| Priority | CTQ - Engineering Characteristics / VOC - Customer Attributes | K | TEC | E | HV | Abrasion resistance | Hot corrosion resistance | Rupture strength (Rm); | Density | Machinability | Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Able to conduct efficiently the heat transmitted by the valve | 9 | | | | | | | | | |
| 5 | Able to follow the thermal deformations of the cylinder head | | 9 | 1 | | | | | | | |
| 2 | Able to follow the mechanical deformation of the cylinder head | | | 9 | | | | | | | |
| 4 | Able to withstand repeated impacts | | | | 9 | | | 3 | | | |
| 3 | Abrasion resistant (good tribological behavior) | | | | 3 | 9 | | | | | |
| 4 | Chemical compatible with the combustion gases | | | | | | 9 | | | | |
| 4 | Mechanical strength | | | | 3 | 3 | | 9 | | 3 | |
| 2 | Low weight | | | | | | | | 9 | | |
| 3 | Easy to machine | 3 | | | 3 | | | 1 | | 9 | |
| 1 | Material cost | | | | | | | | | | 9 |
| | **Rating of CTS** | 54 | 45 | 23 | 66 | 39 | 36 | 51 | 18 | 39 | 9 |
| | **Relative Weights % ($W_j$)** | 0.142 | 0.118 | 0.061 | 0.174 | 0.103 | 0.095 | 0.134 | 0.047 | 0.103 | 0.024 |

**Figure 5.** House of Quality completed.

**Use of C-VIKOR algorithm**

The next step of the Integral Aided Material Selection (IAMS) model [26] is the identification of a set of materials that could be used as fillers for the reinforcement of the cold- sprayed Al 7075 matrix, the list is shown below:

- CuBe (Materion Alloy 165 temper TF00);
- CuBe2;
- Alloy 3 (Materion Alloy 3 temper TF00);
- Alloy 310 (Materion Alloy 310 temper TF00);
- C18150;
- C18000;
- SS 410 martensitic stainless steel;
- 50CrV4 (AISI 6150 steel oil quenched, 540°C tempering, D=50mm);
- x38CrMoV51 (AISI Type H11).

Following the proposed model, we proceeded to collect data about the performance of each of the candidate materials relatively to each of the selection attributes. To collect all the needed technical data, we have consulted numerous sources: on-line database [e.g. MatWeb], scientific papers [31-38] and handbooks (e.g. [39]), Producers and Suppliers on-line catalogues. The obtained selection matrix is shown in Tab. I and collects all the technical data about the different materials.

This data has a maximum and a minimum value, due to the dispersion through the different data sources. The criteria on the abrasion resistance, hot corrosion resistance, machinability are qualitative and have been translated into numerical terms by a simple fuzzy logic. To use the C-VIKOR algorithm the mean value of each datum is used. Then the Selection Matrix is normalized and using the weights of different attributes of selection provided by the HOQ ($W_j$) the value of the parameter $A_j$, $S_i$, $R_i$ and $Q_i$ is calculated through C-VIKOR algorithm [7]. The results are shown in Tab. II.

**Fuzzy logic algorithm to manage data uncertainty.**

Through the mathematical expressions (3), (4) and (5) it is possible to quantitative compute this uncertainty and understand the confidence with which the materials selector can manage the technical ranking. In Tab. III the computation is shown of the $DR_{ij}$ parameters for each selection alternative relative to each selection attribute, and the $DR_i$ parameters values and the data reliability ranking of each material alternative.

**Results**

Under the direct comparison of the value assumed by the parameter $Q_i$ for different alternatives of selection, it is possible to obtain the ranking of solution technical optimality (e.g. lower Qi value means better solution). This ranking is shown in Tab. IV.

As mentioned above in the introduction chapter, to optimize the material selection process it is important to consider the data dispersion as an uncertainty indicator of selection robustness. To manage the balance between the need to maximize the technical effectiveness of the selection process, with the requirement to maximize the selection robustness, the $CRI_i$ parameter is computed for each selection alternative. Tab. V shows the final ranking obtained.

Through the comparison of the technical ranking (Tab. IV) and the total ranking (Tab. V) it is possible to note that the selection alternative with the best technical ranking not necessarily is the best option for the project if this alternative has a low reliability index. In this case, the team can select the CuBe2 with both for technical characteristics and the confidence about the results as the best fillers for the reinforcement of the 7075 matrix Cold Sprayed. Instead, the Alloy 310 and CuBe can be seen in the second order. It is interesting to observe that the Alloy 310 and CuBe invert their position in the ranking due to a higher uncertainty about the characteristic of CuBe than of Alloy 310.

