

Materials Selection for Malleable Cast-Iron Pipe Fittings with a Numerical Method

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Abstract

Malleable cast irons have many applications in the industries includes pipe fittings and automotive industry. The importance and consequence of selecting efficient materials in pipe fittings and its effect on the final quality of products are apparent. In the case of the multiple criteria for selection, implementing a mathematical model is inevitable. In this study, the calculations performed in AHP and TOPSIS models with the aim of achieving the efficient materials of pipe fittings in order to ease the issues raised from trial-and-error decision making. In this regard, five alternatives for cast iron have been identified by experts and analysis carried out according to molten fluidity, shrinkage during solidification, machining capabilities, yield strength, ultimate strength and ductility. By the comparing of the outcome of these models with practical implementation for the five samples malleable cast iron, the alternative GTS-55 alloy was recognized as the best choice. It is also concluded that the difference in results is justifiable because of the similarity of the properties.

Keywords: Multi-criteria decision making; Malleable cast irons; Pipe fittings; AHP; TOPSIS

Introduction

White cast iron is annealed to produce malleable cast Iron with granular graphite in ferrite or perlite matrix depends on chemical composition and heat treatment [1]. Importance of malleable cast irons selection comes from their low manufacturing cost and machining ability. Pipe fittings are the main application of these types of materials in vehicles, oil and petrochemical, mining, iron and steel, agricultural and electrical industries [2]. Nowadays, threaded fittings as oldest methods of joint in piping systems made by malleable cast irons. their properties such as strength, machining ability, erosion and corrosion resistance will enhance by specific heat treatments [3]. Using the mathematical logic is highly necessary when we faced with several criteria in selection. Analytical Hierarchical Process (AHP) is a decision-making technique for ranking the solutions and select their best. This procedure was always a frequently used method in most of the decision-making problems [4]. As indicated in Figure 1, the criteria and the alternatives with regards to the target are housed in a hierarchical tree [5]. In other word, a complex problem breaks down into a simple structure.

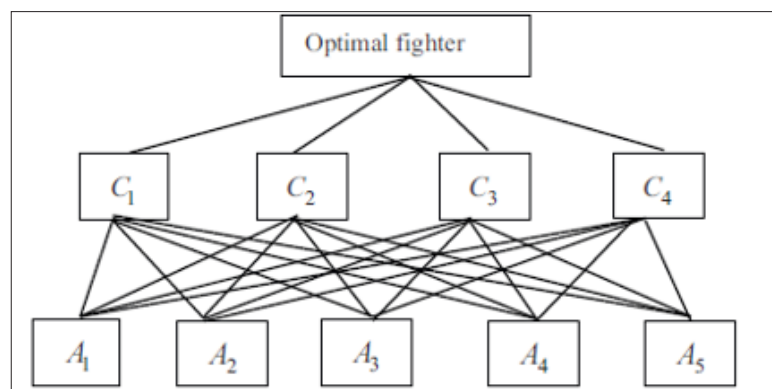


Figure 1: Hierarchical structure for selection the proper alternative [4].

As long ago, there are many studies conducted over the mathematical models in materials selection. Roy et al. [5], revealed that it possible to achieve the optimal parameters in sub-merge weld joint of plain carbon steel using AHP model in the absence of microstructure characterization. Chakladar et al. [6], also presented a new hybrid model of AHP and TOPSIS to rank the metal machining parameters. The TOPSIS method is another decision-making method in alternative selection using the similarity of each alternative to ideal solution. In this method, there is a requirement to calculating the relative weight of criteria by the mean of additional models such as AHP [7]. In this study, the most proper alternative for pipefitting was selected out of five most used malleable cast iron by the means of the presented model with respect to six criteria: melt fluidity, solidification shrinkage, machining ability, yield

strength and Ultimate Strength (UTS).

