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Probabilistic multi-objective robust design and its application in metal cutting

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Abstract:

Introduction/purpose: Cutting is a typical material process. However, an appropriate solution for simultaneous optimization of material machinability and tool life in material cutting processes has not been obtained yet. In this article, probabilistic multi-objective robust design (PMORD) is expounded and the robust design problem in the simultaneous optimization of material machinability and tool life is analyzed by taking the machining of ferrite-bainite dual-phase steel as an example.

Methods: According to PMORD, the arithmetic mean and its deviation of various performance and utility indexes of alternative schemes are evaluated as twin independent responses, which respectively contribute a part of the partial preferable probability to the performance indexes. In the evaluation, the arithmetic average of the utility index is taken as the representative of the utility attribute, and the evaluation is made in accordance with the function or preference of the utility index. However, the deviation term is generally used as an unbeneficial type of the index (that is, the smaller the better) to participate in the evaluation. The product of the two parts of partial preferable probability is the actual partial preferable probability of the corresponding performance index. The product of the partial preferable probability of all performance utility indexes gives the total preferable probability of the corresponding scheme, which is the only index for each scheme to participate in the competition in robust design.

Results: The optimization result of this example is that the tool life is 1297.3333 s (standard deviation is 2.0817 s) and the surface roughness is 2.22μm (standard deviation is 0.2μm), while the corresponding working *conditions are that the heat treatment temperature of the material is 790°C, the cutting speed is 150m/min, the feed speed is 0.15mm/rev, and the cutting depth is 0.2mm.*

Conclusion: The example of the parameter optimization of cutting of ferrite-bainite dual-phase steel by means of PMORD indicates the rationality of the appropriate solution.

Key words: multi-objective optimization, robust design, simultaneous optimization, probability-based method, preferable probability.

Introduction

Product quality is an important issue related to the survival of enterprises. With the increasing international competition of industrial products, more and more attention has been paid to this problem by governments and industries in various countries. In Japan, many new technologies have been developed in past years, which has greatly improved the quality and productivity of industrial products. Among them, a decisive factor is the adoption of important technologies such as robust design. The application of robust design technology aims not only to improve the product quality, but also to enable enterprises to obtain considerable economic benefits. For example, after the application of robust design technology by Nippon Electric Co., Ltd., only one color TV regulated power supply can increase economic benefits by 6.7 billion yen every year due to quality improvement. In recent years, in Japan, the United States, Canada and other developed countries, there has been an upsurge in the research and application of robust design technology, which has made the technology develop continuously. Compared with developed countries in the world, the quality of many products in China is still needed to be further improved with the reduction of cost. Therefore, vigorously popularizing robust design technology is of great practical significance for improving the quality of Chinese products, including the quality and market competitiveness of petrochemical products, and accelerating modernization.

The formation of product quality has two important links: development design and manufacturing. Roughly speaking, product quality is the sum of product development and design quality and product manufacturing quality. In order to improve the quality of products, special attention could be paid to the two important links of development - design and manufacturing.

According to statistics, about 50% ~ 70% of all the quality problems of products are caused by poor product development and design, so it is very important to improve the quality of product development and design. Robust design is an important new technology aiming to achieve high quality products at low cost. It makes full use of the nonlinear nature of the system and makes the product performance least sensitive to all kinds of interference by properly selecting the level combination of controllable factors, so as to improve the product quality and reduce the cost.

In general, the implementation steps of robust design include simplification and system analysis. First, on the basis of detailed research, the system is reasonably simplified. Then, through analysis, specific research objects, product improvement goals and quality characteristics reflecting these goals are determined, and the influencing factors and their levels are listed. The factors are divided into two categories: controllable factors and error factors. Controllable factors are factors that researchers can strictly control, while error factors are factors that researchers are difficult to control or need to spend a lot of money to control. The latter is actually interference.

The main difference between robust experimental design and traditional experimental design is that there is not only the effect of factors on the average of response but also on its deviation of response. Orthogonal design, factorial design, uniform design and comprehensive error factor method can be adopted to study the effect.

