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OPTIMIZATION OF MECHANICAL PERFORMANCE OF ALUMINUM HYBRID COMPOSITES

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Abstract

The hybrid aluminium matrix composites comprising AA7075 as matrix material reinforced by silicon carbide (SiC) and fly ash (FA) were produced by the stir casting process in order to study the effect of the combination of ceramic and industrial waste reinforcements on the mechanical properties. Ten composite compositions were produced by changing the amounts of SiC and FA. The obtained composites were subjected to Ultimate Tensile Strength (UTS), Impact Strength (IS), and Micro Vickers Hardness (MVH) tests. It was found that the range of UTS was 163.56-218.08 MPa, IS was 31.35-90.25 J, and MVH was 79.61-93.18 kgf/mm². This shows the effect of the composition of the reinforcement on the mechanical properties of the composites. Since more than one property was optimized in the present study, Grey Relational Analysis (GRA) was used to turn the multi-response optimization into a single parameter of GRG. These responses were normalized with the higher-the-better rule, and then the deviation series, grey relational coefficient, and GRG values were calculated for ranking the composite mixes. Of all the tested specimens, the one with the highest value of GRG (0.912) was specimen C9 (AA7075 + 9 wt.% SiC + 3 wt.% FA), which showed excellent mechanical properties in terms of tensile strength, impact strength, and hardness. It can be concluded that the incorporation of the materials of interest together with fly ash has greatly improved the mechanical properties of the AA7075-based hybrid composites. Hence, GRA can be effectively used for multi-objective optimization.

Keywords: Fly Ash Composites, Metal Matrix Composites, GRA, Process Innovation, Hybrid reinforcement, Taguchi optimization, Silicon Carbide

I. Introduction

The Metal Matrix Composites (MMCs) represent one of the advanced classes of engineering materials for their remarkable mechanical strength, high strength-to-weight ratio, good wear resistance, and improved thermal stability [XXIV]. The MMCs comprise a metallic matrix, commonly aluminum alloyed with ceramic reinforcement such as particles, fibers, or whiskers. This type of composite is characterized by combining a metallic matrix with a reinforcing phase, which ensures that the limitations of conventional alloys and better performance can be achieved.

Many studies have been done on the development of aluminium MMCs. Ramnath et al. presented a review of the effect of various reinforcements on Al alloy materials and highlighted the fabrication issues [XII]. Allison and Cole discussed the possibilities and the industry challenges in the area of automotive MMCs [I], whereas Casati and Vedani presented a review of nanocomposite reinforced MMCs and identified improved strengths, wear resistance, damping properties and thermal stability [II]. Huang et al. discussed non-destructive evaluation methods of structural MMCs [VI]. Kreider studied the mechanical response of boron-aluminium composites subjected to various loads [X]. Pandey et al. reviewed various fabrication methods of Al-TiC composites and suggested ultrasonic-assisted stir casting to be a cost-effective processing method [XIV]. Reddy et al. further pointed out the increased need for aluminium MMCs in aerospace and automotive industries owing to their high strength-to-weight ratios and corrosion resistance [XIX].

Various authors have conducted studies about the influence of reinforcement on the mechanical performance of Al-based MMCs. Idrisi and Deva found that SiC reinforcements increased the mechanical properties of Al-5XXX alloy [VII]. Thomas and King found that proper heat treatment can increase the strength and fatigue resistance of Al/SiCp composites [XXVI]. Kumar et al. investigated Mg-Al based composites reinforced with MoS_2 and noticed an improvement in density and hardness [VIII].

Multi-criteria optimization methodologies such as Taguchi, GRA, Grey Fuzzy Logic, and TOPSIS have been extensively used for optimizing machining and mechanical properties of MMCs. Papabathina et al. optimized the wear behavior of Al6061-SiC-graphite composites using the Taguchi-GRA method [XV]. Prakash et al. used GRA for optimization of parameters of Wire Electrical Discharge Machining process of aluminum-based MMCs [XVII]. Taşkesen and Kütükde optimized the drilling parameters of B_4C reinforced MMCs using GRA by minimizing the thrust force and torque along with improved surface finish [XXV]. Dharmalingam et al. studied the abrasive wear behavior of hybrid aluminum composites using the Taguchi-GRA methodology [III]. Radhika et al. optimized the machining parameters of Al-Si10Mg composites using the Taguchi-ANOVA method [XVIII]. Manna used Grey Relational Analysis to optimize drilling parameters of LM6Mg15SiC composites [XIII]. Sahoo and Pradhan have used the Taguchi technique to optimize turning parameters of Al/SiCp composites [XX]. Singh et al. optimized drilling parameters of aluminium MMCs by the application of Taguchi analysis [XX], whereas Sahin has proposed a wear optimization model using Taguchi analysis [XXI]. Phate et al. have used a combination of Grey-Fuzzy logic and Taguchi method to optimize WEDM parameters of Al-SiCp composites [XVI]. Gopal and Soorya Prakash have combined GRA, TOPSIS, and Taguchi approaches to optimize milling parameters of magnesium hybrid MMCs [V]. Likewise, Soorya Prakash et al. have optimized turning parameters of aluminium-rock dust composites by GRA [XXIII], whereas Dubourg and St-Georges have optimized laser cladding parameters of WC-reinforced Ni-based MMC coatings [IV]. Other than experimentally optimized research, numerical and systems optimization research has also been carried out. The work carried out by Le et al. introduced a systematic optimization approach for the hybrid MMC simulation platform with consideration of computing time and performance [XI].