Methodology

The selected materials for case study consist of five different malleable cast iron that presented in Table 1. Casting and machining are the essential step in pipe-fitting fabrication [3]. Hence the characteristics affecting those processes are chosen as problem criteria and considered by AHP and TOPSIS models. Dependence of alternatives to criteria for selecting the best alternative is shown in Figure 2. The GTS-55 has been reported as best malleable cast iron by investigating the interactions between criteria based on AHP and TOPSIS and comparing with practical situation. Analyses of results will be discussed as follows.

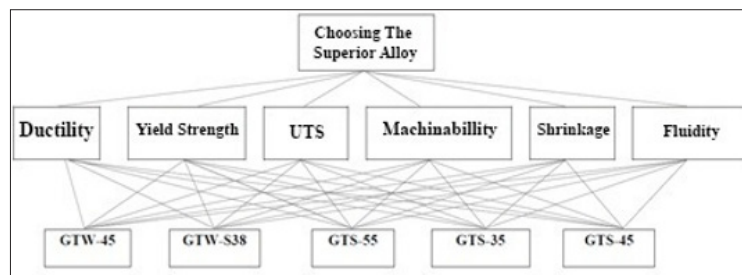


Figure 2: The hierarchy of criteria and alternatives in respect to objective.

Determination of criteria priority by AHP

As said earlier, the objective of this research is selecting the malleable cast iron for pipe fitting with respect to properties related to mainly mechanical properties. Therefore, the melt fluidity, solidification shrinkage, machining ability, yield strength and Ultimate Strength (UTS) have been chosen to achieve these

properties. The procedure of scoring is provided in Table 2 based on pair-wise comparisons. By the using of data achieved from Table 1 & 2, the selected criteria were compared with each other and finally weights have been assigned. Calculating the weights depends on innate properties of materials and other parameters like melt pouring temperature, cooling rate and etc have been discarded in this paper.

Table 1: The alloys properties of case study [15].

	Alloy	Chemical Composition (Wt. %)					Mechanical Properties			
		C	Si	Mn	S	P	Hardness	Elongation	Yield Strength	UTS
DIN EN 1962-63	GTS-35	2.43	1.42	0.42	0.13	0.04	126(HB)	16(%)	245(MPa)	355 (MPa)
	GTS-45	2.55	1.3	0.45	0.1	0.05	215(HB)	8.5(%)	410(MPa)	605 (MPa)
	GTS-55	2.55	1.3	1	0.1	0.05	200(HB)	6(%)	350(MPa)	570 (MPa)
	GTW-S-38	3	0.7	0.24	0.22	0.06	180(HB)	8(%)	230(MPa)	400 (MPa)
	GTW-45	2.7	1.35	0.45	0.13	0.05	150(HB)	7(%)	315(MPa)	568 (MPa)

Analytic Hierarchy Process (AHP) first has introduced by Saaty in 1980 [8]. The AHP approach was designed to incorporate qualitative and quantitative aspects of a complex problem with multiple criteria and solves them by decomposing the problem into hierarchies and the Decision Maker (DM) then make Pair Wise Comparison (PWC) judgments of criteria as to importance of priorities in each hierarch [9]. A fundamental problem in decision-making is to grade the importance of a set of alternative and assign a weight to each of them. The importance of alternative usually

depends on several criteria which can be evaluated within the PWC. Disadvantages of AHP make Saaty and other researcher to improve the model with regard to the effect of the criteria on each other [8].

Hierarchy should be approved by decision making team at the first step and the decision-making matrix provided in the base on real data. Pair wise comparison carried out for criteria to obtains the relative importance of them. The result of comparison summarized in an $n \times n$ matrix (Equation 1). Decision matrix

typically has quantitative values with different dimensions which have to be dimensionless in order to have ability in comparison and calculations using Equation 2. In pair-wise comparison matrix, the 9-point scoring is used by experts to prioritize the criteria (Table 2); [9,10]. The value of each criterion could be more or less than others. In this regard, if importance of the criterion A to criterion

B stated as “a”, then the criterion B worth 1/a to criterion A. In the step ahead, pair-wise comparisons are carried out by experts and weights of criteria will be extracted and the final report summarized in a n×n matrix. it should be mentioned that the consistency of matrix must be validated which is prove the accuracy of judgment (Table 3);[11].