Historically, experimental design originated from the research of Prof. Fisher, a scientist who studied breeding in the 1920s. Dr. Fisher is universally recognized as the founder of this method and strategy. Early in 1925 and 1935, Ronald Aylmer Fisher published the books entitled “Statistical Methods for Research Workers” (Edinburgh: Oliver and Boyd) and “The Design of Experiments. Edinburgh” (Edinburgh: Oliver and Boyd), respectively, which laid the foundation for experimental design.

In 1950s, Genichi Taguchi realized that it was significant to improve product quality by reducing the influence of uncertain or uncontrollable factors on product performance (Mori & Tsai, 2011; Roy, 2010), and put forward the Taguchi method. Taguchi suggested that the influence of controllable and uncontrollable factors on the responses of a product can be studied and analyzed by designing experiments. Taguchi called uncontrollable factors “noises” (Mori & Tsai, 2011; Roy, 2010). The basic idea of robust design is to seek a set of controllable factors to make the product quality insensitive to noise or minimally sensitive to noise (Mori & Tsai, 2011; Roy, 2010). In addition, Taguchi adopted the term of Signal-to-Noise Ratio (SNR) to implement his robust design. It is assumed that at an optimal setting, controllable factors are selected to maximize the signal-to-noise ratio. He further proposed three types of the signal-to-noise ratio, i.e.,

1) The expected value is optimal,

$$SNR_T = 10\log\left(\frac{\mu^2}{s^2}\right), \quad (1)$$

2) The smaller the better,

$$SNR_s = -10\log\left(\frac{1}{m}\sum_{i=1}^{m} y_i^{\,2}\right), \quad (2)$$

3) The bigger the better,

$$SNR_L = -10\log\left(\frac{1}{m}\sum_{i=1}^{m}\frac{1}{y_i^{\,2}}\right). \quad (3)$$

In Eqs. (1) to (3) above, m represents the test times of each experiment, μ represents the arithmetic average of the test results of m experiments, and s represents its standard deviation.

However, in general, the average value μ and the standard deviation s of the test results should be an independent set of responses individually (Box, 1988; Box & Meyer, 1986; Welch et al, 1990; Welch et al, 1992; Nair et al, 1992). However, in Eq. (1), it is unreasonable to attribute the two responses μ and s into a sole performance SNR_T. The optimization of the maximum SNR_T does not mean that s takes the minimum value and μ tends to its expected value at the same time! More seriously, for the cases of "the smaller the better" and "the bigger the better", Eqs. (2) and (3) above even exclude the role of the factor of the standard deviation s.

Statisticians, such as Box, Welch, Nair, et al, have clearly criticized Taguchi's Signal-to-Noise Ratio (SNR) robust design, and they suggested that two independent models should be considered to deal with the response of the mean μ and the variance s (Box, 1988; Box & Meyer, 1986; Welch et al, 1990; Welch et al, 1992; Nair et al, 1992). Therefore, the minimum value of s and the optimization of μ tending to its expected value should be treated simultaneously with separate models to ensure the rationality of robust optimization.

In fact, robust design can be considered as a problem of a bi-objective optimization with μ tending to its target and s minimization, while a mutil-objective optimization is an optimization within a system consisting of multiple objectives.

According to the system theory, the integrity, purpose, openness, stability, hierarchy, mutation, self-organization and similarity are the eight basic characteristics of a system. In accordance with the integrity principle of the system, the system is an integral body with certain new functions, composed of several elements. As a sub-unit of the system, once the elements form the whole system, they have properties and functions that individual systems do not have, thus showing that the properties and functions of the integral system are not equal to a simple sum of its elements. The reason why a system becomes a system is that it must have integrity first.

Furthermore, the optimization of a system is not the superposition of each particle's optimization, but an optimization of a system as a whole. The system has integrity, which determines that system optimization can only be its overall optimization, that is, the whole system obtains the best organizational structure and function.

