Chapter

Selection of Optimal Material from Stir Cast Aluminum Graphene Nano Platelets Composites for Aerospace Applications

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Abstract

Qualitative and quantitative requirements when selecting materials for different properties can be difficult and ambiguous. An insufficient variety of materials can lead to component malfunction and failure at any point during their service. Owing to the vast availability of dissimilar materials, material selection in the engineering design phase is difficult and elusive. This study presents an EDAS (Evaluation based on Distance from Average Solution) and VIKOR (VIse Kriterijumska Optimizacija-kompromisno Resenje) techniques for effective material selection for aviation applications. In this research, the selection index value was calculated using the EDAS and VIKOR entropy-based weight techniques. The MADM (multi-attribute decision making) procedure also selects the best weight per cent combination among pure aluminum reinforced with GNPs (graphene nanoplatelets) for aircraft applications based on its physical and mechanical properties. The results demonstrate that 0.5 wt% GNPs reinforced in pure aluminum has the best combination of both physical and mechanical qualities, according to the EDAS and VIKOR multi-criteria decision-making methodologies. The composites were made using the stir casting technique. MATLAB R2020a is used to grade and compare the composite materials.

Keywords: pure aluminum, multi-attribute decision making, graphene nanoplatelets, VIKOR, EDAS, MATLAB R2020a

1. Introduction

Aluminum Metal Matrix Composites are favored over other conventional materials in aerospace, automotive, and marine applications because of improved properties such as high strength-to-weight ratio, good wear resistance, and so on. Graphene's mechanical, physical, optical, and thermal properties make it an outstanding metal composite reinforcement material. Pure aluminum graphene nanoplatelets (GNPs) were reinforced in a base matrix (pure Al) with different weight percentages to form aluminum metal matrix composites using stir casting [1, 2] powder metallurgy [3] and other techniques. The uniform distribution of graphene nanoplatelets [4, 5] in the aluminum matrix improves mechanical properties significantly. Stephen et al. [6] discovered that graphene-aluminum nanocomposites had lower strength and stiffness than pure aluminum reinforced with multi-walled carbon nanotube composites due to the production of enhanced aluminum carbide with the graphene filler. Venkata Subbaiah et al. [7] investigated the microstructural and mechanical properties of AA7075-GNPs. In an aluminum 7075 base matrix, ultrasonic-assisted stir casting was used to produce graphene nanoplatelets varying from 0.5 to 2.0 wt%. The composite with 0.5% GNPs had the highest tensile strength and microhardness due to the less porosity and uniform distribution of GNPs in the AA7075 matrix. According to Bhanu Prakash et al. [8], the microstructure and mechanical properties of aluminum 7075 graphene nanoplatelets ranged from 0.50 to 2 wt% in base matrix fabricated using the stir casting technique. In comparison with other weight percentages, AA 7075–1.5% GNPs provided the composite with better mechanical properties. Due to the graphene's uniform distribution with the base metal, Muhammed Emre Turan et al. [9] discovered that adding graphene to pure magnesium in different weight proportions improved hardness values. Xin Gao et al. [10] stress the contents of graphene reinforced with base minerals. The effect of graphene on the tensile strength of the prepared composites increases by 0.3 wt% as the graphene content increases. As the proportion of graphene in the composite increases, the tensile strength and percentage of elongation to fracturing decrease. A systematic approach to GNP composites' selection is necessary to choose the best material for a given application. The correct material selection technique entails precisely describing the application requirement in terms of mechanical properties, primarily for the utility class defined in the proposed application. Various researchers have used MADM methods such as VIKOR, EDAS, WSM PROMETHE, and TOPSIS to select the best material for specific applications in a range of fields such as automotive [11–16], marine [17, 18], medical [19], and agriculture [20–22]. The VIKOR method outperformed the other 10 most common methods for selecting suitable materials for a sailing boat mast, a flywheel, and a cryogenic storage tank, according to the author [23]. The optimal material, according to the researcher [24], is solely determined by the criterion's maximum priority value. The most conclusive of the three MCDM methods is VIKOR (TOPSIS, VIKOR, and PROMETHEE). Caliskan et al. [25] rated the materials using the PROMETHEE II, TOPSIS, and VIKOR methods and compared the results obtained by each process. Tungsten carbide-cobalt and Fe-5Cr-Mo-V aircraft steel were found to be the best materials for tool holder production. A new version of the VIKOR method, based on criteria for selecting the best material, particularly in the biomedical field, was proposed by Jahan et al. [26]

2. Problem description and experimental details

In this research, the best material for aircraft application was chosen from five options of aluminum graphene nanoplatelet composites. **Figure 1** depicts the beneficial and non-beneficial criteria. MADM's EDAS and VIKOR methods are used to choose the right option. Procedural steps for criterion methods are represented in **Figure 2**.

