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Crackable Connecting Rod Material Selection by Using TOPSIS Method

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Abstract Fracture splitting method is an innovative processing technique in the field of automobile engine connecting rod (con/rod) manufacturing. Compared with traditional methods, this technique has remarkable advantages. Manufacturing procedures, equipment and tools investment can be decreased and energy consumption reduced remarkably in this method. Furthermore, product quality and bearing capability could be improved. It provides a high quality, high accuracy and low cost route for producing connecting rods (con/rods). This method has attracted manufacturers attention and has been utilized in many types of con/rod manufacturing due to the many advantages mentioned above. In this study, the outranking of crackable connecting rod material has been obtained by using TOPSIS (Technique For Order Preference By Similarity To Ideal Solution), Multiple Criteria Decision Making method. We outrank C70S6 (pearlite, bainite, martensite and tempered martensite), 70MnSV4 and FRACTIM crackable connecting materials with 6 criteria.

Keywords Crackable Connecting Rod, Material Selection, TOPSIS Method, Ranking

1. Introduction

Connecting rods are widely used in variety of automobile engines. The function of the connecting rod is to transmit the thrust of the piston to the crankshaft and translate the transverse motion to rotational motion. It should be strong enough to remain rigid under loading, and also be light enough to reduce the inertia forces, which are produced when the rod and piston stop, change directions and start again at the end of each stroke [1].

The fracture splitting method is an innovative processing technique in the field of the automobile engine connecting rod (con-rod) manufacturing. Compared with traditional method, the technique has remarkable advantages. It can decrease manufacturing procedures, reduce equipment and tools investment and save energy. Hence the total production cost is greatly reduced. Furthermore, the technique can also improve product quality and bearing capability. It provides a high quality, high accuracy and low cost route for producing connecting rods (con/rods). The method has attracted extensive attention and has been used in some types of con/rods manufacturing. In recent years, with the rapid development of the automobile industry, the competition in the international automobile markets has become more severe. New market conditions demand manufacturers employ higher quality, greater efficiency and lower cost manufacturing technology to fabricate automobile parts so as to improve their competitive capability and meet the market requirements [2].

Microalloyed high carbon steels (such as C70S6, SMA40 and FRACTIM) have been considered to be economical alternatives to powder metal and conventional steel, having been used as main crackable con-rod materials (Figure 1 and 2) in recent years used in the fracture splitting method. Compared with powder metal and conventional steel, these microalloyed high carbon steels have remarkable advantages. One of the main advantages is that cost reduction can be achieved by changing the micro-structure of the con-rod. Sawing and machining processes of the rod and cap, in order to mate two faces can be eliminated, and is believed to reduce the production cost by 25%. Another advantage of this production method is that fracture-splitting connecting rods exhibit 30% higher fatigue strength and 13% less weight than conventional connecting rods, and can be splitted into two pieces (big body and cap) by fracturing with an instant impact load. Compared with powder metal and cast con-rods, it also has lower cost for the whole manufacturing process. Hence, it provides more advantageous production opportunities, and is preferred in manufacturing technology mostly [3].

In this study, TOPSIS (Technique For Order Preference By Similarity To Ideal Solution) has been used to outrank the alternatives of crackable connecting rod among C70S6 (pearlite, bainite, martensite and tempered martensite), 70MnSV4 and Fractim. TOPSIS is an outranking method,

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helps the decision maker (DM) to choose the best option among the alternatives or outrank the alternatives with criteria. TOPSIS is one of known classical Multi Criteria Decision Making (MCDM) method.

