_{ym4} are the values of σ_y for the four temperatures. Again, if a term in brackets is negative, the index is set equal to zero. The indices have been normalized to the maximum value. The result is shown in Fig. 6. The superalloys Haynes R-41 and Udimet 700 show the best behavior for this characteristic.

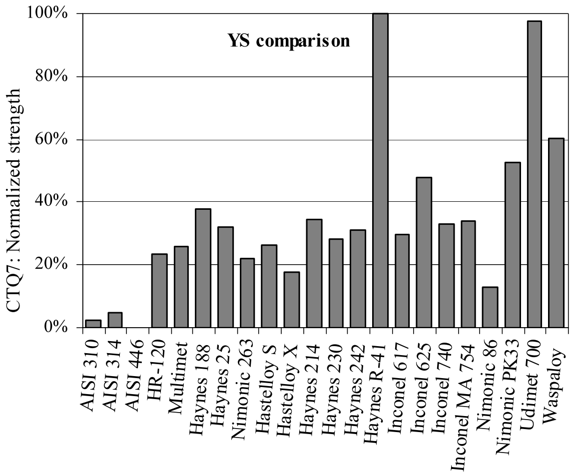

Fig. 6 Comparison for YS values

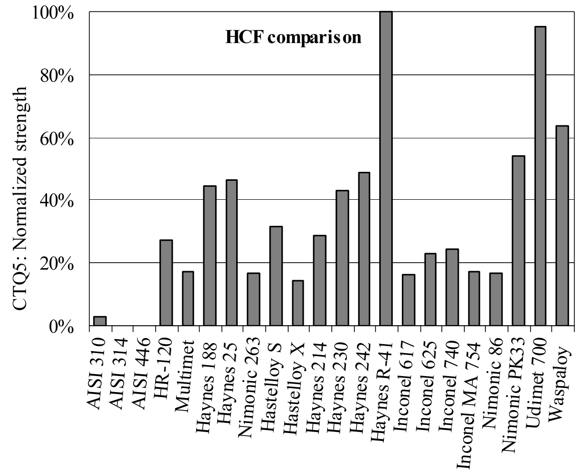

Fig. 7 HCF score

3.6 High cycle fatigue (HCF) comparison

HCF life is expensive to evaluate, because it should be performed with a large amount of tests, in particular to find the fatigue limit. Commonly simplified Whöler's curves are used. On the basis of experimental tests, empirical correlations between UTS and fatigue limit (σ_L) with average stress equal to zero have been determined for some materials. These relations have only a statistical basis but they are very useful when fatigue data of a material are unknown. The σ_L/UTS ratio for steel is around 0.3–0.6, for cast iron and aluminum alloys it varies between 0.35 and 0.5. An approximate Whöler's curve can be determined with these relations, using only UTS data; it is formed by two segments in logarithmic coordinates that represent, respectively, finite and infinite life [11].

In this work, a value for the σ_L/UTS ratio has been found using the available data of Nimonic 263 and Hastelloy-X; the value obtained has been considered constant for all the materials of the selection. Using this procedure, if the results are expressed in a relative way, the comparison can be carried out only on the basis of the ultimate strength value. For this reason, values of UTS, normalized to the maximum value of this parameter, have been used as index for HCF strength in order to compare the materials. Results are shown in Fig. 7.

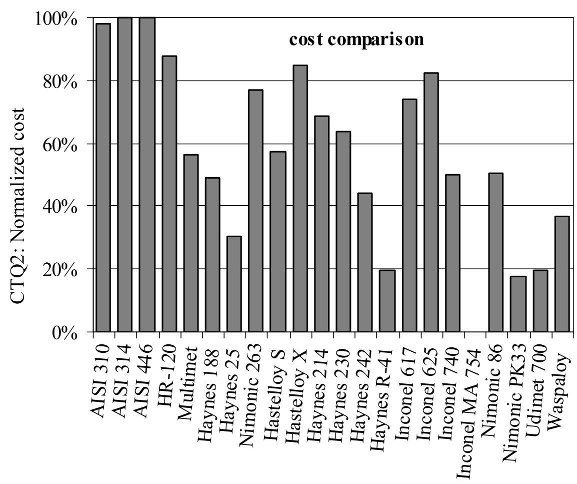

Fig. 8 Cost score

3.7 Cost comparison

The raw material costs have been obtained from materials suppliers. This information is expressed in a relative way, which is suitable for comparisons.

In this section, an alloy with higher cost has been correlated with a lower RC index, while a cheaper alloy has a higher RC index. The index has been calculated by the difference between the cost of the most expensive material (Inconel MA 754) and the cost of the material considered. Then, the RC index has been normalized to its maximum value. The results are shown in Fig. 8.

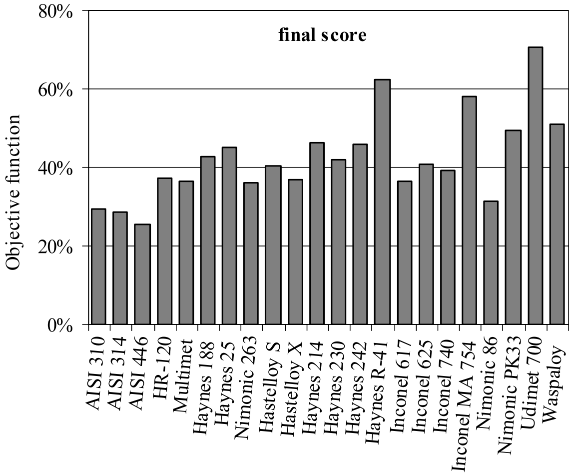

Fig. 9 Final ranking

4 Results

The target function (OF) has been calculated by multiplying the normalized values (CTQ_i) with the associated weight (C_i) values:

$$OF = \sum_i C_i \cdot CTQ_i. \tag{6}$$

By means of OF it is possible to obtain a ranking of the selected materials which permits to identify the best one, i.e. the material that maximizes the performance of the component. The final result is shown in Fig. 9. The figure shows the advantage to substitute the present component's material (Nimonic 263) and suggests some other alloys for this application.

The best part of the considered alloys, with the exception of stainless steels, has a better final ranking with respect to Nimonic 263. From Fig. 9 one deduces that nickel based superalloys are the most suitable materials for the application considered. The best alloy is Udimet 700, although this result should be confirmed with data obtained from the same material in sheet form. Also Haynes R-41 and Inconel MA 754 have a good ranking.

5 Conclusions

A procedure has been described in this paper which allows a comparison among materials in order to optimize—for a specific application—the component performance. Because of the required constraints and elevated temperature of the component, the selection has been restricted to metal alloys. In order to compare the materials, stress and temperature corresponding to design values have been used, and variability of material properties with temperature is taken into account.

The uncertainty on material properties introduces an approximation in the final ranking, which cannot be considered reliable in some details. However, the indication obtained from the procedure used is very clear for the selection of the best alloy for a re-design. In this later phase, necessary since the stress depends on the materials characteristics, data will be required with the maximum obtainable precision.

Moreover, this method allows design criteria of the component—related to the material choice—to be collected and saved, increasing the expertise of the producer.

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