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A hierarchy fuzzy evaluation of CFRP machining processes based on the fuzzy soft set theory and subjectivity control

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ABSTRACT

With the wide application of CFRP (Carbon Fiber Reinforcement Polymers), the related machining processes after molding are required for the assembly object. As the different limitations of the available CFRP machining processes make it hard to determine which one is better and what process conditions should be used. So, a hierarchy fuzzy comprehensive evaluation of CFRP machining processes is proposed in this paper based on the fuzzy soft set theory and subjectivity control, in which the fuzzy transformation is applied to conduct the first level and second-level initial fuzzy evaluation to get the assessment level, membership degree and confidence coefficients of each evaluation object; the "AND" operation of fuzzy soft sets is applied to implement the second-level fine fuzzy evaluation to get the superiority ordering of evaluation objects; the subjectivity check and control of expert opinions is conducted to improve the reasonability of evaluation results. By comparing the evaluation results obtained from the presented comprehensive evaluation approach undergoing the subjectivity control with ones of no subjectivity control and a traditional approach, the effectiveness of the presented comprehensive evaluation approach for three CFRP machining processes such as Mechanical Machining, Laser Cutting and Wet Cutting is validated.

Keywords: Comprehensive Evaluation, Fuzzy Soft Set, Subjectivity Control, CFRP, Machining Processes

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INTRODUCTION

With the wide application of Carbon Fiber Reinforcement Polymers (CFRP) in the field of aircraft, automotive and civil engineering, its machining processes such as trimming and drilling after molding, have attracted more and more attentions in last decades [1]. At present, for sheet CFRP parts, the available CFRP machining processes include Milling [], drilling[3], Laser Cutting [4] and Wet Cutting, which is named after the integrated manufacturing process proposed recently[5]. All of them have their inherent drawbacks. For instance, Milling and Drilling easily lead to machining defects such like delaminating, fibers pulling out and fracture, hole geometric deviation and Entry/Exit Kerf Width[6], sharp tool wear[7], and so on; In spite of the good adaptability and zero tool cost, Laser Cutting tends to cause serious heat damage so the mechanical properties of CFRP parts and the assembly reliability are impaired [8]; By contrast, Wet Cutting can largely overcome the above mentioned defects and has a rather high productivity, but it requires a set of mould specially designed to heat and cut CFRP materials and causes the resin spilling and carbon fiber chippings. Therefore, many researchers focus on the CFRP machining process optimization to promote the CFRP cross-section quality by qualitative comparison. As for the comprehensive evaluation of different machining processes considering the combined impact of CFRP cross-section quality, process cost and production period, the published results are still rare. This situation stops the development and application of novel CFRP machining processes in a large degree. For that reason, a hierarchy fuzzy comprehensive evaluation approach based on the fuzzy soft set theory and subjectivity control proposed in this paper is a helpful attempt for synthetically evaluating various CFRP machining processes.

For the issue of CFRP machining processes evaluation, its features can be summarized as (1) Using some fuzzy and uncertain concepts like "good/bad", "high/low", "long/short" describe the CFRP cross-section quality, process cost and production period; (2) As different applications have their special performance requirements for CFRP parts, it is hard to try finding a proper function to precisely describe relationships between multi evaluation factors and evaluation indicators; (3) For CFRP machining processes with different material removal mechanism, it is impossible to directly compare their severity of CFRP cross-section defects, process cost and production period. For instance, delaminating induced by mechanical machining is unusual for Laser Cutting and Wet cutting that the heat damage and resin spilling are their main machining defects, respectively. So the classic fuzzy mathematic theory is not enough to evaluate synthetically various machining processes unless expert knowledge is adopted; (4) The decision result strongly depends on if more attention is paid to product performance, production cost or production period. So the synthetic evaluation should be conducted for various CFRP machining processes by considering the comprehensive effect of above various factors and their weight so as to get a more economical and reasonable machining process. In conclusion, the CFRP machining processes evaluation is a typical fuzzy, uncertain and subjective comprehensive evaluation issue which is solved by combining the latest fuzzy mathematic theory and expert system. That is also a helpful attempt to expand new application domains of fuzzy mathematics.