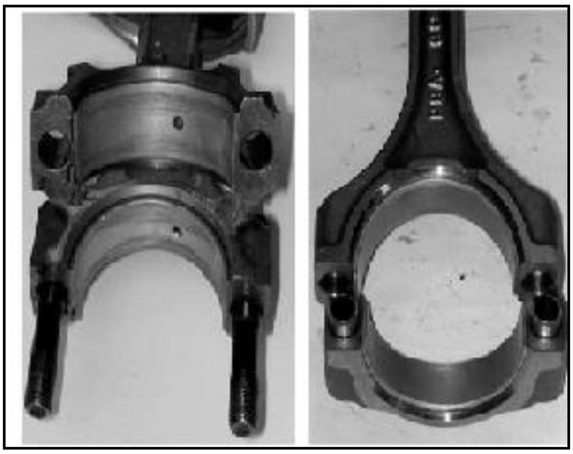

Figure 1. Crackable Connecting Rod Manufacturing Processes, Convensional Machining Method [4]

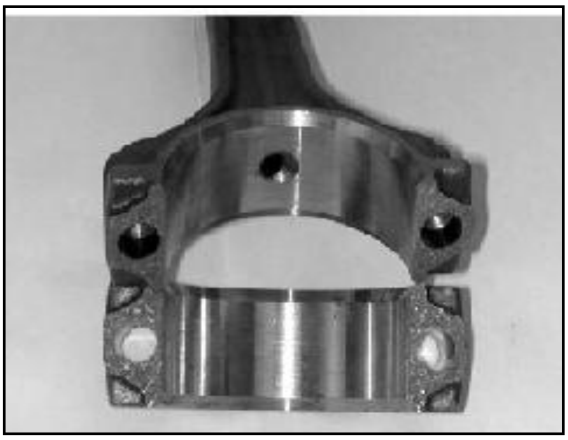

Figure 2. Crackable Connecting Rod Manufacturing Processes, Fracture Splitting Method [4]

MCDM methods, both qualitative and quantitative, were developed to better model decision scenarios. These vary in their mathematical rigor, validity and design. Simple additive and multiplicative models, weighted or not, aggregate scores for each alternative across all criteria [5].

MCDM has been one of the fastest growing areas during the last decades depending on the changings in the business sector. DM(s) need a decision aid to decide between the alternatives and mainly excel less preferable alternatives fast. With the help of computers the decision making methods have found great acceptance in all areas of the decision making processes. Since MCDM has found acceptance in areas of operation research and management science, the discipline has created several methodologies. Especially in the last years, where computer usage has increased significantly, the application of MCDM methods has considerably become easier for the users the decision makers as the application of most of the methods are corresponded with complex mathematics [6].

2. Literature Review

Considerable studies have been made on the fracture splitting parameters of connecting rods. Some of them have been discussed below. Especially C70S6 steel has been investigated mostly. Fractim and C70S6 have been used in industry mostly and carried on academic research.

C70S6 is excellent in fracture-splitability thanks to its small deformation during splitting, It has a coarser structure than the ferrite/pearlite structure of the medium-carbon micro-alloyed steels currently used as con-rod steels. It is therefore low in yield ratio (yield strength/tensile strength) and cannot be applied to high-strength con-rods requiring high yield strength. Moreover, the inferior machinability of C70S6 owing to its pearlite structure has kept the steel from finding extensive utilization [7]. Chemical compositions of materials used for comparing is shown in Table 1 and mechanical properties in Table 2.

Steels for fracture-split components have been developed in response to the foregoing needs. Changing the chemical structure by adding new materials as, Zr, Ca and Al. have been investigated by Manabu Kubota, Shinya Teramoto and Ti adding via FEM method by Qiu et al. [1] recently. The fracture parameters, microstructures and heat treatment effects have been examined by Özdemir et al. in detail [3,4,7,8]. Gu et al. investigated the fracture splitting parameters in automobile engine connecting rods in their study [9]. Manabu Kubota and his friends also investigated similar parameters [10]. Relationship between fracture parameters and microstructure is also investigated by Zhang et al. [11].

Liming, Z. and his friends investigated the lazer effect to the starting notch and fracture parameters [12]. Deen, Z. and his friends investigated the lazer effect to the starting notch depth and Radius [13].

