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EVALUATION OF NONCONVENTIONAL MACHINING PROCESSES CONSIDERING MATERIAL APPLICATION BY USING ADDITIVE RATIO ASSESSMENT METHOD

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ABSTRACT: The increasing usage of advanced materials in the modern industry has resulted that non-conventional machining processes (NCMPs) are becoming increasingly important. As each NCMP posses its own process capabilities, advantages and limitations, the selection of the most suitable NCMP for a given machining application is not straightforward. Over the years, many multi-criteria decision making (MCDM) methods have been proposed to handle complex decision making problems. This paper deals with the application of additive ratio assessment (ARAS) method for evaluation of different NCMPs. Computational procedure of the ARAS method has been demonstrated while solving NCMPs selection problem considering material application. The obtained complete ranking of NCMPs by the ARAS method was compared to ranking obtained by the technique for order preference by similarity to ideal solution (TOPSIS).

KEY WORDS: non-conventional machining, multiple criteria decision making, ARAS method

1. INTRODUCTION

Today's modern industry often requires advanced and newer materials with higher strength, hardness, toughness, and other mechanical and technological properties. In recent years there is an increasing usage of aluminum, stainless steel, super alloys, titanium, refractories, ceramics, plastic and other materials. Machining of these materials by conventional machining processes gives rise to problems such as high cutting forces and temperatures, rapid tool wear and residual stresses generated in the workpiece. Moreover conventional machining processes are not suitable for those materials as the desired level of accuracy and surface finish cannot be easily achieved [1]. From these reasons, during past several decades, there has been a wide application of so called non-conventional machining processes (NCMPs) [2]. Laser beam machining (LBM), abrasive jet machining (AJM), electrical discharge machining (EDM), wire electrical discharge machining (WEDM), plasma arc machining (PAM), electrochemical machining (ECM), ultrasonic machining (USM), electron beam machining (EBM), chemical machining (CHM), ion beam machining (IBM) etc. are typical NCMPs used in today's industry for precision material machining.

Although majority of NCMPs can fulfill the requirements of high surface quality, low tolerance, less surface damage, automation, etc. a particular NCMP found suitable for a given machining conditions may not be equally efficient under other conditions. Therefore, a careful selection of NCMP for a given machining application is essential [1, 3, 4]. However the selection process for a given shape feature and work material combination is often a time-consuming and challenging task as it requires consideration of several conflicting criteria and a vast array of machining capabilities and characteristics of NCMPs [1]. While selecting a NCMP to be employed, the following aspects are usually considered [5]: (*i*) physical parameters, (*ii*) properties of workpiece materials and the shape to be machined, (*iii*) process capability or machining characteristics and (*iv*) economical parameters of different NCMPs.

These aforesaid criteria make the comparison of and selection of different NCMPs difficult task involving a set of conflicting criteria. From the literature it has been observed that different multiple criteria decision making (MCDM) methods have been applied to facilitate decision making process. Analytic hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) methods [3, 6], digraph-based approach [7], analytic network process (ANP) [8] data envelopment analysis (DEA) method [9], integrated preference ranking organization method for enrichment evaluation (PROMETHEE) and geometrical analysis for interactive aid (GAIA) method [4], fuzzy TOPSIS method [10] and evaluation of mixed data (EVAMIX) method [1] have been previously applied by past researchers for solving NCMPs selection problem.

In this paper the application of recently developed MCDM method, i.e. the additive ratio assessment (ARAS) method has been demonstrated in selecting the most appropriate NCMP considering material application. The applicability of the NCMP with respect to various materials is taken care of under these criteria. It determines how often an NCMP can be used for a specific material. This criterion is of prime importance, as it will have a major role to play in the selection of the most suitable NCMP [11]. In order to validate the obtained complete rankings of the ARAS method, the NCMP selection problem is solved using the TOPSIS method.

2. MATERIAL APPLICATION OF NCMPS

NCMPs are able to process most metals, alloys, refractories, ceramics, plastics and glass.

Aluminum is a silvery-white metal with many valuable properties. It is light (density 2.70 g/cm3), non-toxic nonmagnetic and nonsparking. Aluminum is easily formed, machined, and cast. It is used extensively for electrical transmission lines due to electrical conductivity 60% that of copper and a much lower density. Pure aluminum is soft and brittle and lacks strength, but can be strengthened by alloying with small amounts of copper, magnesium, manganese and silicon.