As an important branch of fuzzy mathematics, the fuzzy comprehensive evaluation is widely used in evaluating the software quality [9], mine ventilation system [10], Water quality[11], work safety of hot and humid environments[12], medical diagnosis[13], etc. The fuzzy evaluation approaches commonly used can be divided into two categories, one is realized by fuzzy logic, expert knowledge and inference engine based on nature language [14], the other is realized by fuzzy transformation based on fuzzy quantification [15]. K. D. Liu, et al. [11] pointed out some troubles the fuzzy evaluation approaches based on nature language are facing and proposed a corresponding solution to evaluate the reliability of inertia navigation system simulation. So Y. Zhu and H. Y. Lei [16] thought that the subjective weighing methods based on expert knowledge are still preferable because it doesn't require considering the effects of sample random errors on evaluation result and also doesn't need plenty of sample data. So, at present, many efforts are made to solve some particular comprehensive evaluation problem in various domains by combining the fuzzy information quantification and fuzzy transformation. For example, with the basis model of fuzzy comprehensive evaluation and fuzzy quantification, L. Zhang, et al. [17] and Q. T. Fang, et al. [18] respectively studied on the suitability of down hole inflow control device in mining geological condition and sandstone reservoir, K. M. Han et al. [19] also attempted to assess the stability of strata over gob influenced by construction loads. However, it should be noticed that the recognition criteria of maximum membership used in above researches is no longer available when evaluation sets are ordered, because the order of evaluation sets are very likely to result in an unreasonable evaluation result and a low confidence coefficient[20]. B. S. Nie, et al. [7] realized the fuzzy comprehensive evaluation of coal mine safety investment structure based on the M(1,2,3) model and the recognition criteria of confidence coefficient, where the assessment level and membership degree and confidence coefficient can be obtained but the superiority ordering of evaluation objects cannot be got. In addition, Y. H. Xu and M. J. Shi [21] conducted the fuzzy comprehensive evaluation to beverage enterprise risks using nonlinear fuzzy transformation from the viewpoint of system engineering; M. L. Zhang [22] also studied on the real estate investment risks by considering the product of weight factor and degree of membership as score value calculation method that is apparently irrational as dealing with problems with negative assessment. For instance, for an evaluation indicator with negative assessment, the larger membership degree means the worse evaluation indicator whose score got should be less rather than added as in the above mentioned work.

For that reason, considering the improper subjectivity of expert opinions and the ordering of evaluation sets, this paper presents a new hierarchy fuzzy comprehensive evaluation approach that combines fuzzy transformation with "AND" operation of fuzzy soft sets to evaluate synthetically the CFRP machining processes. Moreover, a corresponding fuzzy evaluation model that consists of eleven evaluation factors, three first-level evaluation indicators, a second-level evaluation indicators and three evaluation objects is established. Using the hierarchy fuzzy comprehensive evaluation approach presented and model built, the second-level initial fuzzy evaluation and the second-level fine fuzzy evaluation can be implemented to reach assessment level, membership degree, confidence coefficient of each CFRP machining process and their superiority ordering, respectively. Above assessment results can provide a direct guidance for determine a proper CFRP machining process and organize efficiently production. By simply expanding, this evaluation approach can be adapted to evaluate other machining processes.

The rest of this paper is organized as follows: in section 2, some definitions and necessary explanations are given; in section 3, the basic idea of the presented evaluation approach and its steps are described in detail; in section 4, taking three CFRP machining processes including Mechanical Machining, Laser Cutting and Wet Cutting as examples, the comprehensive evaluation is conducted to verify the presented evaluation approach, the evaluation results got are compared with that of other evaluation approaches; in section 5, some conclusions drawn are summarized.