Table 1. Chemical Compositions of Materials Used as Crackable Con-Rod Steels (weight %, nominal) [7]

Specification	C	Si	Mn	P	S	Ni
C70S6 (pearlite)	0.69	0.18	0.50	0.020	0.064	0.060
C70S6 (bainite)	0.69	0.18	0.50	0.020	0.064	0.060
C70S6(martenzite)	0.69	0.18	0.50	0.020	0.064	0.060
C70S6 (tempered martenzite)	0.69	0.18	0.50	0.020	0.064	0.060
FRACTIM	0.63	0.25	0.76	0.042	0.088	0,025
70MnSV4	0.70	0.22	0.83	0.009	0.061	0.080

Table 2. Some Important Mechanical Properties of Crackable Connecting Rods [14]

Con-Rod Material	σ_{yield} [MPa] Ave.	$\sigma_{tensile}$ [MPa] Ave.	Sertlik [HRB] Ave.	% ε strain Ave.	$S_{e\ fatigue\ limit}$ [MPa] Ave.
C70S6 (pearlite)	560	850	280	10	428,4
C70S6 (bainite)	590	920	278	10	463,68
C70S6 (martenzite)	892	1100	352	6	554,4
C70S6 (tempered martenzite)	612	900	310	9	453,6
FRACTIM	540	810	300	12	433,44
70MnSV4	570	860	255	11	408,24

The selection of a material for a specific engineering purpose is a lengthy and expensive process. Approximately always more than one material is suitable for an engineering application, and the final selection is a compromise that brings some advantages as well as disadvantages. Selection, sorting and outranking of the alternatives in engineering can be executed in MCDM methods. There are several studies in this area. Amongst them; Jahan et al. [15] examined the MCDM approaches to find an answer to the questions: What is the contribution of the literature in the field of screening and choosing the materials? What are the methodologies/ systems/tools for material selection of engineering components? Which approaches were prevalently applied? Is there any inadequacy of the approaches? In the conclusion of the study, their research provided evidence that the MCDM approaches has the potential to greatly improve the material selection methodology and aided the researchers and decision makers in applying the approaches effectively. Shanian and Savadogo [16] used TOPSIS method for solving the material selection problem of metallic bipolar plates for polymer electrolyte fuel cell (PEFC), which often involves multiple and conflicting objectives. In their study, a list of all possible choices, from the best to the worst materials is obtained by taking into account all the material selection criteria, including the cost of production.

Jahan et al. [17] suggested an extension of VIKOR method that can enhance exactness of material selection results in different applications, especially in biomedical application where the implant materials should possess similar properties to those of human tissues. In the study, five examples were included to illustrate and justify the suggested method. Chatterjee et al. [18] applied VIKOR and ELECTRE, MCDM methods to outrank the materials. Two examples are cited in order to demonstrate and validate the effectiveness and flexibility of these two MCDM approaches. In each example, a list of all the possible choices from the best to the worst suitable materials is obtained taking into account different material selection criteria. They demonstrated that the rankings of the selected materials almost corroborate with those as obtained by the past researchers.

The researchers have no met any research about multiple decision criteria on crackable connecting rods in literature.

In this paper, selected crackable connecting rod materials will be outranked according to the chosen criteria. We will use TOPSIS method which requires minimum subjective additional parameters that should be decided by decision maker. The outranking process will be examined in latter sections. The next section briefly describes TOPSIS method notations. The outranking process of TOPSIS is in the third section. And in the conclusion part, the results of the research are discussed.

3. TOPSIS Method

MCDM is used to select a project from several alternatives according to various criteria. TOPSIS method was first developed by Hwang and Yoon [19] based on the concept that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS) for solving a MCDM problem. Thus, the best alternative should not only have the shortest distance from the positive ideal solution, but also should have the largest distance from the negative ideal solution. In short, the ideal solution is composed of all best values attainable of criteria, where as the negative ideal solution is made up of all worst values attainable of criteria [20].

The TOPSIS method consists of the following process [21, 22].