**CONCLUSIONS**

The material selection during design phase is usually a critical step. An important part of this criticality is due to data uncertainly about the different materials that can be selected. This paper introduces a material selection model that is able to evaluate the best material alternative considering both material characteristics and data uncertainty. The approach considers the whole process of materials selection from the definition of the customer needs, to the final materials ranking and, can consider the different reliability level of the data connected with each Engineering Characteristic. The approach integrates QFD, C-VIKOR algorithm and Fuzzy logic to create a ranking of the selection alternatives using data provided with different confidence level, as in the case of different source of the data. As shown in the case study about the material selection for the production of the valve seats component in a high-performance engine, it is of primary importance to conjugate the technical effectiveness with the material characteristics robustness to optimize the materials selection and to guarantee project functionality and reliability. In fact, the best material is the one that can combine both technical effectiveness and material characteristics robustness. This way only can the functionality and the reliability of the project be guaranteed. Such information can help the design team to better and easier identify the best design solution among a complex list of different materials and reduce the iteration in the design phase.

**Table I**: Completed Selection Matrix.

| | **K** [W/mK] | | **TEC** [$10^{-6}$/K] | | **E** [GPa] | | **Hardness** [HV] | | **Abrasion Resistance** [null] | | **Hot corrosion resistance** [null] | | **Rupture strength** [MPa] | | **Density** [g/cm$^3$] | | **Machinability** [null] | | **Cost** [€/kg] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Optimization type** | **LTB** | | **Target** | | **Target** | | **Target** | | **LTB** | | **LTB** | | **LTB** | | **STB** | | **LTB** | | **LTB** | |
| **Best Value** | | | 22 | | 80 | | 270 | | 5 | | 5 | | 5 | | | | 5 | | | |
| **Materials** | min | MAX | min | MAX | min | MAX | min | MAX | min | MAX | min | MAX | min | MAX | min | MAX | min | MAX | min | MAX |
| **1. CuBe** | 105 | 118 | 16.7 | 17 | 130 | 132 | 318 | 382 | 4 | 4 | 2 | 3 | 1030 | 1310 | 8.26 | 8.41 | 4 | 4 | 20.8 | 25.2 |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2. CuBe2** | 105 | 130 | 16.7 | 17 | 131 | 134 | 353 | 413 | 4 | 5 | 2 | 3 | 1140 | 1380 | 8.25 | 8.36 | 5 | 5 | 23.5 | 25.9 |
| **3. Alloy 3** | 240 | 240 | 17.6 | 17.6 | 138 | 138 | 195 | 250 | 2 | 3 | 3 | 3 | 690 | 900 | 8.83 | 8.83 | 3 | 4 | 21.9 | 24.1 |
| **4. Alloy 310₂** | 235 | 235 | 17.6 | 17.6 | 135 | 135 | 234 | 260 | 2 | 3 | 3 | 3 | 720 | 820 | 8.8 | 8.8 | 3 | 4 | 22.5 | 23.6 |
| **5. C18150** | 280 | 324 | 17 | 17 | 117 | 120 | 130 | 155 | 1 | 2 | 2 | 2 | 380 | 520 | 8.89 | 8.9 | 4 | 5 | 7.6 | 7.84 |
| **6. C18000** | 185 | 225 | 16.2 | 17.5 | 114 | 130 | 185 | 195 | 2 | 2 | 2 | 3 | 585 | 605 | 8.75 | 8.84 | 4 | 4 | 8.73 | 10 |
| **7. SS 410** | 24.9 | 24.9 | 9.9 | 9.9 | 200 | 200 | 339 | 410 | 4 | 5 | 5 | 5 | 985 | 1310 | 7.74 | 7.8 | 1 | 2 | 1 | 13 |
| **8. 50CrV4** | 46.6 | 46.6 | 12.2 | 12.2 | 205 | 205 | 309 | 350 | 4 | 5 | 3 | 4 | 1020 | 1145 | 7.83 | 7.85 | 2 | 3 | 0.7 | 0.8 |
| **9. x38CrMoV51** | 18 | 21 | 11 | 11.8 | 207 | 215 | 551 | 632 | 5 | 5 | 3 | 4 | 1835 | 2100 | 7.8 | 7.8 | 2 | 3 | 4.24 | 5 |