For a determined goal, the relationship between the integrity and the part should be handled well under the principle of an optimal overall benefit. On the premise of overall optimization, give consideration to local interests. If the overall benefit is good, it will promote the local development and benefit local elements. For overall optimization, even if there are local defects, overall optimization can be realized through coordination.

Recently, probabilistic multi-objective optimization methodology (PMOO) was proposed to perform the overall optimization of a system and to solve the inherent problems of "addition" operation with subjective factors in traditional multi-objective optimization (Zheng et al, 2022a; Zheng et al, 2022b; Zheng et al, 2023). A new concept, preferable probability, is introduced to reflect the preference degree of performance and utility indicators of candidate schemes in the optimization process. In this new methodology, the performance and utility indexes of all schemes can be preliminarily divided into two basic types in accordance with their functions in optimization or pre-required preferences, namely, beneficial type and unbeneficial type. Each performance utility index of the alternative scheme can quantitatively contribute its partial preferable probability. In addition, according to probability theory, the total preferable probability of alternatives is equal to the product of the partial preferable probabilities of all performance and utility indexes, which is the only decisive index in the optimization process of alternatives. This treatment thus transforms a multi-objective optimization problem into a single-objective optimization problem.

The specific advantage of probabilistic multi-objective optimization is that a clear goal of multi-objective optimization is the integral optimum point of the system in the viewpoint of the system theory, which has both the viewpoint and the method, while other previous approaches have only methods but without any viewpoint on ″the intrinsic meaning and definition of multi-objective optimization″.

This paper aims to provide the detail of probabilistic multi-objective robust design for material cutting, showing the general procedures of the integral combination of probabilistic multi-objective optimization with Taguchi's for experimental design in utilization of robust design. Specifically, the cutting process of ferrite-bainite dual-phase steel is taken as a typical example to conduct the simultaneous robust design of tool life and surface roughness of the sample by means of probability-based multi-objective optimization. The input parameters to be optimized include heating temperature, cutting speed, feed speed, and cutting depth. Through this study, the general principle and procedure of robust design of industrial processing could be provided so as to improve the quality of products in industrial production.

Robust design process of probabilistic multi-objective optimization

Basis of probability-based multi-objective optimization

In probability-based multi-objective optimization methodology (Zheng et al, 2022a; Zheng et al, 2022b; Zheng et al, 2023), a brand-new concept of preferable probability is introduced to represent the preferable degree of performance utility indicators in optimization. The performance utility indicators of all alternatives can be preliminarily divided into two basic types in accordance with their roles in optimization or pre-required preferences, namely, beneficial type or nonbeneficial type. Each performance utility index of the alternative scheme quantitatively contributes to the partial preferable probability. In addition, from the viewpoint of probability theory, the total preferable probability of alternatives is equal to the product of partial preferable probabilities of all performance and utility indicators, which can reflect the essence of simultaneous optimization. The total preferable probability of the scheme is the only decisive index in the optimization process, and through it, a simultaneous optimization problem of multiple objectives is transformed into a single objective optimization problem. Figure 1 shows the operation process of the probabilistic multi-objective optimization method.

The meanings of the parameters and coefficients in Figure 1 are as follows: P_{ij} represents the partial preferable probability of the j-th performance utility index Y_{ij} of the i-th alternative; *n* represents the total number of alternatives; m reflects the total number of target utility; μ_j represents the arithmetic value of the *j-th* target utility index; Y_{jmax} and Y_{jmin} represent the maximum and minimum values of the *j-th* performance utility index, respectively; η_j and λ_j represent the normalization factor of the *j-th* utility index Y_{ij} of the beneficial and unbeneficial indicators, respectively; the classification of the *j-th* utility index Y_{ij} is determined in accordance with its specific role or preference in the discussed problem; and P_i represents the total preferable probability of the i-th alternative (Zheng et al, 2022a; Zheng et al, 2022b; Zheng et al, 2023).