Calculate the normalized decision matrix. The normalized value r_{ij} is calculated as it follows:

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \qquad i=1,.....,m; \quad j=1,......,n \tag{1}$$

After the normalization, the normalized decision matrix can be seen below;

$$R_{ij} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}$$

Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as it follows;

$$v_{ij} = w_n \cdot r_{mn} \qquad i=1,\ldots,m; \; j=1,\ldots,n \tag{2}$$

A set of weights $w=(w_1, w_2, w_3, \ldots, w_n)$, (where: $\sum w_n = 1$) defined by the DM is accommodated to the decision matrix to generate the weighted normalized matrix V as follows:

$$v_{ij} = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \cdots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \cdots & w_n r_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ w_1 r_{m1} & w_2 r_{m2} & \cdots & w_n r_{mn} \end{bmatrix}$$

The ideal A^+ and the negative-ideal A^- solutions are defined as follows:

$$A^+ = \left\{\left(\max_i v_{ij} \mid j \in J\right), \left(\min_i v_{ij} \mid j \in J'\right)\right\}$$
$$i = 1,2,\ldots,m = \left\{A_1^+, A_2^+, \ldots, A_j^+, \ldots, A_k^+\right\} \tag{3}$$

$$A^- = \left\{\left(\min_i v_{ij} \mid j \in J\right), \left(\max_i v_{ij} \mid j \in J'\right)\right\}$$
$$i = 1,2,\ldots,m = \left\{A_1^-, A_2^-, \ldots, A_j^-, \ldots, A_k^-\right\} \tag{4}$$

For the benefit criteria, the decision maker wants to have a maximum value among the alternatives. For the cost criteria, the decision maker wants to have a minimum value among alternatives. Obviously, A^+ indicates the most preferable alternative or ideal solution. Similarly, A^- indicates the least preferable alternative or negative-ideal solution.

Calculate the separation measure. In this step the concept of the N-dimensional Euclidean distance is used to measure the separation distances of each alternative to the ideal solution and negative-ideal solution. S_i^+ (distances to the ideal solution) and S_i^- (distances to the negative-ideal solution) are calculated with given formulas.

$$S_i^+ = \sqrt{\sum_{j=1}^{k}\left(v_{ij} - A_j^+\right)^2} \text{ and } S_i^- = \sqrt{\sum_{j=1}^{k}\left(v_{ij} - A_j^-\right)^2} \tag{5}$$

Calculate the relative closeness to the ideal solution. The relative closeness of the alternative A_i with respect to A^+ is defines as it follows. It specifies that $0 \le C_i^* \le 1$, an alternative *i* is closer to A^+ as C_i^* approaches to 1.

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-} \qquad 0 < C_i^* < 1 \tag{6}$$

Rank the preference order. Choose an alternative with maximum C_i^* or outrank the alternatives according to C_i^* in descending order.

The best (optimal) alternative can now be decided according to the preference rank order of C_i^*. Therefore, the best alternative is the one that has the shortest distance to the ideal solution. The previous definition can also be used to demonstrate that any alternative which has the shortest distance from the ideal solution is also guaranteed to have the longest distance from the negative-ideal solution.

4. Materials and Methods

In this study TOPSIS has been used to choose the best alternative material for crackable connecting rod. The alternative materials list is shown in Table 3. Choice criteria are shown in Table 4. These criteria are cost, tensile strength, fatigue limit, fracture toughness, productivity-machining and first fracture brittleness.

It is desired that tensile strength, fatigue limit, fracture toughness values, productivity-machining and first fracture brittleness values to be maximized and cost to be minimized.

A decision matrix is shown in Table 5 for selected materails. It is assumed that the most satisfying degree material is to be chosen for crackable connecting rod material.

Table 3. Crackable Connecting Rod Materials

Crackable Connecting Rod Materials	Symbol
C70S6 - Pearlite	A_1
C70S6 - Tempered Martensite	A_2
C70S6 - Bainite	A_3
C70S6 - Martensite	A_4
70MnSV4	A_5
FRACTIM	A_6

Table 4. Crackable Connecting Rod Choice Criteria

Choice criteria	Symbol	Orientation
Cost (TL/kg.)	C	Minimization
Tensile Strength (N/mm^2)	TS	Maximization
Fatigue limit (N/mm^2)	FL	Maximization
Fracture Toughness ($N/mm^{3/2}$)	FT	Maximization
Productivity-Machining (Nominal Value Best:10, Worst:0)	PM	Maximization
First Fracture Brittleness (Nominal Value Best:10, Worst:0)	FFB	Maximization

To carry out the TOPSIS method, first of all, decision matrix is made out as shown in Table 5 then weighted normalized decision matrix is developed. Weighted normalized decision method values are shown in Table 6.