2. Preliminaries

2.1 Definition of expert evaluation fuzzy soft sets [13]. Suppose $U=\{x_1,x_2,x_3,x_4,x_5,x_6\}$ be the initial universe set where the evaluation factors x_1, x_2, x_3, x_4, x_5 and x_6 respectively denote typical CFRP cross-section defects such as "Heat damage" , "Resin spilling ","Delaminating", "Hole geometric deviation and Kerf width", "Carbon fiber pulling out and fracturing", "Carbon fiber splitting", etc. Let $E=\{e_1,e_2,e_3,e_4,e_5\}$ be the parameter set in which the evaluation level e_1, e_2, e_3, e_4 and e_5 respectively describe the severity degree of CFRP cross-section defects such as "Very severe", "Severe", "General", "Slight" and "no defect". Suppose the set $F(e_i)=\{e_1/\mu_{i,1},e_2/\mu_{i,2},...,e_5/\mu_{i,5},i=1,2,...,6\}$ to represent the membership degree of the evaluation factor x_i to the target option e_j is $\mu_{i,j}$ ($0\le\mu_{i,j}\le 1$), then the fair (F,E) is the expert evaluation fuzzy soft set of CFRP machining cross-section quality. Then, the expert evaluation fuzzy soft sets of process cost and production period can also be defined with similar method.

2.2 Definition of "AND" operation of fuzzy soft sets [9]. According to the definition in section 2.2, suppose the fuzzy soft set (F,A), (G,B) and (H,C) respectively represent the expert evaluation fuzzy soft sets of CFRP machining cross-section quality and process cost and production period, after "AND" operation, a new fuzzy soft set $(F',E')=(F,A)\wedge(G,B)\wedge(H,C)$ called as the CFRP machining process evaluation fuzzy soft set can form, where F' and E' are respectively defined as $F'=\{e_1^{'}/\mu_1^{'},e_2^{'}/\mu_2^{'},...,e_{n^p}^{'}/\mu_{n^p}^{'}\}$ and $E'=\{e_1^{'},e_2^{'},...,e_{n^p}^{'}\}$, the $e_{i'}^{'}$ is merged by e_A^i, e_B^j and e_C^k which respectively represents the ith , jth and kth parameter of the parameter sets A, B and C, so it is formulated as $e_{i'}^{'}=e_A^i\wedge e_B^j\wedge e_C^k)$,where $i'=(i-1)\times 25+(j-1)\times 5+k$, $(i,j,k=1,2,...n)$, the membership degree $\mu_{i'}^{'}$ takes the minimum among μ_A^i, μ_B^j and μ_C^k which respectively represent the corresponding membership degree of the ith , jth and kth parameter of the parameter set A, B, C and can be expressed as $\mu_{i'}^{'}=\mu_A^i\wedge\mu_B^j\wedge\mu_C^k=\min(\mu_A^i,\mu_B^j,\mu_C^k)$. The p and n are the number of fuzzy soft sets attending the "AND" operation and that of the evaluation indicators, respectively.

3. Hierarchy fuzzy evaluation of CFRP machining processes

3.1 Basic principle. For the presented hierarchy fuzzy comprehensive evaluation approach, its basic idea is to, as shown in Fig. 1, describe expert opinions as expert evaluation fuzzy soft sets, conduct the subjectivity control for expert opinions with inappropriate subjectivity by majority rule, build new weight factor vectors by contracting the distinguishing weigh factors with the initial weigh factors, implement the first-level fuzzy evaluation and the second-level initial fuzzy evaluation by fuzzy transformation, and realize the second-level fine fuzzy evaluation by the "AND" operation of fuzzy soft sets and the score calculation approach designed specially. This evaluation approach can provide more information about evaluation results including assessment level, membership degree, confidence coefficients and the superiority ordering of evaluation objects to guide process decision and organize production.

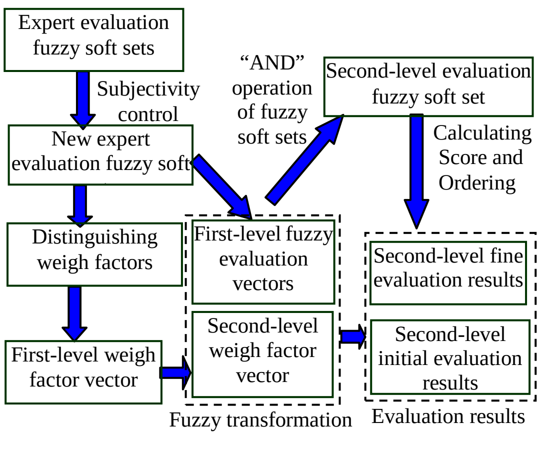

Fig. 1 Diagram of the presented hierarchy fuzzy comprehensive evaluation approach

3.2 Establishment of fuzzy evaluation model. For three different CFRP machining processes respectively named as Mechanical machining, Laser cutting and Wet cutting, a hierarchy fuzzy evaluation model is established as shown in Table 1, where eleven evaluation factors, three first-level evaluation indicators, a second-level are considered and the corresponding weights are determined by the contribution of each evaluation factor to the related evaluation indicator.