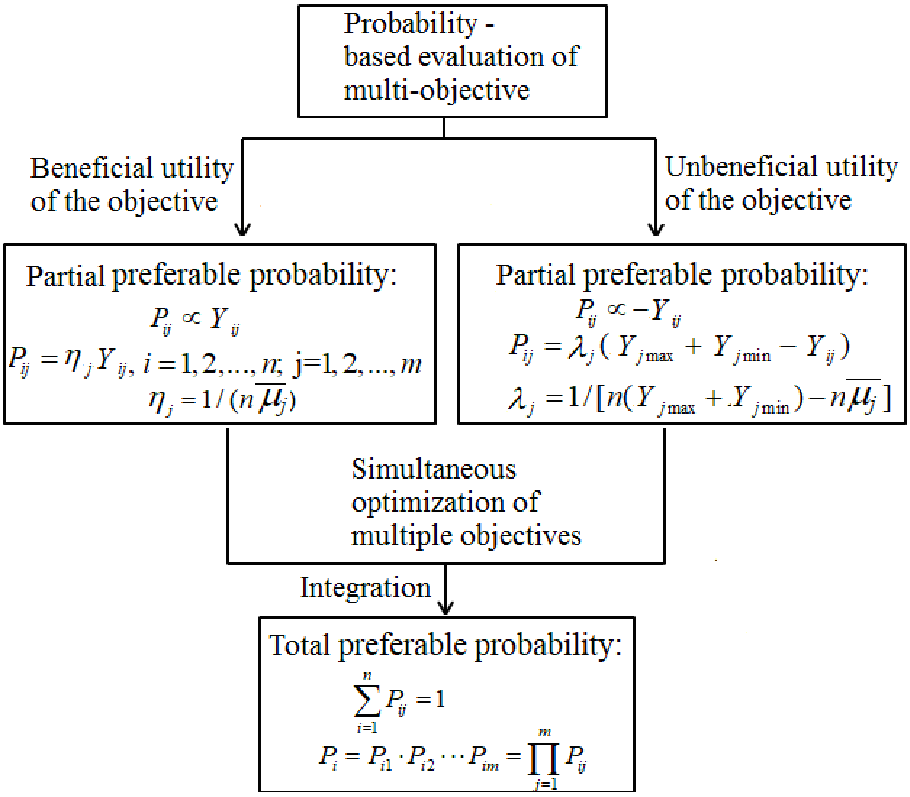

Figure 1 – Probability-based multi-objective optimization process

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New robust design process based on probabilistic multi-objective optimization

According to the statisticians' suggestion and the probabilistic multi-objective optimization method, two separate models should be used to consider the response of the mean value μ and the variance s at the same time (Zheng et al, 2022a; Zheng et al, 2022b; Zheng et al, 2023). The process of robust design using probabilistic multi-objective optimization is described as follows:

A) The arithmetic average and its deviation of the performance indexes of alternatives can be used as two independent responses of alternatives for robust design. In the robust design process, each of the above two responses contributes a part of partial preferable probability to the corresponding performance index of the alternative scheme;

B) The arithmetic average of the utility index, as the representative of its effect index, is evaluated by probability of partial preferable in accordance with its function and preference, while deviation is generally evaluated as an unbeneficial index;

C) The product of the partial preferable probability of the arithmetic mean and the partial preferable probability of the deviation of the performance index constitutes the actual partial preferable probability of the performance utility index;

D) The product of the partial preferable probability of all performance utility indicators is equal to the total preferable probability of alternatives, which is the overall and unique final evaluation index of each alternative in the robust optimal scheme;

E) Take the total preferable probability of each scheme as the decisive index in robust design to perform competition.