2.1 Composite fabrication

Stir casting has been used for the manufacturing of pure aluminum GNPs composites because it has a lower initial cost than other fabrication techniques. The author detailed the manufacturing of Al-GNPs composites in his prior work [1]. Mechanical stirring was used to distribute the reinforcing phases in the molten matrix metal during the fabrication process. **Table 1** displays the matrix and reinforcing materials used in the composite fabrication process.

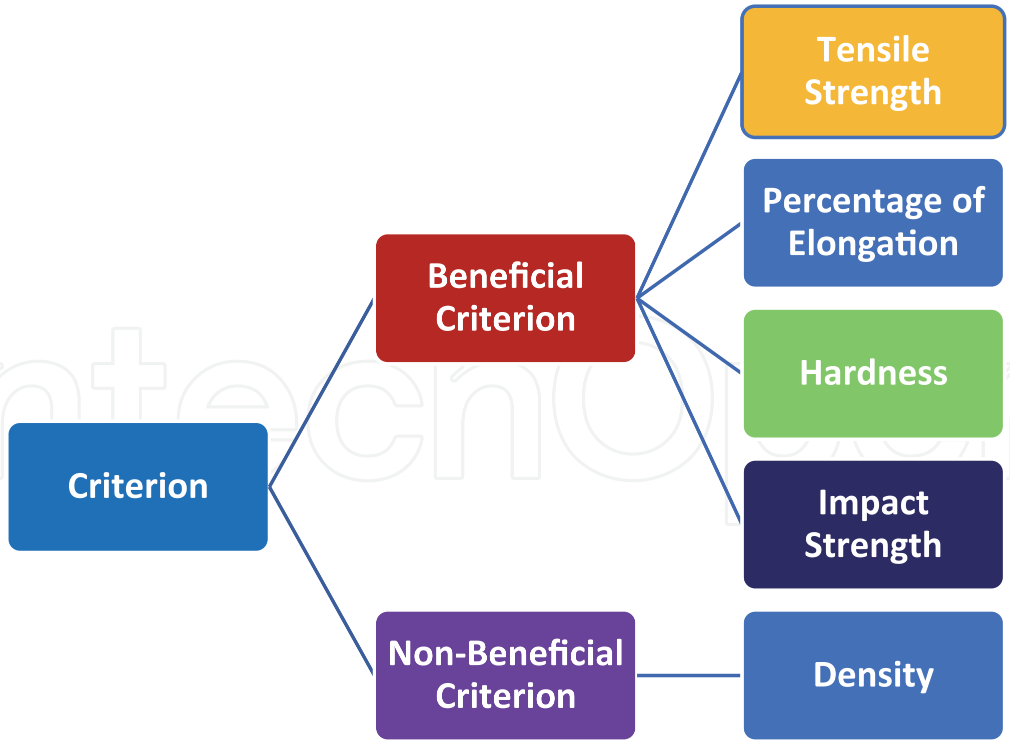

Figure 1.
Beneficial and non-beneficial criterion.

