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Original scientific papers

Application of probability-based multi–objective optimization in material engineering

Применение многоцелевой оптимизации, основанной на вероятности в материаловедении

Примена вишекритеријумске оптимизације заснована на вероватноћи у технологији материјала

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Abstract:

Introduction/purpose: Althought many methods have been proposed to deal with the problem of material selection, there are inherent defects of additive algorithms and subjective factors in such methods. Recently, a probability-based multi–objective optimization was developed to solve the inherent shortcomings of the previous methods, which introduces a novel concept of preferable probability to reflect the preference degree of the candidate in the optimization. In this paper, the new method is utilized to conduct an optimal scheme of the switching material of the RF-MEMS shunt capacitive switch, the sintering parameters of natural hydroxyapatite and the optimal design of the connecting claw jig.

Methods: All performance utility indicators of candidate materials are divided into two groups, i.e., beneficial or unbeneficial types for the selection process; each performance utility indicator contributes quantitatively to a partial preferable probability and the product of all partial preferable probabilities makes the total preferable probability of a candidate, which transfers a multi–objective optimization problem into a single–objective optimization one and represents a uniquely decisive index in the competitive selection process.

Results: Cu is the appropriate material in the material selection for RF - MEMS shunt capacitive switches; the optimal sintering parameters of natural hydroxyapatite are at 1100°C and 0 compaction pressure; and the optimal scheme is scheme No 1 for the optimal design of a connecting claw jig.

Conclusion: The probability-based multi-objective optimization can be easily used to deal with an optimal problem objectively in material engineering.

Keywords: multi-objective optimization, probability theory, preferable probability, material engineering, scheme selection.

Резюме:

Введение/цель: Несмотря на то, что существует множество методов решения проблемы выбора материала на основе аддитивных алгоритмов, такие алгоритмы по своей сути содержат недостатки и субъективные факторы. С целью преодоления недостатков этих методов, недавно была разработана многокритериальная вероятностная оптимизация, которая вводит новую концепцию предпочтительной вероятности, показывающую степень предпочтительности кандидата в процессе оптимизации. В данной статье используется новый метод в разработке оптимальной схемы материала для емкостного шунтирующего переключателя в радиочастотных микроэлектромеханических системах (РЧ МЭМС), параметрах спекания природного гидроксиапатита, а также для оптимальной разработки кулачковой муфты.

Методы: Все показатели полезности материалов–кандидатов делятся на две группы, полезные или невыгодные для процесса отбора; каждый показатель полезности вносит количественный вклад в частичную предпочтительную вероятность, а произведение всех частичных предпочтительных вероятностей составляет общую предпочтительную вероятность кандидата, что переводит проблему многокритериальной оптимизации в проблему оптимизации с одним критерием и представляет собой уникальный индекс в процессе конкурсного отбора.

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Результаты: Медь оказалась подходящим материалом при выборе материалов для емкостных шунтирующих переключателей в радиочастотных микроэлектромеханических системах (РЧ МЭМС); оптимальные параметры спекания природного гидроксиапатита – 1100° C при нулевом давлении сжатия, а оптимальной схемой проектирования кулачковой муфты является схема №1.
Выводы: Многокритериальная оптимизация на основе вероятностей может широко применяться при принятии объективных решений оптимальных проблем в матереаловедении.

Ключевые слова: многокритериальная оптимизация, теория вероятностей, предпочтительная вероятность, материаловедение, выбор схемы.