Table 2: Numerical scale for weight scoring and relative importance of criteria and options relative to each other in the pairwise judgment matrix based on 1 to 9 values [8,16].

Numerical Value	Linguistic Values
1	Equal priority (Eq)
2	Intermediate
3	Low priority (L)
4	Intermediate
5	Medium priority (M)
6	Intermediate
7	High priority (H)
8	Intermediate
9	Very High priority (VH)

Table 3: Units and terms.

Weight vector of j_{th} criteria	W_j	Carbon equivalent	CE
Decision matrix	D	Metallization degree	MD
Elements of matrix D	x_{ij}	Pair-wise comparison Matrix	A
Elements of normalized matrix D	r_{ij}	Consistency ratio	CR
Distance from positive solution (PIS)	A^+	Consistency Index	CI
Distance from negative solution (NIS)	A^-	Random index	RI
Distance between PIS and NIS	$D(\bar{A}, \bar{B})$	The largest special amount	λ_{max}
Distance of each alternative from PIS	d_i^+	Elements of matrix Anorm	P_{ij}
Distance of each alternative from NIS	d_i^-	Elements of matrix A	a_{ij}
Similarity to ideal solution	CC_j	Calculated entropy of jth alternatives	E_j
Standard deviation of j_{th} criteria	d_j	Alternative's count	m

The Consistency Ratio (CR) of each Pair-wise comparison matrix (equation 3) let someone to know whether the comparisons are consistent or not. The CR calculated by Consistency Index (CI) that obtainable by equation 4 and Random Index (RI) which could be extracted from databases [12].

$$A = \begin{matrix} & C_1 & C_2 & \dots & C_j & \dots & C_n \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_j \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1j} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2j} & \dots & a_{2n} \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ a_{j1} & a_{j2} & \dots & a_{jj} & \dots & a_{jn} \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nj} & \dots & a_{nn} \end{bmatrix} \end{matrix} \quad (1)$$

$$r_j = \frac{x_j}{\sqrt{\sum_{i=1}^n x_i^2}}, j = \{1, 2, \dots, n\}, i = \{1, 2, \dots, m\} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

$$CI = (\lambda_{max} - n) / (n - 1) \quad (4)$$

The upper limit of acceptance is 0.1 and if the CR exceed of this value then the procedure must be repeat [13]. In this model the Shannon entropy technique applied for calculating the weights [14].

TOPSIS Method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) which was first introduced by Yoon and Hwang [14] is the most common method to rank alternatives by criteria weights obtained by other method such as AHP. The basic concept of this method is that the selected alternative should have the shortest distance from the ideal solution and the farthest distance from the negative ideal solution [15,16]. The Euclidean distance approach was proposed to evaluate the relative closeness of the alternatives to the ideal solution [17].

$$D = \begin{matrix} & F_1 & F_2 & \dots & F_j & \dots & F_n \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_j \\ \vdots \\ A_n \end{matrix} & \begin{bmatrix} f_{11} & f_{12} & \dots & f_{1j} & \dots & f_{1n} \\ f_{21} & f_{22} & \dots & f_{2j} & \dots & f_{2n} \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ f_{j1} & f_{j2} & \dots & f_{jj} & \dots & f_{jn} \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ f_{n1} & f_{n2} & \dots & f_{nj} & \dots & f_{nn} \end{bmatrix} \end{matrix} \quad (10)$$

Decision matrix in Eq.10 typically has quantitative values with different dimensions which have to be dimensionless in order to have ability in comparison and calculations using Equation 11 [18].

$$N_{ij} = r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^m x_{ij}^2}}, J = \{1, 2, \dots, n\}, I = \{1, 2, \dots, m\} \quad (11)$$