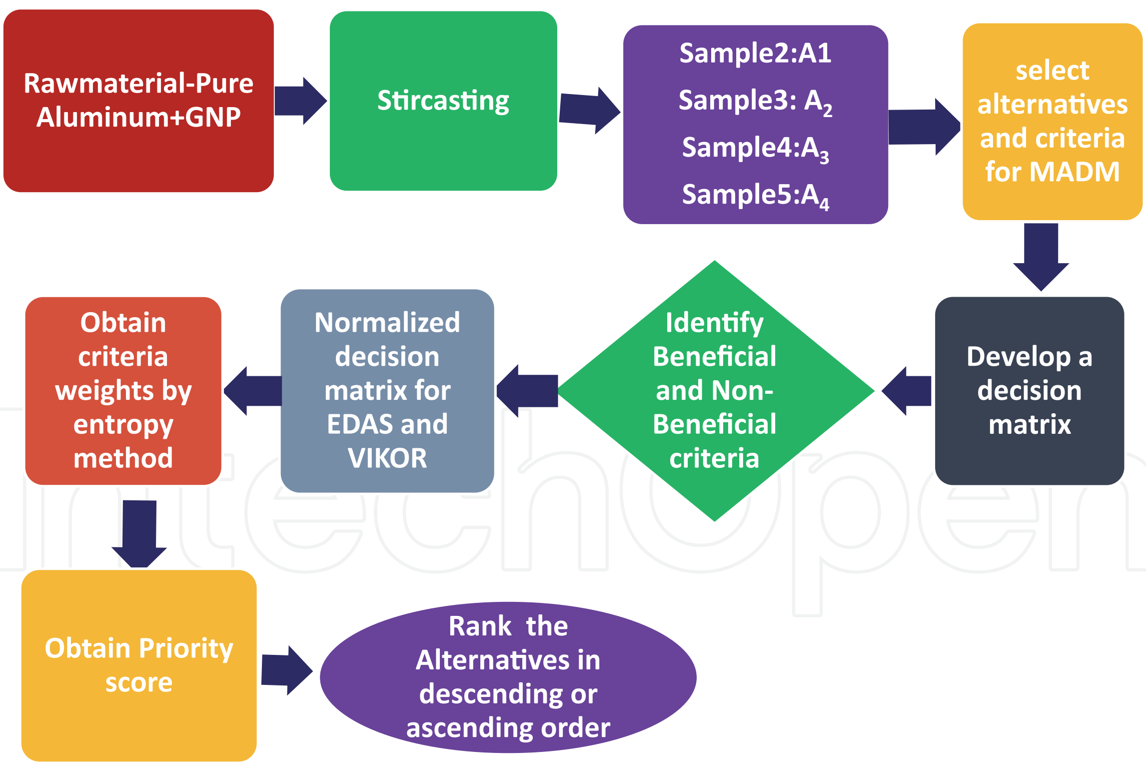

Figure 2.
Applied steps for EDAS and VIKOR.

Sl. no.	Matrix materials	Reinforcements	Size of reinforcements
1	Pure aluminum (99.5%)	GNPs (0.5–2.0 wt.%)	2–10 nm

Table 1.
Material and reinforcement for composite fabrication.

2.2 Characterization of a composite of pure aluminum and graphene nanoplatelets

Physical and mechanical tests on the fabricated composite were used to classify the pure aluminum GNPs composite. These experiments were carried out on well-prepared specimens prepared according to ASTM Standards such as ASTM E8 & ASTM A370 for Tensile Test and Impact test, to investigate the impact of reinforcements in pure aluminum for aircraft applications.

3. Decision methods

A multi-attribute decision-making problem is represented by a matrix X, which contains n alternatives and m criteria.

$$X = \begin{pmatrix} X_{11} & X_{12} & X_{13} & - & - & - & X_{1m} \\ X_{21} & X_{22} & X_{23} & - & - & - & X_{2m} \\ X_{31} & X_{32} & X_{33} & - & - & - & X_{3m} \\ X_{41} & X_{42} & X_{43} & - & - & - & X_{4m} \\ - & - & - & - & - & - & - \\ - & - & - & - & - & - & - \\ X_{n1} & X_{n2} & X_{n3} & - & - & - & X_{nm} \end{pmatrix} \tag{1}$$

where X_{ij} is the ith alternative's output on the jth criterion. In MADM methods, the weight value (w_j) for each criterion must be determined such that the number of all criterion weights equals to one. The entropy approach is used to calculate these weights.