Abstract:

Увод/циљ: Иако постоји много метода за решавање проблема селекције материјала заснованих на адитивним алгоритмима, такви алгоритми инхерентно садрже недостатке и субјективне факторе. Ради превазилажења слабости поменутих метода, недавно је развијена вишекритеријумска оптимизација заснована на вероватноћи која уводи нови концепт пожељне вероватноће који показује степен пожељности кандидата при оптимизацији. У овом раду користи се нов метод за извођење оптималне шеме за материјал за капацитивну склопку шанта у радиофреквенцијским микроелектромеханичким системима (РФ МЕМС), за параметре синтеровања природног хидроксиапатита, као и за оптимално пројектовање канџасте спојнице.
Методе: Сви показатељи перформанси корисности материјала – кандидата деле се на корисне и некорисне за селекцију. Сваки показатељ перформанси корисности квантитативно доприноси делимичној пожељној вероватноћи, док производ свих делимичних пожељних вероватноћа чини укупну пожељну вероватноћу кандидата, чиме се проблем вишекритеријумске оптимизације преводи у проблем једнокритеријумске оптимизације и представља јединствени одлучујући индекс у компетитивном процесу селекције.
Резултати: Бакар се показао као одговарајући материјал при селекцији материјала за капацитивне склопке шанта у радиофреквенцијским микроелектромеханичким системима (РФ МЕМС). Оптимални параметри синтеровања природног хидроксиапатита су 1100°C и нулти притисак сабијања, а оптимална шема за пројектовање канџасте спојнице јесте шема број 1.
Закључак: Вишекритеријумска оптимизација на бази вероватноће може се једноставно применити за објективно решавање оптималног проблема у технологији материјала.

Keywords: вишекритеријумска оптимизација, теорија вероватноће, пожељна вероватноћа, технологија материјала, селекција шеме.

Introduction

It has been more than 40 years (Ashby, 2000) early works in material selection appeared; many methods have been proposed to analyze a big amount of data involved in the material selection process so as to obtain an appropriate result.

Various algorithms (techniques) have been developed, including Ashby's method (Ashby, 2000; Ashby et al, 2004), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR), Multi Attribute Decision Making (MADM), Analytical Hierarchy Process (AHP), Simple Additive Weighted (SAW) method and Multi–Objective Optimization on the basis of Ratio Analysis (MOORA), etc (Zheng et al, 2021). Ashby's method is difficult to be applied in cases which involve multiple criteria of selection (Ashby, 2000; Ashby et al, 2004; Zheng et al, 2021). Deshmukh et al employed the multi–objective optimization (MOO) techniques of TOPSIS and VIKOR to perform the material selection of the switching structure for RE-MEMS shunt capacitive switches (Deshmukh & Angira, 2019). However, there exist inherent problems of additive algorithms and subjective factors in the MADM, AHP, MOORA, TOPSIS and VIKOR due to their fatal scaling or normalization processes (Zheng et al, 2021).

Recently, a new probability-based multi-objective optimization method was developed (Zheng et al, 2021), attempting to solve the inherent problems of personal and subjective factors in the previous multi–objective optimization methods. The novel concept of preferable probability was introduced to reflect the preference degree of a candidate in the optimization where all performance utility indicators of candidates are divided into beneficial or unbeneficial types for the selection. Each performance utility indicator of a candidate contributes to a partial preferable probability quantitatively, and the total preferable probability of a candidate is the product of all partial preferable probabilities from the viewpoint of the probability theory, which is the overall and unique decisive index in the competitive selection process. The new multi-objective optimization method was also extended with the application of the multi-objective orthogonal test design method (OTDM) and the uniform test design method (UTDM), which results in appropriate achievements (Zheng et al, 2021).

In this paper, the new probability-based multi–objective optimization method is used to perform the optimal scheme in material engineering, which includes the selection of switching material of the RF-MEMS shunt capacitive switch, the optimization of the sintering parameters of natural hydroxyapatite and the optimal design of a connecting claw jig.

Brief introduction to the new multi–objective optimization method

In the new probability-based multi–objective optimization method (Zheng et al, 2021) beneficial utility index of material performance indicator contributes to a partial preferable probability in a positively linear manner, i.e.,

$$P_{ij}=\alpha_{ij}X_{ij}, \; i=1, 2, \ldots, n; \; j=1, 2 \ldots m. \quad (1)$$

In Eq. (1), X_{ij} is the j^{th} beneficial utility index of the material performance indicator of the j^{th} candidate material; P_{ij} represents the partial preferable probability of the beneficial utility index X_{ij}; n is the total number of candidate materials in the material group involved; m is the total number of the utility indices of each candidate material in the group; α_j is the normalized factor of the j_{th} utility index of the material performance indicator, $\alpha_{ij}=1/(n\overline{X_j})$ and Xj is the arithmetic mean value of the utility index of the material performance indicator in the material gropu involved.