Table 1 Hierarchy fuzzy evaluation model of CFRP machining processes

First-level evaluation		**Second-level evaluation**
Factors(Weight)	Indicator(Weight)	Evaluation Indicator
Heat Damage(0.3)		
Resin Spilling(0.3)		
Delaminating(0.15)		
Hole geometric deviation and Kerf width(0.15)	Cross-section quality (0.5)	
Carbon fiber pulling out and fracturing(0.07)		Process adaptability
Carbon fiber splitting(0.03)		
Tool cost(0.3)	Process cost(0.3)	
Device cost(0.5)		
Energy consumption(0.2)		
Production preparation cycle(0.4)	Production period(0.2)	
Actual machining time(0.6)		

3.3 Hierarchy fuzzy evaluation of three CFRP machining processes. For the given evaluation model of CFRP machining processes in Table 1, the hierarchy evaluation is implemented by the following steps:

Step1: Collect expert opinions and form expert evaluation fuzzy soft sets. For an evaluation object, separately invite N experts to select a target option to each evaluation factor. And then, take the probability of every target option as the membership degree of the first-level evaluation indicators to form the initial expert evaluation fuzzy soft set $(\mathbf{F}_0, \mathbf{E}) = \{\mathbf{F}_{0,i}(e), i = 1,2,...,m\}$ where $\mathbf{F}_{0,i}(e)$ is defined as $\mathbf{F}_{0,i}(e) = \{e_1/\mu_{i,1}, e_2/\mu_{i,2},..., e_n/\mu_{i,n}\}$ that represents the initial membership degree vector of the ith evaluation factor, and m, n are the number of evaluation factors and target options, respectively.

Step 2: Subjectivity check and control of expert opinions. Suppose n_1 be the number of non-zero elements in the vector $\mathbf{F}_{0,i}(e)$. If $n_1 > (n+1)/2+1$ is satisfied, then it means that the subjectivity control is needed. To do that, find the minimum element $\mu_{i,\min} = \min(\mu_{i,j})$ from the vector $\mathbf{F}_{0,i}(e)$ and calculate $n_2 = \mu_{i,\min} \times N$ where n_2 are the number of experts who selected the target option with the minimum membership degree $\mu_{i,\min}$, and then invite the other n_2 experts to assess once more to update and rebuilt the new expert evaluation fuzzy soft set $(\mathbf{F}, \mathbf{E}) = \{\mathbf{F}_i(e), i = 1,2,...,m\}$.

Step 3: Determine the weight vector. For the set $(\mathbf{F}, \mathbf{E})$, its weigh vector $\mathbf{W}_1 = \{W_1, W_2,..., W_m\}$ can be determined by the equation $W_i = W_i^o \times W_i^{'}$ where W_i^o is the initial weight factor of each evaluation factor vectors given in Table 1, and $W_i^{'}$ is determined by the equation $W_i^{'} = V_i / \sum_{i=1}^{m} V_i$ where $V_i = 1 - 1/(n \times H_i)$ and $H_i = \sum_{j=1}^{n} \mu_{i,j}^2$.