Construct the weighted normalized decision matrix. With the set of weights, the weighted normalized matrix V can be generated as Eq. 12 [18].

$$V = N_{ij} W_{j \text{ norm}}, W = \{w_1, w_2, \dots, w_n\} \approx (\text{Assuming from DM}), \sum_{j=1}^n W_j = 1 \quad (12)$$

Determination the positive (A+) and negative (A-) ideal solutions by Eq 13 and Eq 14 respectively for benefit and cost criteria [18].

$$A^+ = \{(\max_i V_{ij} | j \in J), (\min_i V_{ij} | j \in J) | i = 1, 2, \dots, m\} = \{V_1^+, V_2^+, \dots, V_n^+\} \quad (12)$$

$$A^- = \{(\min_i V_{ij} | j \in J), (\max_i V_{ij} | j \in J) | i = 1, 2, \dots, m\} = \{V_1^-, V_2^-, \dots, V_n^-\} \quad (13)$$

Calculating the separation measure form positive and negative points by Eq 15 and 16 respectively and calculating the relative

closeness to the ideal solution and final ranking of alternatives using Eq 17 [18].

$$d_i^+ = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^+)^2}, i = 1, 2, \dots, m \quad (14)$$

$$d_i^- = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^-)^2}, i = 1, 2, \dots, m \quad (15)$$

$$C_i^* = \frac{d_i^-}{d_i^+ + d_i^-}, 0 \leq C_i^* \leq 1, i = 1, 2, \dots, m \quad (16)$$

In the first instance, weights assigned to the alternatives according to criteria. Carbon equivalent of material is the main agent in fluidity. The closest carbon percent to the eutectic leads to raise the fluidity due to the diminution of mushy solicitation [16]. Besides, the shrinkage determinate by present of silicon. The higher the silicon, the lower the shrinkage [19]. The machinability is defined by hardness number, in such a way that the number reduces the machinability [1]. In the production of metallic joints, it is better to use a cast iron with higher yield and UTS strength [20]. Elongation obtained from tensile test shows alloy ductility (Tables 4-6).

Table 4: Pair comparison matrix criteria affecting cast iron selection.

	(a)	(b)	(c)	(d)	(e)	(f)
(a)	1	7	4	3	3	5
(b)		1	(4)	(5)	(5)	(3)
(c)			1	(3)	(3)	3
(d)				1	1	4
(e)					1	4
(f)	Inconsistency=0.05					1

Table 5: Normalization of pairwise comparison of effective criteria.

	(a)	(b)	(c)	(d)	(e)	(f)
(a)	0.442	0.279	0.343	0.519	0.519	0.288
(b)	0.063	0.04	0.021	0.034	0.034	0.019
(c)	0.11	0.159	0.085	0.057	0.057	0.173
(d)	0.147	0.199	0.26	0.173	0.173	0.23
(e)	0.147	0.199	0.26	0.173	0.173	0.23
(f)			0.088 0.121 0.028 0.043 0.043			0.057

Table 6: Specified Weight for criteria in TOPSIS method.

Criterion type	(a)	(b)	(c)	(d)	(e)	(f)
Weight	0.197	0.197	0.107	0.035	0.398	0.063

Results and Discussion

Units and terms

Determining the priority of effective criteria on the selection of ideal Ductility of cast iron by AHP: The criteria for selecting the

ideal hammer cast iron are determined by the experts and named in the following order:

- a) Molten viscosity,
- b) Shrinkage,

- c) Machinability,
- d) Yield strength,
- e) Ultimate strength, and
- f) Ductility.

alternatives in columns. It should be mentioned that the molten fluidity, yield strength, UTS strength and ductility are the positive criteria, and the shrinkage and hardness number are negative. Now the matrix 6 will be normalized using equation 11 and then will be weighted (Tables 7-12).