Steel is the name for alloys based on iron containing carbon (usually 0.1-1.7 per cent) and often small quantities of other elements such as phosphorus, sulphur, manganese, chromium, and nickel. Its properties vary widely depending on the chemical composition, but in general, it posses high strength, good toughness and hardness, high density and a good conductivity of heat and electricity. The modulus of elasticity is about of 2.15 GPa. In general, steel is not resistant to corrosion, but this property can be improved by the addition of certain alloying elements such as chromium, nickel and nitrogen. It is used to machine parts subjected to mechanical loads exposed to high and low temperatures.

Superalloys are heat resisting alloys based on nickel, nickel - iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation. Superalloys are primarily used in gas turbines, coal conversion plants, chemical process industries, and for other specialized applications requiring heat and/or corrosion resistance. Superalloys are commonly used in parts of gas turbine engines that are subject to high temperatures and require high strength, excellent high temperature creep resistance, fatigue life, phase stability, and oxidation and corrosion resistance. Examples of superalloys are: Hastelloy, Inconel, Waspaloy, Rene alloys.

Titanium has an excellent combination of high strength, stiffness, toughness, low density, and good corrosion resistance. Titanium is a low-density element (approximately 60% of the density of iron) wherefore it allows weight savings in aerospace structures and other high-performance applications. Titanium and its alloys possess tensile strengths from 210-1380 MPa, which are equivalent to the strengths found in most of alloy steels. This metal is nonmagnetic and has good heat-transfer properties, while it is a poor conductor of electricity. Its coefficient of thermal expansion is somewhat lower than that of steels and less than half that of aluminum. It has been well established that titanium is completely inert and immune to corrosion by all body fluids and tissue and is thus completely biocompatible.

Refractories are inorganic nonmetallic material which can withstand high temperature without undergoing physico–chemical changes while remaining in contact with molten slag, metal and gases. Depending upon the application, refractories must resist chemical attack, withstand molten metal and slag erosion, thermal shock, physical impact, catalytic heat and similar adverse conditions. Refractories are more heat resistant than metals and are required for heating applications above 538°C.

Ceramics are inorganic materials composed of metal and non-metal elements. They have crystalline structure which is the most complex of all materials. Ceramic is characterized by great hardness and compressive strength, high elastic modulus, low density and thermal expansion coefficient. These materials are chemical inert and poor conductors of electricity and heat, and they have low plasticity and extremely high brittleness.

Plastics are the most popular synthetic polymer. Compared to metals, they have better resistance to corrosion and chemicals. In addition, they have a lower density, hardness, modulus of elasticity, thermal and electrical conductivity.

Plastics posses a higher coefficient of thermal expansion as well as a ratio strength-mass, compared to the metals. Their main advantage in relation to the metals is relatively low cost and possibility for production of complex structure parts.

Glass is an inorganic material with amorphous structure and high performance. It is a uniform, transparent material, which is obtained in a complex technological process. There is no specific melting and solidification temperature wherefore its properties are similar to the properties of amorphous alloys. The glass has at least 50% of silicon, while the properties can be modified by adding various metal oxides. It is characterized by a high modulus of elasticity (55-90 GPa) and very high embrittlement. Glass has relatively low strength (140 MPa), middle hardness value and negligible thermal expansion coefficient. This material does not corrode in the presence of base, acid and water.

The material applications of various NCMPs are summarized in Table 1.

3. ARAS METHOD

The additive ratio assessment (ARAS) method was introduced by Zavadskas and Turskis [12] and subsequently extended into fuzzy environment (ARAS-F) [13] and grey criteria scores (ARAS-G) [14]. The ARAS method is based on quantitative measurements and utility theory. According to the ARAS method a utility function value determining the complex relative efficiency of an alternative is directly proportional to the relative effect of values and weights of the main criteria considered in a MCDM problem [14]. The procedure of the application of the ARAS method consists of the following steps [12, 14, 15]:

Step 1. The first stage in any decision making problem involves decision matrix forming.

$$X = \left[x_{ij}\right]_{m\times n} = \begin{bmatrix} x_{11}\; x_{12} \ldots x_{1n} \\ x_{21}\; x_{22} \ldots x_{2n} \\ \ldots\; \ldots\; \ldots\; \ldots \\ x_{m1}\; x_{m2} \ldots x_{mn} \end{bmatrix} \tag{1}$$

where x_{ij} is the assessment value of *i*-th alternative in respect to *j*-th criterion, *m* is the number of alternatives and *n* is the number of criteria.