**Table II.** Selection matrix with the value of the parameters Aj, Si, Ri and Qi.

| | **K** | **TEC** [$10^{-6}$/°C] | **E** [GPa] | **Hardness** [HV] | **Abrasion Resistance** [null] | **Hot corrosion resistance** [null] | **Rupture strength** [MPa] | **Density** [kg/m³] | **Machinability** [null] | **Cost** [€/kg] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Best Value** | **302** | **22** | **80** | **270** | **5** | **5** | **1967.5** | **7.77** | **5** | **0.75** | | | |
| **$A_j$** | **282.5** | **12.1** | **131** | **449** | **3.5** | **2.5** | **1517.5** | **1.125** | **3.5** | **23.95** | | | |
| **$W_j$** | **0.142** | **0.118** | **0.061** | **0.174** | **0.103** | **0.095** | **0.134** | **0.047** | **0.103** | **0.024** | | | |
| **Optimization type** | **LTB** | **Target** | **Target** | **Target** | **LTB** | **LTB** | **LTB** | **STB** | **LTB** | **STB** | **$S_i$** | **$R_i$** | **Qi** |
| **Material** | | | | | | | | | | | | | |
| 1. CuBe | 0.070 | 0.041 | 0.020 | 0.028 | 0.026 | 0.060 | 0.055 | 0.019 | 0.026 | 0.014 | **0.357** | **0.070** | **0.310** |
| 2. CuBe2 | 0.068 | 0.041 | 0.020 | 0.039 | 0.014 | 0.060 | 0.050 | 0.018 | 0.000 | 0.015 | **0.324** | **0.068** | **0.000** |
| 3. Alloy 3 | 0.028 | 0.036 | 0.022 | 0.017 | 0.052 | 0.052 | 0.072 | 0.029 | 0.036 | 0.014 | **0.359** | **0.072** | **0.399** |
| 4. Alloy 310₂ | 0.030 | 0.036 | 0.021 | 0.009 | 0.052 | 0.052 | 0.073 | 0.028 | 0.036 | 0.014 | **0.352** | **0.073** | **0.372** |
| 5. C18150 | 0.000 | 0.040 | 0.015 | 0.043 | 0.065 | 0.066 | 0.085 | 0.030 | 0.014 | 0.006 | **0.364** | **0.085** | **0.815** |
| 6. C18000 | 0.041 | 0.041 | 0.017 | 0.028 | 0.059 | 0.060 | 0.080 | 0.028 | 0.026 | 0.007 | **0.387** | **0.080** | **0.852** |
| 7. SS 410 | 0.089 | 0.075 | 0.036 | 0.036 | 0.014 | 0.000 | 0.056 | 0.000 | 0.065 | 0.000 | **0.371** | **0.089** | **0.991** |
| 8. 50CrV4 | 0.085 | 0.066 | 0.037 | 0.022 | 0.014 | 0.043 | 0.059 | 0.003 | 0.052 | 0.000 | **0.380** | **0.085** | **0.935** |
| 9. x38CrMoV51 | 0.090 | 0.069 | 0.038 | 0.089 | 0.000 | 0.043 | 0.000 | 0.001 | 0.052 | 0.004 | **0.386** | **0.090** | **1.140** |

**Table III.** Computation of the $DR_{ij}$ parameters for each selection alternative relative to each selection attribute.