3.1 Evaluation based on distance from average solution (EDAS) method

The EDAS method is a distance-based technique that employs positive and negative distances from the average solution. The options are listed in ascending order. The procedural steps for n alternative composite and m parameters suggested [27, 28] are as follows:

$$\text{Let } [X]_{n*m} \text{ be the decision} - \text{making matrix} \tag{2}$$

Step 1. The average solution (AV_j).

$$AV_j = \sum_{i=1}^{n} X_{ij}/n \tag{3}$$

Step 2. The positive distance from average (PDA) for beneficial and non-beneficial criterion.

$$\left.\begin{array}{c} \text{If } j^{th} \text{ criterion is beneficial,} \\ PDA_{ij} = \dfrac{\max\left(0, \left(X_{ij} - AV_j\right)\right)}{AV_j} \\ \text{And if } j^{th} \text{criterion is non-beneficial,} \\ PDA_{ij} = \dfrac{\max\left(0, \left(AV_j - X_{ij}\right)\right)}{AV_j} \end{array}\right\} \tag{4}$$

Step 3. The negative distance from average (NDA) for beneficial and non-beneficial criterion.

$$\left.\begin{array}{c}\text{If } j^{th} \text{ criterion is beneficial,} \\ NDA_{ij} = \dfrac{\max\left(0, (AV_j - X_{ij})\right)}{AV_j} \\ \text{And if } j^{th} \text{criterion is non-beneficial,} \\ NDA_{ij} = \dfrac{\max\left(0, (X_{ij} - AV_j)\right)}{AV_j}\end{array}\right\} \tag{5}$$

Step 4. Eq. (6) calculates the positive and the negative weighted sums.

$$SP_i = \sum_{j=1}^{m} \left(W_j * PDA_{ij}\right) \tag{6}$$

$$SN_i = \sum_{j=1}^{m} \left(W_j * NDA_{ij}\right) \tag{7}$$

W_j = weight of jth criterion.
Step 5. Normalized values of SP_i and SN_i.

$$NSP_i = \frac{SPi}{max\, i\, SPi} \tag{8}$$

$$NSN_i = \frac{SNi}{max\, i\, SNi} \tag{9}$$

Step 6. The appraisal score (AS_i) for all alternatives is calculated using Eqs. (8) and (9).

$$AS_i = 0.5 * (NSPi + NSN_i) \tag{10}$$

Where $0 \leq AS_i \leq 1$.

The alternative with the outstanding appraisal score is chosen as the best, among the other selective alternatives.

3.2 VIse Kriterijumska Optimizacija kompromisno Resenje (VIKOR) method

According to the VIKOR technique given by Rao [29] and Chatterjee et al. [30] for material selection, the compromise may be common for resolving the dispute, and the practicable option may be nearest to the ideal solution. The options are primarily assessed based on all of the characteristics taken into account.

Step 1. Determine the decisive criteria and select the best alternatives based on those criteria.

Step 1: (a) In the decision matrix, determine the best, (x_{ij}) max and the worst, (x_{ij}) min values of all the criteria.

$$X_i^+ = \max{}_i \left(X_{ij}\right)[J = 1, 2 \ldots, m] \tag{11}$$

$$X_i^- = \min{}_i \left(X_{ij}\right)[J = 1, 2 \ldots, m] \tag{12}$$

Step 2: Compute the values of utility measure (S_i) and regret measure (R_i).

$$S_i = \sum_{j=1}^{m} \left(W_j^* \left((X_i^+ - X_{ij})/(X_i^+ - X_i^-)\right)\right) \tag{13}$$

$$R_i = \max_j \left(W_j^* \left(\left(X_i^+ - X_{ij} \right) / \left(X_i^+ - X_i^- \right) \right) \right) \tag{14}$$

Step 3: Find the values of S^*, S^-, R^*, R^-.

$$S* = \min_i(S_i) \;\; S^- = \max_i(S_i) \tag{15}$$

$$R* = \min_i(R_i) \;\; R^- = \max_i(R_i) \tag{16}$$

Step 4. Compute the value of Q_i for j = 1, 2, … , m.

$$Q_i = N * ((S_i - S*)/(S^- - S*)) + (1 - N) * ((R_i - R*)/(R^- - R*)) \tag{17}$$

The alternatives are ranked in the ascending order for the Q_i values. The one having the lower value of Q_i is considered as the best alternative.

4. Results and discussions

Table 2 displays the decision matrix for the pure aluminum graphene nanoplatelets (GNP's) composites, which contains five alternatives and five parameters (1 & 2). The entropy method was used to calculate the objective weights, which are described in **Table 3**. MATLAB R2020a software was used to create a programme that used the formulae for the methods (EDAS and VIKOR) to determine performance measures. The entropy methods are used to measure the weights of different parameters such as mass, percentage elongation, tensile strength (TS), hardness, and impact strength (IS). The material that is used for fuselage construction is of lightweight and good strength and is more corrosion resistant. An attempt was made by developing an alternative material to serve the purpose.