Equivalently, the unbeneficial utility index of the material performance indicator contributes to a partial preferable probability in a negatively linear manner, i.e.,

$$P_{ij}=\beta_{ij}\left(X_{jmax}+X_{jmin}-X_{i}\right), \; i=1, 2, \ldots, n; \; j=1, 2 \ldots m. \quad (2)$$

In Eq. (3), X_{jmax} and X_{jmin} represent the maximum and minimum values of the utility indices X_j of the material performance indicator in the material group, respectively, and β_j is the normalized factor of the j^{th} utility indices of the material performance indicator, $\beta_{ij}=1/[n(X_{jmin}+X_{jmax})-n\bar{X}_j]$.

Moreover, the total / comprehensive preferable probability of the i^{th} candidate material is the product of its partial preferable probability P_{ij} of each utility index of the material performance indicator in the overall selection due to the "simultaneous optimization" of the multi-objects in the viewpoint of probability theory (Zheng et al, 2021), i.e.,

$$P_i=P_{i1}\cdot P_{i2}\cdots P_{im}=\prod_{j=1}^{m} P_{ij}. \quad (3)$$

The total preferable probability of a candidate is the uniquely decisive index in the overall selection process competitively, which transfers a multi–objective optimization problem (MOOP) into a single – objective optimization one. The main characteristic of the new probability-based multi–objective optimization is that the treatment for both beneficial utility index and unbeneficial utility index is equivalent and conformable, which is without any artificial or subjective scaling factors involved in the process.

Application of probability-based multi–objective optimization in material engineering

1) Multi–objective optimization in the material selection of RF#MEMS shunt capacitive switches

Radio Frequency Micro Electro Mechanical Systems (RF-MEMS) is a promising technology for implementing passive devices in future wireless communication systems (Deshmukh & Angira, 2019). Switches have drawn more attention due to their frequent use in many cases in wireless communication systems. An RF-MEMS technology-based switch has low insertion loss, high isolation, high linearity and less power consumption (Deshmukh & Angira, 2019). Its shunt capacitive switch has two stable states i.e., up-state and down-state (Deshmukh & Angira, 2019). Power can flow from the input port to the output port in the switch upstate, while it stands at the off-state in its down-state (Deshmukh & Angira, 2019; Angira & Rangra, 2015a; Angira & Rangra, 2015b).

The optimization of the performance of the switching structure involves many parameters (criteria), such as pull-in voltage, RF response (insertion loss and isolation), maximum displacement, thermal conductivity, etc (Deshmukh & Angira, 2019; Angira & Rangra, 2015a; Angira & Rangra, 2015b). Since many parameters are involved, it can be seen as a MOOP in the performance optimization of the switching material selection. Therefore, a MOOP can be used to decrease human effort since a large number of materials are available in practice, forming a material bank together with many manufacturing processes and selection attributes (Zheng et al, 2021).

Yang et al pointed out that if different normalization methods are applied, significant different results may be produced (Yang et al, 2021). Podviezko et al also stressed that different normalization of data applying to popular MCDM methods such as SAW or TOPSIS could lead to significant differences in the assessment (Podviezko & Podviezko, 2015). As a consequence, many researchers paid a lot of attention to the choice of the normalization type. However, it is still puzzling which normalization method is better and how to determine final results of material selection from different normalization algorithms.