Industrial application of probabilistic multi-objective optimization robust design

Taking the robust design of dual-phase steel cutting as an example, the specific application of this new method is explained in detail. Hegde et al. (2022) once designed the machining of ferrite-bainite dual-phase steel (AISI1040 F-B) robustly. Through experiments, the tool life and the sample surface roughness were taken as their simultaneous optimization goals, and the heating temperature, cutting speed, feed speed and cutting depth of ferrite-bainite dual-phase steel (AISI1040 F-B) were taken as the input parameters. The four control factors, heating temperature, cutting speed, feed speed and cutting depth, are marked as the factors A, B, C and D, respectively. Each factor has three levels, and three samples were tested under each experimental condition (Hegde et al, 2022). Hegde et al. adopted Taguchi $L_9(3^4)$ for experimental design, and the arithmetic value and the standard deviation of the experimental results are listed in Table 1.

In experimental design, the tool life and the sample surface roughness are taken as the simultaneous optimization objectives. In Table 1, T_{LA} and δT_L respectively represent the arithmetic mean and the standard deviation of the tool life, while S_{RA} and δS_R reflect the arithmetic mean and the standard deviation of the sample surface roughness, and their marks are *E*, *F*, *G* and *H,* respectively.

Table 2 gives the evaluation results of the preferable probability and the ranking of this problem. In the evaluation, in accordance with the requirements of robust optimization, only quantity $T_{LA}(E)$ belongs to the beneficial type, while all other responses are attributed with the characteristics of the unbeneficial type.

Table 1 – Design and experimental results of the cutting parameters of dual-phase steel with $L_9(3^4)$

Exp. No.	Input parameter				Optimization goals			
					Mean value of life	Deviation of life	Mean value of roughness	Deviation of roughness
No.	A (°C)	B (m/min)	C (mm/rev)	D (mm)	T_{LA}, E (s)	δT_L, F (s)	S_{RA}, G (μm)	δS_R, H (μm)
1	750	80	0.13	0.2	2646	29.4618	4.2633	0.0416
2	750	115	0.15	0.4	1907	1.7321	4.0833	0.1589
3	750	150	0.18	0.6	994	3.6056	2.6233	0.0551
4	770	80	0.15	0.6	1464	6.9282	4.07	0.0458
5	770	115	0.18	0.2	2168.333	16.0728	3.11	0.0854
6	770	150	0.13	0.4	1172	19	2.5567	0.0551
7	790	80	0.18	0.4	1528.333	2.0817	3.1067	0.0902
8	790	115	0.13	0.6	700	4.3589	2.42	0.0889
9	790	150	0.15	0.2	1297.333	2.0817	2.22	0.02

Table 2 – Evaluation results of the preferable probability and the ranking of the dual-phase steel cutting experiments

Exp. No.	Partial preferable probability				Total preferable probability	
No.	P_E	P_F	P_G	P_H	$P_i \times 10^4$	Ranking
1	0.1907	0.0089	0.0743	0.1417	0.1778	9
2	0.1374	0.1508	0.0803	0.0206	0.3432	8
3	0.0716	0.1412	0.1291	0.1277	1.6679	3
4	0.1055	0.1242	0.0807	0.1373	1.4523	4
5	0.1563	0.0774	0.1128	0.0965	1.3162	5
6	0.0845	0.0624	0.1313	0.1277	0.8842	6
7	0.1101	0.1490	0.1129	0.0915	1.6961	2
8	0.0504	0.1373	0.1359	0.0929	0.8743	7
9	0.0935	0.1490	0.1426	0.1640	3.2564	1

The evaluation results in Table 2 show that experimental scheme No 9 has the highest total preferable probability value of P_i. Therefore, the configuration of robust design is near the parameters of experimental scheme No 9.

In addition, Table 3 shows the results of the range analysis of the total preferable probability of each group of the schemes shown in Table 2.

Table 3 shows that the order of the impact intensity of the input variables is $A > B > C > D$, which reveals that the optimal configuration is $A_3B_3C_2D_1$, which is experimental scheme No 9 exactly. Hegde and others used ANOVA technology to statistically analyze the relative contributions of various factors to T_L and S_R, and their optimization results were close to experimental scheme No 2 (Hegde et al, 2022).

Obviously, from the point of view of probability theory, the result of experimental scheme No 2 is worse than that of experimental scheme No 9.