Step 2. In the second stage the assessment values of alternatives are normalized – defining values $\bar{x}_{ij}$ of normalized decision-making matrix $\bar{X}$.

$$\bar{X} = \left[\bar{x}_{ij}\right]_{m\times n} = \begin{bmatrix} \bar{x}_{11}\; \bar{x}_{12} \ldots \bar{x}_{1n} \\ \bar{x}_{21}\; \bar{x}_{22} \ldots \bar{x}_{2n} \\ \ldots\; \ldots\; \ldots\; \ldots \\ \bar{x}_{m1}\; \bar{x}_{m2} \ldots \bar{x}_{mn} \end{bmatrix} \tag{2}$$

For beneficial criteria, whose preferable values are maxima, normalization is done by using linear normalization procedure (as in simple additive weighting method) [12]:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{3}$$

For non-beneficial criteria, the normalization procedure is done in two steps. In the first step, the reciprocal values of assessment values with respect to all the criteria are taken as follows:

$$x_{ij}^{*} = \frac{1}{x_{ij}} \tag{4}$$

In the second step, the normalized values are calculated as follows:

$$\bar{x}_{ij} = \frac{x_{ij}^{*}}{\sum_{i=1}^{m} x_{ij}^{*}} \tag{5}$$

When the dimensionless values of the criteria are known, all the criteria, originally having different dimensions, can be compared [12].

Step 3. In this step normalized-weighted matrix – $\hat{X}$ is defined:

$$\hat{X} = \left[\hat{x}_{ij}\right]_{m\times n} = \begin{bmatrix} \hat{x}_{11}\; \hat{x}_{12} \ldots \hat{x}_{1n} \\ \hat{x}_{21}\; \hat{x}_{22} \ldots \hat{x}_{2n} \\ \ldots\; \ldots\; \ldots\; \ldots \\ \hat{x}_{m1}\; \hat{x}_{m2} \ldots \hat{x}_{mn} \end{bmatrix} \tag{6}$$

Table 1. Material application of NCMPs [5]

	Aluminum	Steel	Super alloy	Titanium	Refractories	Ceramics	Plastic	Glass
USM	P	F	P	F	G	G	F	G
AJM	F	F	G	F	G	G	F	G
ECM	F	G	G	F	F	N	N	N
CHM	G	G	F	F	P	P	P	F
EDM	F	G	G	G	G	N	N	N
IBM	F	F	F	F	G	G	F	F
LBM	F	F	F	F	P	G	F	F
PAM	G	G	G	F	P	N	P	N
G – good, F – fair, P – poor, N – not applicable								

Elements of matrix $\hat{X}$, $\hat{x}_{ij}$, are obtained by using the following equation:

$$\hat{x}_{ij} = \bar{x}_{ij} \cdot w_j , i = 1,2,...,m; \ j = 1,2,...,n \qquad (7)$$

where w_j is the weight of j-th criterion.

It is possible to evaluate the criteria with weights $0 \le w_j \le 1$. The values of weight w_j are usually determined by the expert evaluation method. The sum of weights w_j is limited as follows:

$$\sum_{i=1}^{n} w_j = 1 \qquad (8)$$

Step 4. In this step, optimality function values are determined:

$$S_i = \sum_{j=1}^{n} \hat{x}_{ij} , i = 1,2,...,m \qquad (9)$$

where S_i is the value of optimality function of i-th alternative.

Higher the S_i value, the better is the alternative. Taking into account the calculation process, the optimality function S_i has a direct and proportional relationship with the values x_{ij} and weights w_j of the investigated criteria and their relative influence on the final result. Therefore, the greater the value of the optimality function S_i, the more effective the alternative [12].

Step 5. This step involves the calculation of the degree of the utility (U_i) for each alternative. The degree of the alternative utility is determined by a comparison of the variant, which is analyzed, with the ideally best one S_0. The equation used for the calculation of the U_i value is:

$$U_i = \frac{S_i}{S_0} \cdot 100, i = 1,2,...,m \qquad (10)$$

where S_i and S_0 are the optimality criterion values, obtained from equation (9).

It is clear that the calculated utility values of the alternatives range from 0% to 100%. The greater the value of U_i, the higher is the priority of the alternative. Based on alternative's utility values a complete ranking of the competitive alternatives can be obtained.

4. RESULTS AND DISCUSSION

Initially the evaluation of NCMPs considering material application is qualitative measured i.e. suitability of each NCMP for machining a given material is described linguistically.

Using the scales of absolute values [6, 16] decision maker is able to transform the qualitative evaluation into crisp values. In this paper, using the 10-point scale [6] suitability of considered NCMPs with respect to different materials was evaluated. Thus, value of 0 was assigned to NCMP which has no possibility to machine a given material. On the other hand, value of 7 was assigned to NCMP which has good machining performance. Similarly, the values of 5 and 3 are assigned to NCMP which has fair and poor machining performance, respectively. Thus the decision matrix is now as shown in Table 2.