Step 4: Fuzzy transformation. Conduct fuzzy transformation by the equation $\mathbf{E}_k(e) = \mathbf{W}_1 \bullet (\mathbf{F}, \mathbf{E})$ and $\mathbf{C}(e) = \mathbf{W}_2 \bullet (\mathbf{E}_1^{'}, \mathbf{E})$ to get the first-level fuzzy evaluation vector $\mathbf{E}_k(e)$ that can be described as $\mathbf{E}_k(e) = \{e_1/\mu_{k,1}, e_2/\mu_{k,2},..., e_n/\mu_{k,n}\}$ and the first-level and second-level initial fuzzy evaluation soft sets $(\mathbf{E}_1^{'}, \mathbf{E}) = \{\mathbf{E}_k(e), k = 1,2,..p\}$ and $\mathbf{C}(e) = \{e_1/\mu_1, e_2/\mu_2,..., e_n/\mu_n\}$, where p is the number of the first-level evaluation indicators. Then, the assessment level C_k and confidence coefficient R can be determined by equation $C_k = \begin{cases} \min\{k \mid R = \sum_{j=1}^{k} \mu_j \geq \lambda\} \\ \max\{k \mid R = \sum_{j=n}^{k} \mu_j \geq \lambda\} \end{cases}$, where $0.5 < \lambda < 1$ is the critical value specified by the recognition criteria of confidence coefficient.

Step 5: Conduct the "AND" operation of fuzzy soft sets. Take separately a target option from each row of $(\mathbf{E}_1^{'}, \mathbf{E})$ and merge them to form the second-level fine fuzzy evaluation soft set $(\mathbf{G}, \mathbf{E}') = \{\mathbf{G}(e')\} = \{e_1^{'}/\mu_1^{'}, e_2^{'}/\mu_2^{'}, ..., e_s^{'}/\mu_s^{'}\}$ by the "AND" operation, where $e_i^{'}$, $\mu_i^{'}$ can be defined respectively as $e_i^{'} = e_{1,s_1} \wedge e_{2,s_2} \wedge, ..., \wedge e_{p,s_p}$ and $\mu_i^{'} = \min\{\mu_{1,s_1}, \mu_{2,s_2}, ..., \mu_{p,s_p}\}$ where e_{k,s_k} and μ_{k,s_k} represent the s_k th evaluation target option of the k th row of the set $(\mathbf{E}_1^{'}, \mathbf{E})$ and their membership degree, so $s = n^p$.

Step 6: Calculate score of each evaluation object and conduct the superiority ordering. For the set $(\mathbf{G}, \mathbf{E}')$, the score vector $\mathbf{S} = \{S_1, S_2, ..., S_s\}$ can be calculated by $S_i = \sum_{k=1}^{p} s_k$. If the number of evaluation objects is q, then the comparison table $\mathbf{C}$ with q rows and q columns can be formed by $\mathbf{C}(i, j) = \sum_{k=1}^{q} S'(k)$. Where, if $S_k \geq S_{average}$ and $\mu_{i,k}^{'} \geq \mu_{j,k}^{'}$ or $S_k < S_{average}$ and $\mu_{i,k}^{'} \leq \mu_{j,k}^{'}$, then $S'(k) = S_k$, or else $S'(k) = 0$, and $S_{average} = (\sum_{j=1}^{n} j)/n$ is the average score of target options, $\mu_{i,k}^{'}$ and $\mu_{j,k}^{'}$ denote the membership degree of the k th target option of the i th and j th evaluation object, respectively. If the score value V_i of the i th evaluation object can be got by $V_i = Sr_i - Sc_j$ where Sr_i and Sc_j are the sum of elements of the i th row and j th column of the comparison table $\mathbf{C}$, respectively, then the superiority ordering of evaluation objects is carried out by the score value, that means the larger the score value is, the better the evaluation object is.

4 Illustration and Discussions

For samples obtained from Mechanical machining, Laser cutting and Wet cutting, invite N experts to select the evaluation levels from "More severe(e_1)", "Severe(e_2)", "General(e_3)", "Less severe(e_4)" and "Not severe(e_5)" to each cross-section quality evaluation factor given in Table 1 so as to form expert opinions and the corresponding initial expert evaluation fuzzy soft sets $(\mathbf{F}_{1,M}, \mathbf{E})$, $(\mathbf{F}_{1,L}, \mathbf{E})$ and $(\mathbf{F}_{1,C}, \mathbf{E})$ by step1 in section 3.3. They are given as:

$$(\mathbf{F}_{1,M}, \mathbf{E}) = \begin{bmatrix} \frac{e_1}{0} & \frac{e_2}{0.2} & \frac{e_3}{0.3} & \frac{e_4}{0.4} & \frac{e_5}{0.1} \\ 0 & 0 & 0 & 0 & 1 \\ 0.2 & 0.5 & 0.2 & 0.1 & 0 \\ 0.1 & 0.4 & 0.2 & 0.2 & 0.1 \\ 0.2 & 0.3 & 0.3 & 0.1 & 0.1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (\mathbf{F}_{1,L}, \mathbf{E}) = \begin{bmatrix} \frac{e_1}{0.3} & \frac{e_2}{0.4} & \frac{e_3}{0.2} & \frac{e_4}{0.1} & \frac{e_5}{0} \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0.2 & 0.3 & 0.2 & 0.3 \\ 0 & 0 & 0 & 0.2 & 0.8 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (\mathbf{F}_{1,C}, \mathbf{E}) = \begin{bmatrix} \frac{e_1}{0} & \frac{e_2}{0} & \frac{e_3}{0} & \frac{e_4}{0.1} & \frac{e_5}{0.9} \\ 0.1 & 0.5 & 0.2 & 0.1 & 0.1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.1 & 0.9 \\ 0 & 0.3 & 0.4 & 0.3 & 0 \end{bmatrix}.$$

Similarly, after being assessed by "Higher (e_1)", "High (e_2)", "General (e_3)", "Low (e_4)", "Low (e_5)" to three process cost evaluation factors , and by "Longer (e_1)", "Long (e_2)", "General (e_3)", "Short (e_4)" and "Shorter (e_5)" to two production period evaluation factors given in Table 1, the corresponding initial expert evaluation fuzzy soft sets $(\mathbf{F}_{2,M}, \mathbf{E})$, $(\mathbf{F}_{2,L}, \mathbf{E})$, $(\mathbf{F}_{2,C}, \mathbf{E})$ and $(\mathbf{F}_{3,M}, \mathbf{E})$, $(\mathbf{F}_{3,L}, \mathbf{E})$, $(\mathbf{F}_{3,C}, \mathbf{E})$ are got as:

$$(\mathbf{F}_{2,M},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0.3 & 0.4 & 0.2 & 0.1 & 0\\ 0 & 0.2 & 0.4 & 0.3 & 0.1\\ 0.2 & 0.3 & 0.3 & 0.2 & 0\end{bmatrix}\end{array},\ (\mathbf{F}_{2,L},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0 & 0 & 0 & 0 & 1\\ 0.3 & 0.4 & 0.2 & 0.1 & 0\\ 0.2 & 0.4 & 0.2 & 0.1 & 0.1\end{bmatrix}\end{array},\ (\mathbf{F}_{2,C},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0.2 & 0.5 & 0.3 & 0 & 0\\ 0 & 0 & 0.4 & 0.5 & 0.1\\ 0 & 0 & 0.5 & 0.2 & 0.3\end{bmatrix}\end{array},$$

$$(\mathbf{F}_{3,M},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0.1 & 0.3 & 0.5 & 0.1 & 0\\ 0.3 & 0.5 & 0.2 & 0 & 0\end{bmatrix}\end{array},\ (\mathbf{F}_{3,L},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0.3 & 0.4 & 0.3 & 0 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}\end{array},\ (\mathbf{F}_{3,C},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0.4 & 0.4 & 0.2 & 0 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}\end{array}.$$

After subjectivity check and control, rebuild the initial expert evaluation fuzzy soft sets that failed to pass so the sets $(\mathbf{F}^{'}_{1,M},\mathbf{E})$, $(\mathbf{F}^{'}_{1,C},\mathbf{E})$ and $(\mathbf{F}^{'}_{2,L},\mathbf{E})$ updated by $(\mathbf{F}_{1,M},\mathbf{E})$, $(\mathbf{F}_{1,C},\mathbf{E})$, $(\mathbf{F}_{2,L},\mathbf{E})$ are presented as follow:

$$(\mathbf{F}^{'}_{1,M},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0 & 0.2 & 0.3 & 0.4 & 0.1\\ 0 & 0 & 0 & 0 & 1\\ 0.2 & 0.5 & 0.2 & 0.1 & 0\\ 0.1 & 0.4 & 0.3 & 0.2 & 0\\ 0.2 & 0.3 & 0.3 & 0.2 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}\end{array},\ (\mathbf{F}^{'}_{1,C},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0 & 0 & 0 & 0.1 & 0.9\\ 0.1 & 0.5 & 0.2 & 0.2 & 0\\ 0 & 0 & 0 & 0 & 1\\ 0 & 0 & 0 & 0 & 1\\ 0 & 0 & 0 & 0.1 & 0.9\\ 0 & 0.3 & 0.4 & 0.3 & 0\end{bmatrix}\end{array},\ (\mathbf{F}^{'}_{2,L},\mathbf{E})=\begin{array}{c}\begin{matrix} e_1 & e_2 & e_3 & e_4 & e_5\end{matrix}\\ \begin{bmatrix} 0 & 0 & 0 & 0 & 1\\ 0.3 & 0.4 & 0.2 & 0.1 & 0\\ 0.2 & 0.4 & 0.2 & 0.2 & 0\end{bmatrix}\end{array}.$$

Using the weigh factors given in Table 1, three initial weight vectors $\mathbf{W}_1^o$, $\mathbf{W}_2^o$, $\mathbf{W}_3^o$ and the weight vector $\mathbf{W}_2$ of first-level evaluation targets can be respectively defined by step 4 in section 3.3. where, $\mathbf{W}_1^o=\{0.3,0.3,0.15,0.15,0.07,0.03\}$, $\mathbf{W}_2^o=\{0.3,0.5,0.2\}$, $\mathbf{W}_3^o=\{0.4,0.6\}$, $\mathbf{W}_2=\{0.5,0.3,0.2\}$.

After conducting the first-level and second-level fuzzy transformation, the second-level initial fuzzy evaluation soft sets（$\mathbf{C}_{\mathrm{M}}$, $\mathbf{E}$), （$\mathbf{C}_{\mathrm{L}}$, $\mathbf{E}$) and （$\mathbf{C}_{\mathrm{C}}$, $\mathbf{E}$) can be obtained, by which the assessment level of the Mechanical machining, Laser cutting and Wet cutting process can be determined by the recognition criteria of confidence coefficient at the critical confidence coefficient $\lambda=0.6$. They are respectively “General”, “General” and “Suitable” and the corresponding confidence coefficients are not less than 66.1%, 64.3% and 61.1%, respectively.

After the second-level fuzzy fine evaluation by step 6 and step 7 in section 3.3, the score values of three different CFRP machining processes mentioned above respectively are -512, 188 and 324 by which the superiority ordering of evaluation objects from high to low can be realized to be Wet cutting , Laser cutting, Mechanical machining in sequence.

In order to verify the necessity of the subjectivity check and control of expert opinions and the validity of the hierarchy fuzzy evaluation method presented in this work, name the hierarchy fuzzy evaluation method undergoing and not undergoing subjectivity control of expert opinions as A1 and A2, respectively. And name the traditional fuzzy comprehensive evaluation approach as A3. The evaluation results obtained from three different evaluation methods are listed in Table 2 where the notation M1, M2 and M3 respectively stand for Mechanical machining, Laser cutting and Wet cutting process, the notation Ck, α, No and S respectively refer to the assessment level, confidence coefficient, order and score value of evaluation objects.

Table 2 Evaluation results of different evaluation methods

Process /	Method	Result vector	Evaluation results		
			C_k	α	No. (S)
M1	A3	{0.0945,0.2381,0.2144,0.1373,0.3157}	e5	31.6%	/
	A2	{0.0945,0.2381,0.2144,0.1373,0.3157}	e3	66.7%	1(-446)
	A1	{0.0962,0.2428,0.2217,0.1402,0.2991}	e3	66.1%	1(-512)
M2	A3	{0.1425,0.2144,0.1377,0.0621,0.4434}	e5	44.3%	/
	A2	{0.1425,0.2144,0.1377,0.0621,0.4434}	e3	64.3%	3(258)
	A1	{0.1425,0.2144,0.1377,0.0694,0.4361}	e3	64.3%	2(188)
M3	A3	{0.0668,0.1516,0.1722,0.0990,0.5104}	e5	51.0%	/
	A2	{0.0668,0.1516,0.1722,0.0990,0.5104}	e4	60.9%	2(188)
	A1	{0.0654,0.1514,0.1723,0.1113,0.4997}	e4	61.1%	3(324)