Table 3 – Analysis results of the total preferable probability range for the two-phase steel cutting experiments

	Factors			
Level	A	B	C	D
1	0.7296	1.1087	0.6454	1.5835
2	1.2176	0.8446	1.6840	0.9745
3	1.9423	1.9362	1.5600	1.3315
Range	1.2126	1.0916	1.0386	0.6090
Impact order	1	2	3	4
Optimal configuration	A_3	B_3	C_2	D_1

Conclusion

The above discussion shows that the robust design of probabilistic multi-objective optimization is a reasonable design method. The arithmetic mean and its deviation of the performance index of the scheme are regarded as two independent responses of the scheme in processing, and each contributes a part of partial preferable probability to the scheme. As the representative of the utility index, the arithmetic average of the utility index is evaluated in accordance with its function and preference, and the deviation is that the utility index is the unbeneficial type of the index. The total preferable probability of each scheme is the only final index parameter in robust optimization design.

The algorithm of the present probabilistic multi-objective objective robust design accepts the idea that the arithmetic mean and its deviation of the performance index of the scheme can be regarded as two independent responses of the scheme; the agorithm is rational, adequately overcoming the puzzling problem of previous robust design approaches. The application of the model to more diverse real-life problems needs to be conducted in future.

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Diseño robusto probabilístico multiobjetivo y su aplicación en el corte de metales

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CAMPO: procesamiento de materiales, optimización
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: El corte es un proceso material típico. Sin embargo, aún no se ha obtenido una solución adecuada para la optimización simultánea de la maquinabilidad del material y la vida útil de la herramienta en los procesos de corte de materiales. En este artículo, se expone el diseño robusto probabilístico multiobjetivo (PMORD) y se analiza el problema del diseño robusto en la optimización simultánea de la maquinabilidad del material y la vida útil de la herramienta tomando como ejemplo el mecanizado de acero de doble fase ferrita-bainita.

Métodos: Según PMORD, la media aritmética y su desviación de varios índices de desempeño y utilidad de esquemas alternativos se evalúan como respuestas gemelas independientes, que contribuyen respectivamente con una parte de la probabilidad parcial preferible a los índices de desempeño. En la evaluación se toma como representante del atributo de utilidad la media aritmética del índice de utilidad, y la evaluación se realiza de acuerdo con la función o preferencia del índice de utilidad. Sin embargo, el término de desviación se utiliza generalmente como un tipo de índice no beneficioso (es decir, cuanto más pequeño, mejor) para participar en la evaluación. El producto de las dos partes de la probabilidad parcial preferible es la probabilidad parcial preferible real del índice de desempeño correspondiente. El producto de la probabilidad preferible parcial de todos los índices de utilidad de desempeño da la probabilidad preferible total del esquema correspondiente, que es el único índice para que cada esquema participe en la competencia en diseño robusto.

Resultados: El resultado de la optimización de este ejemplo es que la vida útil de la herramienta es 1297,3333 s (la desviación estándar es 2,0817 s) y la rugosidad de la superficie es 2,22 µm (la desviación estándar es 0,2 µm), mientras que las condiciones de trabajo correspondientes son que la temperatura de tratamiento térmico del material es 790°C, la velocidad de corte es 150 m/min, la velocidad de avance es 0,15 mm/rev y la profundidad de corte es 0,2 mm.

Conclusión: El ejemplo de optimización de parámetros de corte de acero bifásico ferrita-bainita mediante PMORD indica la racionalidad de la solución adecuada.

Palabras claves: optimización multiobjetivo, diseño robusto, optimización simultánea, método basado en probabilidad, probabilidad preferible.

Вероятностное многокритериальное проектирование и его применение при резке металла

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РУБРИКА ГРНТИ: 81.09.00 Материаловедение
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Резка является типичным процессом обработки материалов. Однако подходящего решения для одновременной оптимизации обрабатываемости материала и срока службы инструмента в процессах резки материалов пока не найдено. В данной статье представлено вероятностное многоцелевое робастное проектирование (PMORD) и проанализирован вопрос робастного проектирования при одновременной оптимизации обрабатываемости материала и стойкости инструмента на примере механической обработки ферритно-бейнитной двухфазной стали.