The application of the ARAS method is as follows. Firstly, since all criteria (different materials) are beneficial criteria, the normalization of initial decision matrix is performed by applying equation (3). If equal importance of different materials is assumed, the criteria weights of 1/8=0.125 are obtained.

If unequal importance for different materials is assumed, one can use AHP or entropy method for determining the criteria weights. By applying equations (6) and (7) normalized-weighted matrix is obtained (Table 3).

By applying equation (9), the optimality function (S_i) for each of NCMP is calculated. Then the corresponding values of the utility degree (U_i) are determined for all alternatives by applying equation (10). The S_i and U_i values upon which the complete ranking of NCMPs is obtained are given in Table 4.

Table 2. Initial decision matrix

	Aluminum	Steel	Super alloy	Titanium	Refractories	Ceramics	Plastic	Glass
USM	3	5	3	5	7	7	5	7
AJM	5	5	7	5	7	7	5	7
ECM	5	7	7	5	5	0	0	0
CHM	7	7	5	5	3	3	3	5
EDM	5	7	7	7	7	0	0	0
IBM	5	5	5	5	7	7	5	5
LBM	5	5	5	5	3	7	5	5
PAM	7	7	7	5	3	0	3	0

Table 3. Weighted normalized decision matrix of ARAS method

	Aluminum	Steel	Super alloy	Titanium	Refractories	Ceramics	Plastic	Glass
USM	0.0536	0.0893	0.0536	0.0893	0.1250	0.1250	0.1250	0.1250
AJM	0.0893	0.0893	0.1250	0.0893	0.1250	0.1250	0.1250	0.1250
ECM	0.0893	0.1250	0.1250	0.0893	0.0893	0.0000	0.0000	0.0000
CHM	0.1250	0.1250	0.0893	0.0893	0.0536	0.0536	0.0750	0.0893
EDM	0.0893	0.1250	0.1250	0.1250	0.1250	0.0000	0.0000	0.0000
IBM	0.0893	0.0893	0.0893	0.0893	0.1250	0.1250	0.1250	0.0893
LBM	0.0893	0.0893	0.0893	0.0893	0.0536	0.1250	0.1250	0.0893
PAM	0.1250	0.1250	0.1250	0.0893	0.0536	0.0000	0.0750	0.0000

Table 4. Complete ranking of NCMPs

	S_i	U_i	Rank
USM	0.7857	88	3
AJM	0.8929	100	1
ECM	0.5179	58	8
CHM	0.7000	78.4	5
EDM	0.5893	66	7
IBM	0.8214	92	2
LBM	0.7500	84	4
PAM	0.5929	66.4	6

It is observed that AJM is the most suitable NCMP considering material application. From Table 4 it is revealed that IBM is the second best choice, followed by USM, LBM and CHM. PAM, EDM and ECM have the lowest ranking. Capability of AJM to machine virtually any material without superheating the area adjacent to the cut is one of the major advantages of this NCMP over the others.

Here it should be noted that in order to achieve best cut quality (smooth surface finish and perpendicular cut) main process parameters are to be set adequately.

Identification of EDM and ECM as the least preferred choices is logical considering that these NCMP are not applicable for machining three materials i.e. ceramics, plastic and glass.

In order to validate the rankings of NCMP obtained by the ARAS method, the same NCMPs selection problem is solved using the TOPSIS method as one of the most commonly used MCDM method. The computational details and step-by-step procedure of the TOPSIS method is explained in details in [16]. The obtained rankings showed perfect correlation which shows the potentiality and suitability of the ARAS method for solving NCMPs selection problems.

5. CONCLUSIONS

During the past years different MCDM methods have been proposed by the past researchers to address the issue of NCMPs evaluation and selection.

Evaluation and selection of the most appropriate NCMP is difficult MCDM problem involving a set of different and opposite criteria. In this paper the application of recently developed MCDM method, i.e. the ARAS method has been demonstrated in selecting the most appropriate NCMP considering material application.

The obtained results suggested that AWJ is the best alternative NCMP, while IBM is the second one. EDM and ECM obtained the lowest rankings due to theirs inability to machine ceramics, plastic and glass.

In order to validate the complete ranking of NCMPs obtained by the ARAS method, the considered MCDM selection problem was solved by using the TOPSIS method. It was observed that ranking of competitive NCMPs perfectly match.

The ARAS method can simultaneously take into account any number of criteria, both quantitative and qualitative, and offers a relatively simple computational procedure.

Application of this method in a wider range of selection problems in real-time manufacturing environment is future research scope.

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