4.1 Evaluation based on distance from average solution (EDAS) method

Table 1 decision matrix displays the average solution (AVj) determined using Eq. (3). Eqs. (4) and (5) were used to quantify positive and negative distances based

S. no	Al + wt.% GNPs	Density (g/cc)	% Elongation	UTS (MPa)	Micro-hardness	Impact strength (kJ/m^2)
1	Pure Al	2.68	38	77	25	127
2	Pure Al + 0.5	2.68	64	88	56	850
3	Pure Al + 1.0	2.68	56	85	44	775
4	Pure Al + 1.5	2.68	38	77	38	750
5	Pure Al + 2.0	2.68	35	65	35	735
AV_J		2.681	46	79	39	647

Table 2.
Decision matrix.

Weight	Density	%Elongation	UTS	Micro-hardness	Impact strength
W	0.000005	0.170289	0.028746	0.183363	0.617597
Based on the Entropy method, weights were calculated and used for criterion selection.					

Table 3.
Entropy weights of criteria.

S. no	Al + GNP wt%	Density	% Elongation	UTS	Hardness	IS
1	Pure Al	0	0	0	0	0
2	Pure Al + 0.5	0.00067	0.38977	0.12573	0.41989	0.31311
3	Pure Al + 1.0	0.00067	0.21625	0.08064	0.1034	0.19725
4	Pure Al + 1.5	0.00067	0	0	0	0.15863
5	Pure Al + 2.0	0.00067	0	0	0	0.13546

Table 4.
(PDA) positive distance from average.

S. no	Al + Wt.%GNP	Density	% Elongation	UTS	Micro-hardness	Impact strength
1	Pure Al	0.00268	0.18176	0.01806	0.36702	0.80445
2	Pure Al + 0.5	0	0	0	0	0
3	Pure Al + 1.0	0	0	0	0	0
4	Pure Al + 1.5	0	0.18176	0.01806	0.03484	0
5	Pure Al + 2.0	0	0.24251	0.17025	0.12143	0

Table 5.
(NDA) negative distance from average.

S. no	Al + wt% GNP	SP_i	SN_i	NSP_i	NSN_i	AS_i	Rank
1	Pure Al	0.000000	0.595597	0	0	0	5
2	Pure Al + 0.5	0.340359	0.000000	1	1	1	1
3	Pure Al + 1.0	0.179926	0.000000	0.52864	1	0.76432	2
4	Pure Al + 1.5	0.097970	0.037858	0.28784	0.93644	0.61214	3
5	Pure Al + 2.0	0.083658	0.068456	0.24579	0.88506	0.56543	4

Table 6.
Normalized positive and negative weighted sums, appraisal scores, and rank of alternatives.

on the types of beneficial and non-beneficial parameters mentioned in **Tables 4** and **5**. Eqs. (6) and (7) are used to measure the positive and negative weighted sums (7). Eqs. (8) and (9) are used to measure the normalized positive and negative weighted sums (9). Eq. (10) is used to measure the final assessment score (AS_i) for all alternatives, as shown in **Table 6**. 5-1-2-3-4 is the ranking of alternative composite materials. The best composite for the fuselage in aircraft applications is pure aluminum reinforced with 0.5wt% GNP, though pure aluminum is the least favored.

4.2 VIse Kriterijumska OptimizacijaKompromisno Resenje (VIKOR) method

The related utility and regret measures, as well as Qi values for the five alternative composite materials and the parameters, are determined using Eqs. (13)–(17), as shown in **Table 7** (taking N = 0.5). **Table 8** shows the best and worst values for the beneficial and non-beneficial criteria measured using Eqs. (11) and (12). The ranks of alternative composite materials are 5-1-2-3-4. The first place winner is pure

S. no	Al + wt% GNP	S_i	R_i	Q_i	Rank
1	Pure Al	0.96886	0.6176	1	5
2	Pure Al + 0.5	0	0	0	1
3	Pure Al + 1.0	0.18889	0.07375	0.15718	2
4	Pure Al + 1.5	0.35922	0.15393	0.31	3
5	Pure Al + 2.0	0.42335	0.17029	0.35634	4

Table 7.
Utility and regret measure values and rank of the alternatives.