In Table 2, the notation e1, e2, e3, e4 and e5 respectively represent the evaluation result level are "Very Unsuitable", "Unsuitable", "General", "Suitable" and "More Suitable,. The symbol "/" in the last column implies that the corresponding evaluation method cannot implement the score calculation. Moreover, the larger the score of a CFRP machining process, the higher its superiority ordering is and the better its process adaptability.

From the Table 2, it can be noticed that, comparing with Approach A3, Approach A1 and Approach A2 can not only attain the assessment level of evaluation object, but also get the superiority ordering of multi evaluation objects by the "AND" operation of fuzzy soft sets and two-level score calculation method. In addition, by using the recognition criteria of confidence coefficient instead of the maximum membership degree criteria, Approach A1 and Approach A2 can obtain more reasonable evaluation results and higher confidence coefficient than Approach A3. For example, the membership degree of evaluation results obtained from Approach A3 is 31.6%, 44.3%, 51.0% for Mechanical machining, Laser cutting, and Wet cutting, respectively, which is much lower than that of Approach A1(66.1%, 64.3%, 60.9%) and Approach A2 (66.7%, 64.3%, 60.9%). Finally, the subjectivity control used in Approach A1 can eliminate the bad effect caused by the strong subjectivity of expert opinions to promote the reasonability of evaluation results. For instance, in spite of the real small difference of confidence coefficients and the same two-level fuzzy initial assessment result as Approach A1, which is "General"(e3), "General"(e3), "Suitable"(e4) for Mechanical machining, Laser cutting and Wet cutting, Approach A2 that no subjectivity control is conducted get the superiority ordering of the three CFRP machining processes from high to low is "Laser cutting(e3)","Wet cutting(e4) , "Mechanical machining(e3)" in sequence. That implies the "Laser cutting" process whose assessment level is "General" (e3) is better than the "Wet cutting" process whose assessment level is "Suitable" (e4). Whereas, after undergoing the subjectivity control, Approach A1 gets the superiority ordering is "Wet cutting (e4), "Laser cutting (e3)", "Mechanical machining (e3)" in sequence, which is consistent with their assessment levels and also verifies the necessity and beneficial effect of subjectivity control on the reasonable evaluation results.

CONCLUSION

For three CFRP machining processes such as "Mechanical machining", "Laser cutting", and "Wet cutting", a hierarchy fuzzy evaluation approach is presented based on the "AND" operation of fuzzy soft sets and subjectivity control. By considering synthetically some key factors like CFRP cross-section quality, process cost and production period, the corresponding fuzzy evaluation model is established to evaluate their process adaptability. The following conclusions can be drawn:

(1) By using the subjectivity control of expert opinions, the recognition criteria of confidence coefficients and fuzzy transformation, the two-level initial fuzzy evaluation can be implemented to get the evaluation results covering the assessment level, membership degree and confidence coefficients so that the evaluation results are more reasonable and creditable.

(2) The two-level fine fuzzy evaluation is carried out by adopting the "AND" operation of fuzzy soft sets and the two-level score calculation method to realize the superiority ordering of evaluation objects, which can provide a direct guidance for process optimization and production decision.

(3) The subjectivity check and control of expert opinions based on majority rule can validly suppress the bad effect caused by a very few improper expert opinions so as to promote the reasonability of evaluation results.

(4) the used two-level score calculation method considering the ordering of evaluation levels in the expert evaluation fuzzy soft sets, takes the average score of evaluation options as the boundary value and works out the score of evaluation objects by a more reasonable rule, which is if an evaluation object has a larger (or smaller) score than the boundary value and a larger (or smaller) membership degree than others, then it is considered to be better than others so the corresponding score value should be added to it; else nothing be done. This score calculation method overcomes the irrationality of conventional methods in which adding score is only conducted to the evaluation object with larger membership degree.

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