Table 5. Decision Matrix for Crackable Connecting Rod Material [3, 4]

Material	C	TM	FL	FT	PM	FFB
A_1 C70S6 Pearlite	10	850	528,4	21,96	9	9
A_2 C70S6 Tempered Martenzite	11	900	503,6	18,12	6	7
A_3 C70S6 Bainite	12	920	613,68	22,35	9	9
A_4 C70S6 Martenzite	10,5	1100	554,4	10,67	1	1
A_5 70MnSV4	9	810	408,24	20,63	7	8
A_6 FRACTIM	10	860	453,44	21,85	9	9

Table 6. Weighted Normalized Decision Matrix

Material	C	TS	FL	KT	PM	FFB
A_1	0,065	0,063	0,070	0,076	0,083	0,079
A_2	0,072	0,067	0,067	0,063	0,055	0,062
A_3	0,078	0,069	0,081	0,077	0,083	0,079
A_4	0,068	0,082	0,073	0,037	0,009	0,009
A_5	0,059	0,060	0,054	0,071	0,064	0,070
A_6	0,065	0,064	0,060	0,075	0,082	0,079

Ideal and negative ideal solutions are shown in Table 7 solved via (3) and (4) equations.

Table 7. The Ideal and Negative-Ideal Solutions

	C	TS	FL	KT	PM	FFB
A^+	0,059	0,082	0,081	0,077	0,083	0,080
A^-	0,078	0,060	0,054	0,037	0,009	0,009

İdeal (Si^+) and negative ideal (Si^-) values have been calculated by using equations (5) and (6) as shown in Table 8. The best choice is here is A_1 (C70S6 - Pearlite) and the worst one is A_4 (C70S6 -Martenzite).

Table 8. Outranking of TOPSIS

Material	S_i^+	S_i^-	C_i^*	TOPSIS Outranking
A_1	0,022794	0,111066	0,8297165	1
A_2	0,043460	0,076295	0,6370925	5
A_3	0,023696	0,113213	0,8269199	2
A_4	0,110311	0,030616	0,2172472	6
A_5	0,040710	0,091746	0,6926527	4
A_6	0,028551	0,109974	0,7938943	3

5. Results and Discussion

In Table 8, it is not so much surprising that C70S6-pearlite (A_1) is the dominant material for crackable connecting rod material. C70S6-bainite (A_3) outranking TOPSIS value is at close quarters to C70S6-pearlite. The chemical composition of A_1 is same as A_3, but when austempering is applied, the microstructure is transformed into bainite; so some mechanical properties change.

Then it could be seen FRACTIM (A_6) and 70MnSV4 (A_5) are the next alternatives for crackable connecting rod materials. It was concluded that tempered martensite (A_2) could be used as another alternative but martensite (A_4) is not a choice for crackable connecting rods.

Due to its' mechanical properties; martensite is too hard and is not a suitable material composition for use in machines, but it can gain some toughness by tempering so called tempered marten site. It has been shown experimentally by Z.Özdemir and his friends [7,8] that tempered martenzite and bainite [23] could also be an important material alternative for crackable connecting rods.

Pearlite, FRACTIM and 70MnSV4 is still used technologically for crackable connecting rods.

6. Conclusions

In this study the material choice has been studied and investigated for crackable connecting rods. TOPSIS method is used in this analysis. As a result it was concluded that the best choices for crackable connecting rod materials are pearlitic and bainitic C70S6.

This result is very much adequate to the material selection and mechanics references for material design. Pearlitic structure is preferred in most of the materials used in machines. Bainite is also used but it is much more high-cost production because of heat-treatment method (austempering) as compared with pearlite.

FRACTIM is another alternative and it is also used in technology widespread with 70MnSV4. Tempered martenzite is not cost effective but it could be used mechanically. Martenzite is neither cost effective nor mechanically proper for use.

This study could be applied to other materials and analysed with other MCDM methods such as PROMETHEE, VIKOR, etc.

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