Type	Density	% Elongation	UTS	Micro-hardness	Impact strength
Best X_i^+	2.68	64.075	88.39	56.08	850
Worst X_i^-	2.689	34.924	65.15	25	126.58

Table 8.
Best and worst of criterion.

aluminum reinforced with 0.5 wt% GNPs. VIKOR is more beneficial compared to EDAS, though the results are comparatively same. All the expressions were objective with respective to VIKOR to EDAS.

5. Conclusion

The EDAS and VIKOR methods were used in this research to assist in the selection of the best alternative composite material for aircraft applications. The study was performed on pure aluminum graphene nanoplatelets composites manufactured using the stir casting technique. As shown in **Figure 3**, decision-making using EDAS and VIKOR methodology using MATLAB R2020a shows that out of the five alternatives, alternative 2 (pure Al + 0.5 wt% GNP) is the best suitable material for fuselage construction in the aerospace industry.

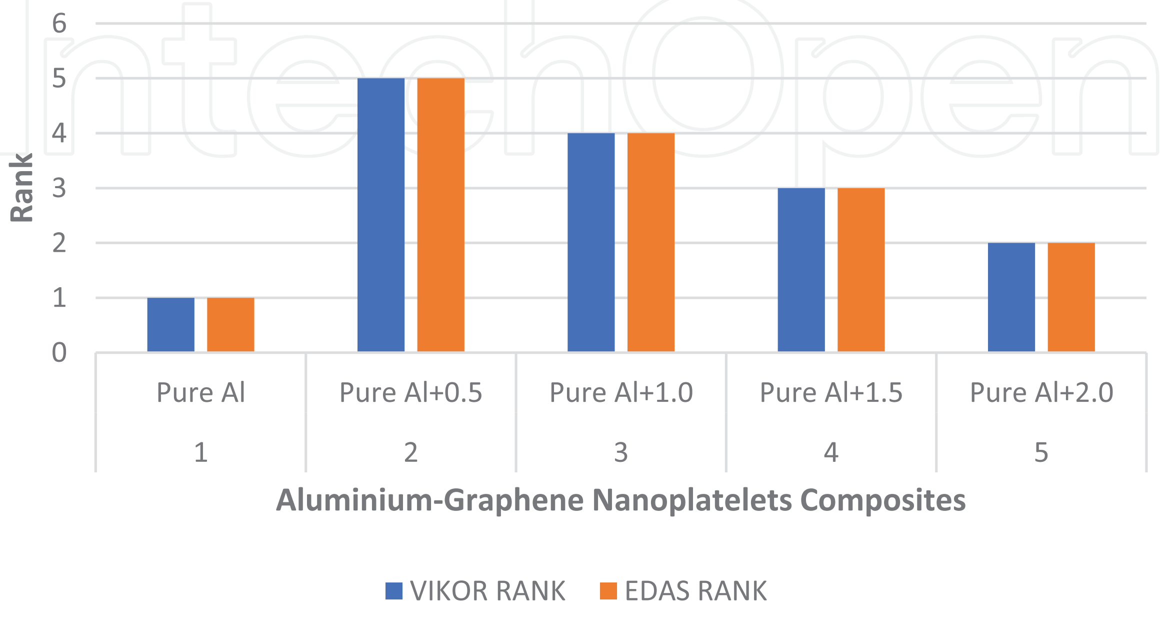

Figure 3.
Comparison of ranks.

Nomenclature

Symbols

X_i^+, X_i^-	ideal best and worst solutions
SP_I, SN_i	positive and negative weighted sums
NSP_I, NSN_i	normalized weighted sums
AS_i	appraisal score

Acronyms

MADM	multi-attribute decision making
AHP	analytical hierarchy process
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	VIse Kriterijumska OptimizacijaKompromisno Resenje
EDAS	Evaluation based on Distance from Average Solution
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
ELECTRE	ELimination and Choice Expressing REality
UTS	ultimate tensile strength
IS	impact strength
GNPs	graphene nanoplatelets

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