| | **K** | | **TEC** [$10^{-6}$/°C] | | **E** [GPa] | | **Hardness** [HV] | | **Abrasion Resistance** [null] | | **Hot corrosion resistance** [null] | | **Rupture strength** [MPa] | | **Density** [kg/m$^3$] | | **Machinability** [null] | | **Cost** [€/kg] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Optimization type** | **LTB** | | **Target** | | **Target** | | **Target** | | **LTB** | | **LTB** | | **LTB** | | **STB** | | **LTB** | | **LTB** | | |
| **Materials** | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | $\widehat{X_j}$ | $DR_{ij}$ | **$DR_i$** |
| 1. CuBe | 0.05 | 0.94 | 0.01 | 0.99 | 0.01 | 0.99 | 0.08 | 0.91 | 0.00 | 1.00 | 0.18 | 0.80 | 0.10 | 0.88 | 0.01 | 0.99 | 0.00 | 1.00 | 0.09 | 0.90 | **0.530** |
| 2. CuBe2 | 0.09 | 0.89 | 0.01 | 0.99 | 0.01 | 0.99 | 0.06 | 0.92 | 0.10 | 0.89 | 0.18 | 0.80 | 0.08 | 0.90 | 0.01 | 0.99 | 0.00 | 1.00 | 0.05 | 0.95 | **0.491** |
| 3. Alloy 3 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.10 | 0.88 | 0.18 | 0.80 | 0.00 | 1.00 | 0.11 | 0.87 | 0.00 | 1.00 | 0.13 | 0.86 | 0.05 | 0.95 | **0.497** |
| 4. Alloy $310_2$ | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.04 | 0.95 | 0.18 | 0.80 | 0.00 | 1.00 | 0.06 | 0.94 | 0.00 | 1.00 | 0.13 | 0.86 | 0.02 | 0.98 | **0.593** |
| 5. C18150 | 0.06 | 0.93 | 0.00 | 1.00 | 0.01 | 0.99 | 0.07 | 0.91 | 0.30 | 0.67 | 0.00 | 1.00 | 0.13 | 0.84 | 0.00 | 0,99 | 0.10 | 0.89 | 0.02 | 0.98 | **0.411** |
| 6. C18000 | 0.08 | 0.90 | 0.03 | 0.96 | 0.06 | 0.93 | 0.02 | 0.97 | 0.00 | 1.00 | 0.18 | 0.80 | 0.01 | 0.98 | 0.00 | 1.00 | 0.00 | 1.00 | 0.07 | 0.93 | **0.576** |
| 7. SS 410 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.08 | 0.91 | 0.10 | 0.89 | 0.00 | 1.00 | 0.12 | 0.86 | 0.00 | 1.00 | 0.30 | 0.67 | 0.13 | 0.87 | **0.399** |
| 8. 50CrV4 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.05 | 0.94 | 0.10 | 0.89 | 0.13 | 0.86 | 0.05 | 0.94 | 0.00 | 1.00 | 0.18 | 0.80 | 0.07 | 0.93 | **0.502** |
| 9. x38CrMoV51 | 0.07 | 0.92 | 0.03 | 0.96 | 0.02 | 0.98 | 0.06 | 0.93 | 0.00 | 1.00 | 0.13 | 0.86 | 0.06 | 0.93 | 0.00 | 1.00 | 0.18 | 0.80 | 0.08 | 0.92 | **0.478** |

**Table IV.** Ranking of solution technical optimality.

| **Place** | **Ranking based on $Q_i$** | **$Q_i$** |
|---|---|---|
| | | **LTB** |
| *1st* | CuBe2 | 0.00 |
| *2nd* | CuBe (Materion Alloy 165 temper TF00) | 0.310 |
| *3th* | Alloy 310 (Materion Alloy 310 temper TF00) | 0.372 |
| *4th* | Alloy 3 (Materion Alloy 3 temper TF00) | 0.399 |
| *5th* | C18150 | 0.815 |
| *6th* | C18000 | 0.852 |
| *7th* | 50CrV4 (AISI 6150 steel oil quenched, 540°C tempering, D=50mm) | 0.935 |
| *8th* | SS 410 martensitic stainless steel | 0.991 |
| *9th* | x38CrMoV51 (AISI Type H11) | 1.140 |

**Table V.** Ranking of solution technical optimality with uncertainty evaluation.

| Place | Ranking | $CRI_i$ |
|---|---|---|
| | | **STB** |
| *1st* | CuBe2 | 0.491 |
| *2th* | Alloy 310 (Materion Alloy 310 temper TF00) | 0.399 |
| *3nd* | CuBe (Materion Alloy 165 temper TF00) | 0.386 |
| *4th* | Alloy 3 (Materion Alloy 3 temper TF00) | 0.323 |
| *5th* | C18150 | 0.146 |
| *6th* | C18000 | 0.117 |
| *7th* | 50CrV4 (AISI 6150 steel oil quenched, 540°C tempering, D=50mm) | 0.090 |
| *8th* | SS 410 martensitic stainless steel | 0.052 |
| *9th* | x38CrMoV51 (AISI Type H11) | 0.000 |

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