According to equation 13 to 14:

$$A^* = \{0.101, 0.012, 0.047, 0.146, 0.133, 0.766\} \quad (17)$$

$$A^- = \{0.081, 0.025, 0.081, 0.082, 0.073, 0.028\} \quad (18)$$

Selecting ideal ductile cast iron by TOPSIS method: In TOPSIS method, Alternatives will be compared with each other. At the first stage, the decision matrix is formed consist of criteria in rows and

Table 7: Data of five types of cast iron used in pipe fittings. By dividing the matrix values by the value obtained.

Cast Iron	(f)	(e)	(d)	(c)	(b)	(a)
GTS 35	2.43	1.42	126	245	235	16
GTS 55	2.55	1.3	215	410	605	8.5
GTS 45	2.55	1.3	200	330	570	6
GTW S38	3	0.7	180	230	400	8
GTW 45	2.7	1.35	150	315	568	7
Criterion type	Positive	Negative	Negative	Positive	Positive	Positive
Weight for criteria	0.2	0.05	0.15	0.25	0.25	0.1

Table 8: The decision matrix normalization of five types of cast iron pipe fittings.

With the relative weight coefficient, the criteria in the normal matrix are.

Cast Iron	(f)	(e)	(d)	(c)	(b)	(a)
GTS 35	0.409	0.511	0.318	0.35	0.212	0.732
GTS 55	0.429	0.468	0.542	0.586	0.545	0.389
GTS 45	0.429	0.468	0.504	0.471	0.514	0.274
GTW S38	0.505	0.252	0.454	0.328	0.36	0.366
GTW 45	0.455	0.486	0.378	0.45	0.512	0.32

Table 9: Weighting of the normalized decision matrix for five types of cast iron pipe fittings.

Cast Iron	(f)	(e)	(d)	(c)	(b)	(a)
GTS 35	0.081	0.025	0.047	0.087	0.053	0.073
GTS 55	0.086	0.023	0.081	0.146	0.136	0.038
GTS 45	0.086	0.023	0.075	0.118	0.128	0.027
GTW S38	0.101	0.012	0.068	0.082	0.09	0.036
GTW 45	0.091	0.024	0.056	0.112	0.128	0.032

Table 10: Calculating the solution of positive and negative ideal.

The optimal solution	(f)	(e)	(d)	(c)	(b)	(a)
+	0.101	0.012	0.047	0.146	0.136	0.073
-	0.081	0.025	0.081	0.082	0.05	0.027

Table 11: Calculate the size of the distance from the ideal positive and negative solution.

Cast Iron	distance from ideal positive solution	distance from the negative ideal solution
GTS 35	0.1048	0.0571
GTS 55	0.0516	0.1061
GTS 45	0.0641	0.0839
GTW S38	0.0896	0.0467
GTW 45	0.0569	0.0853

Table 12: Calculating the similarity to the ideal solution and ranking the alternatives.

Cast Iron	Closeness to ideal solution
GTS 35	0.6729
GTS 55	0.5997
GTS 45	0.5669
GTW S38	0.3527
GTW 45	0.3425

To get the distance of each option from the ideal solution, the relation between equation 15 and 16 should be used:

$$S^* = \{0.030, 0.023, 0.049, 0.097, 0.075, 0.083, 194\} \quad (19)$$

In the last step of Equation 17, the relative similarity to the ideal solution is calculated:

$$C^* = \{0.411, 0.365, 0.472, 0.449, 0.557, 0.377\} \quad (20)$$

Nearest alternatives to 1, is introduced as most suitable alternative. Based on analyses, The GTS-55 has been selected as best material for pipe-joint.

Conclusion

In reference to conducted analysis and using the combination methods:

According to the calculations and analyses performed, the table was set, the results of which are described below. Using the combined AHP and TOPSIS methods, the best available GTS-55 cast iron option was determined. The discrepancy in the results obtained with the actual conditions is somewhat justified due to data fluctuations related to the properties of the options.

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