A) Utility indices of the material performance indicators in the material selection of RF - MEMS shunt capacitive switches

In the study of Deshmukh & Angira (2019), the optimal objectives for this purpose are low pull–in voltage, low RF loss, high thermal conductivity and maximum displacement of the beam structure. As a result, the square root of Young's modulus of the material $E^{0.5}$, the electrical resistive coefficient ρ_e ρ_e, the thermal conductivity of the material λ, the ratio of the fracture strength σ_f to Young's modulus E of the material, σ_f/E, are taken as the optimal utility indices of the material attribute indicators (Deshmukh & Angira, 2019).

B) Divisions of the utility indices in the material selection of RF - MEMS shunt capacitive switches

From analyzing the requirements of the optimizations of the bridge of RF-MEMS shunt capacitive switches, i.e., higher pull-in voltage (V_p), lower RF loss, higher thermal conductivity and the higher maximum displacement of the switch beam (Deshmukh & Angira, 2019), the utility indices of the square root of Young's modulus of the material, $E^{0.5}$, the thermal conductivity of the material, λ, the ratio of the fracture strength σ_f, to Young's modulus *E* of the material, σ_f/E belong to the beneficial type of the material performance index, while the electrical resistive coefficient, ρ_e belongs to the unbeneficial type of the material performance index in the assessment.

C) Assessment results

The values of the conventional material performance indicators for various materials are given in Table 1 (Deshmukh & Angira, 2019).

The partial preferable probabilities of the utility indices of $E^{0.5}$, λ and ρ_e and σ_f/E and the total preferable probabilities are assessed according to Equations (1) through (5), respectively, shown in Table 2. In addition, the ranking here by using the new probability-based multi–objective optimization method is given in Table 2 together with those of Vikor and Topsis from Ref. (Deshmukh & Angira, 2019) for comparison.

TABLE 1
Conventional material performance indicators for various materials

Mat.	Young's modulus *E* (GPa)	Electrical resistive coefficient r_e (Ω m) 10^{-8}	Thermal conductivity l (W/m•K)	Fracture strength s_f (MPa)	(s_f/E) ´10^3
Ni	193	6.99	90	345	1.7876
Au	70	2.44	315	220	3.1429
Al	70	2.82	204	47	0.6714
Ag	83	1.59	407	110	1.3253
Pt	168	10.5	73	125	0.7440
Cu	117	1.68	386	314	2.6838
Cr	279	12.9	90	370	1.3262
W	411	5.28	163	1725	4.1971
Co	209	6.24	69	675	3.2297
Fe	211	9.61	73	540	2.5592

(Deshmukh & Angira, 2019)

TABLE 2
Partial preferable probabilities and total preferable probabilities
for various materials for shunt capacitive switch optimization

Mat.	$P_{E^{\wedge}0.5}$	P_{re}	P_l	$P_{sf/E}$	$P_t \cdot 10^4$	Rank here	Rank Vikor	Rank Topsis
Ni	0.1073	0.0884	0.0481	0.0825	0.3766	6	6	6
Au	0.0646	0.1420	0.1684	0.1451	2.2423	3	1	1
Al	0.0646	0.1375	0.1091	0.0310	0.3005	7	4	4
Ag	0.0704	0.1520	0.2176	0.0612	1.4242	4	3	3
Pt	0.1001	0.0470	0.0390	0.0343	0.0631	10	8	9
Cu	0.0835	0.1510	0.2064	0.1239	3.2248	1	2	2
Cr	0.1290	0.0187	0.0481	0.0612	0.0712	9	10	10
W	0.1566	0.1085	0.0872	0.1937	2.8697	2	9	7
Co	0.1117	0.0972	0.0369	0.1490	0.5971	5	5	5
Fe	0.1122	0.0575	0.0390	0.1181	0.2975	8	7	8

It can be seen from Table 2 that the appropriate material from the new multi–objective optimization method is Cu, which is different from those of Vikor and Topsis from (Deshmukh & Angira, 2019); this is because of the inherent defects of personal and subjective factors in Vikor and Topsis (Deshmukh & Angira, 2019).

In fact, the evaluation result of the new probability-based method for multi–objective optimization in material selection is no need to equal to those of other previous approaches exactly due to their involvements of personal or other subjective coefficients.