Методы: Согласно ВМРП среднее арифметическое и его отклонение различных показателей эффективности и полезности альтернативных схем оцениваются как два независимых отклика, которые своими показателями эффективности частично способствуют частичной предпочтительной вероятности. При оценке среднее арифметическое индекса полезности берется как признак полезности атрибута, а оценка производится в соответствии с функцией или предпочтением индекса полезности. Однако термин «отклонение» обычно используется как бесполезный тип индекса (иными словами, по принципу: «чем меньше, тем лучше») при оценке. Произведение двух частей вероятности частичного предпочтения представляет собой фактическую вероятность частичного предпочтения соответствующего индекса производительности. Произведение вероятностей частичного предпочтения всех индексов эффективности полезности дает общую предпочтительную вероятность соответствующей схемы, которая является единственным индексом каждой схемы, участвующей в состязании робастных проектов.

Результаты: Результаты оптимизации в этом примере следующие: срок службы инструмента составляет 1297,3333 с (стандартное отклонение - 2,0817 с), а шероховатость *поверхности - 2,22 μm (стандартное отклонение - 0,2 μm), при соответствующих условиях эксплуатации: температура термообработки материала составляет 790°C, скорость резки составляет 150 м/с./мин, скорость подачи − 0,15 мм/об, а глубина резки − 0,2 мм.*

Выводы: Пример оптимизации параметров резки ферритно-бейнитной двухфазной стали с помощью ВМРП свидетельствует о рациональности соответствующего решения.

Ключевые слова: многоцелевая оптимизация, робастное проектирование, одновременная оптимизация, вероятностный метод, предпочтительная вероятность.

Пробабилистички вишекритеријумски робустни дизајн и његова примена у сечењу метала

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ОБЛАСТ: обрада материјала, оптимизација
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Резање је типични процес обраде материјала. До сада још није пронађено одговарајуће решење за истовремену оптимизацију обрадивости материјала и животног века алата приликом обраде материјала резањем. У чланку је представљен пробабилистички вишекритеријумски робустни дизајн (ПМОРД – PMORD). Анализиран је проблем робустног дизајна у истовременој оптимизацији обрадивости материјала и животног века алата на примеру машинске обраде феритно-баинитног двофазног челика.

Методе: Према ПМОРД, средња аритметичка вредност и њено одступање различитих индекса перформанси и корисности шема алтернатива процењују се као два независна одговора који доприносе, једним делом парцијалне пожељне вероватноће, индексима перформанси. При процени, средња аритметичка вредност индекса корисности узима се као представник атрибута корисности, а процена се врши у складу са функцијом или преференцијом индекса корисности. Међутим, термин одступања се генерално користи као некорисни тип индекса (по принципу мање је боље) при процени. Производ два дела парцијалне пожељне вероватноће је стварна парцијална пожељна вероватноћа *одговарајућег индекса перформанси. Производ парцијалних пожељних вероватноћа свих индекса перформанси корисности даје укупну пожељну вероватноћу одговарајуће шеме, што представља једини индекс сваке шеме који учествује у такмичењу у робустном дизајну.*

Резултати: Резултат оптимизације у овом примеру је следећи: животни век алата је 1297,3333 с (стандардна девијација је 2,0817 с), храпавост површине је 2,22 μm (стандардна девијација је 0,2 μm), а одговарајући радни услови су: температура термичке обраде материјала је 790°C, брзина резања 150 м/мин, посмична брзина 0,.15 мм/об и дубина резања 0,2 мм.

Закључак: Пример оптимизације параметара резања феритно-баинитног двофазног челика помоћу ПМОРД указује на рационалност одговарајућег решења.

Кључне речи: вишекритеријумска оптимизација, робустни дизајн, истовремена оптимизација, метод заснован на вероватноћи, пожељна вероватноћа.

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