2) Optimization of sintering parameters of natural hydroxyapatite

Abifarin conducted the optimization of hydroxyapatite (HAp) mechanical characteristics using Taguchi grey relational analysis design which includes hardness and compressive strength (Abifarin, 2021). Three levels of sintering temperature and two levels of compaction pressure are employed during sintering (Abifarin, 2021). The design and the results are shown in T able 3. Again, the probability-based multi-objective optimization is used to conduct the assessment with hardness and compressive strength as the beneficial type index. The evaluation results are shown in Table 4.

TABLE 4
Evaluation results of HAp

No	Pressure	Temperature °C	Hardness	Compressive Strength
1	0	900	0.54	0.39
2	0	1000	0.838	0.58
3	0	1100	0.940	0.84
4	5	900	0.656	0.34
5	5	1000	0.929	0.5
6	5	1100	1.103	0.69

TABLE 4
Evaluation results of HAp

	Partial preferable probability		Total	
No	Hardness	Strength	Pt^*10^2	Rank
1	0.1079	0.1168	1.2596	6
2	0.1674	0.1737	2.9069	3
3	0.1878	0.2515	4.7225	1
4	0.1311	0.1018	1.3340	5
5	0.1856	0.1497	2.7781	4
6	0.2203	0.2066	4.5518	2

Table 4 indicates that the optimal sintering parameters of natural hydroxyapatite are at 1100°C and 0 compaction pressure.

3) Optimal design of a connecting claw jig

Yan et al conducted the multi-objective optimal design of a connecting claw jig with ANSYS Workbench finite element analysis software (Yan et al, 2021). The maximum equivalent stress (MPa) Y_1 , the weight (kg) Y_2 , the minimum safety factor Y_3 and the maximum deformation (mm) Y_4 of the claw jig are taken as the optimization objectives, while the thickness of the substrate FD_1 (mm) x_1 , the angle of the connecting claw A1 (°) x_2 , the thickness of the connecting claw FD_2 (mm) x_3 , and the outside diameter of the jig base R_1 (mm) x_4 are taken as the input variables.

After the simulation and the analysis, three candidate schemes with good objective functions are selected by the system, as shown in Table 5. The object Y_3 is a beneficial type index, while Y_1, Y_2 and $Y._4$are all unbeneficial type indexes. The evaluation results are shown in Table 6.

Table 6 shows that the optimal scheme is scheme No 1.

TABLE 5
Three candidate schemes of the connecting claw jig

Original scheme	x_1 (mm)	x_2 (°)	x_3 (mm)	x_4 (mm)	Y_1 (MPa)	Y_2 (kg)	Y_3	Y_4 (mm)
	56	79	38	32.5	151.22	6.176	1.6532	1.171
1	54.125	73.13	35.414	31.051	128.42	5.615	1.9467	0.923
2	48.125	73.77	37.982	32.395	143.31	5.577	1.7444	1.043
3	46.625	76.38	39.908	30.715	161.48	5.620	1.5482	1.375

TABLE 6
Evaluation results of the connecting claw jig

No.	Partial preferable probability				Total	
	Y_1	Y_2	Y_3	Y_4	Pt*100	Rank
1	0.3700	0.3327	0.3716	0.3870	1.7697	1
2	0.3358	0.3349	0.3329	0.3532	1.3229	2
3	0.2942	0.3324	0.2955	0.2598	0.7507	3

Conclusion

The application of the new probability-based multi–objective optimization method in dealing with three optimal problems of material engineering has shown that: the appropriate material (Cu) is successfully selected, which meets the requirements of the optimizations of the bridge of RF # MEMS shunt capacitive switches; the optimal sintering parameters of natural hydroxyapatite are at 1100°C and 0 compaction pressure; and the optimal scheme of the connecting claw jig is scheme No 1. The main feature of the new probability-based multi–objective optimization method is that the treatment is equivalent and conformable for both the beneficial utility index and the unbeneficial utility index, without any artificial or subjective scaling factors involved in the process.

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