Despite the many studies conducted on the development, machinability, and optimization of aluminum alloy-based MMCs, few studies have addressed the optimization of the mechanical properties of AA7075 hybrid composite reinforced with SiC and FA via stir casting [9]. Besides, the effects of hybrid reinforcement of SiC and FA on UTS, IS, and MVH via Grey Relational Analysis have not been extensively addressed.

Hence, in the current study, an effort has been made to analyze the hybrid metal matrix composite using AA7075 alloy as a matrix material combined with different weight percentages of SiC and FA by the technique of stir casting. In order to find out the optimum composition of the MMC for enhanced mechanical properties, grey relational analysis has been implemented.

II. Materials and methods

Aluminium AA7075 is an alloy that belongs to the precipitation-hardened family and is widely employed in aerospace, automobile, and structural engineering industries because of its high specific strength, high fatigue resistance, corrosion resistance, and good machinability properties. Because of these features, the use of this alloy as the matrix material for the fabrication of aluminium MMCs becomes possible. In order to increase the mechanical performance of the alloy, ceramic and industrial waste reinforcements like SiC and FA are added to the aluminium matrix.

The high-performance ceramic reinforcement SiC is well-known for its high hardness, high elastic modulus, good wear resistance, and high thermal stability. SiC provides increased tensile strength, hardness, stiffness, and loading capacity of the AA7075 matrix alloy. The good wetting of the molten aluminium by SiC leads to the improved dispersion of the particles in the matrix.

The fly ash, which is an industrial waste produced in coal-fired thermal power plants, mainly comprises SiO_2, Al_2O_3, and Fe_2O_3. Since the FA has low density, high hardness, and good wear resistance, it is used as a light and cost-effective material for reinforcement in the aluminium composites. The high availability and low price of FA make it an environmentally friendly substitute for traditional ceramics as reinforcement, besides reducing the weight of the composite. The synergistic combination of SiC and FA in the AA7075 matrix enhances the strength, hardness, wear resistance, and effectiveness of the composite.

III. Design of Experiments

Design of Experiments (DOE) methodology was utilized to conduct systematic research on the impact of variation in reinforcement types on the mechanical behavior of AA7075-based hybrid metal matrix composites. AA7075 aluminium alloy was chosen as the matrix material, while SiC and FA served as reinforcement materials. The levels of SiC and FA reinforcements were varied from 0 to 3, 6, and 9 wt.% to formulate ten different composite formulations as shown in Table 2 below. It provided the basis for investigating the impact of different combinations of reinforcements on the mechanical performance of the formulated composites. The main goal of the study was to find out the best SiC-FA reinforcement combination that will provide maximum UTS, IS, and MVH.

Table 2: Design of Experiments

Composition Code	Matrix Material	SiC (wt.%)	FA (wt.%)
C1	AA7075	0	0
C2	AA7075	3	3
C3	AA7075	6	6
C4	AA7075	9	9
C5	AA7075	3	6
C6	AA7075	3	9
C7	AA7075	6	3
C8	AA7075	6	9
C9	AA7075	9	3
C10	AA7075	9	6

IV. Experimental Work

The sand casting process was used for the production of hybrid metal matrix composites reinforced with AA7075 due to the process simplicity, low cost, and suitability for fabricating aluminum particulate composites. A sand mould with dimensions 200 mm × 30 mm was made for casting the composite samples. Reinforcement particles, which are SiC and FA, were heated up to 300 °C to eliminate moisture and make them wettable with molten aluminum alloy. Heating decreased gas porosity and provided homogeneous dispersion of reinforcement particles in the matrix.

AA7075 alloy was melted in a crucible furnace and reinforced with heated SiC and FA particles by certain weight fractions. Molten composite slurry was well stirred to provide uniform distribution of reinforcement particles in the matrix. Molten composite slurry was then poured into the sand mould. After solidification of the molten slurry, the casting was taken out of the mould and machined to the necessary size for performing mechanical tests. The full cycle of fabrication adopted in this work is shown in Figure 1 below.

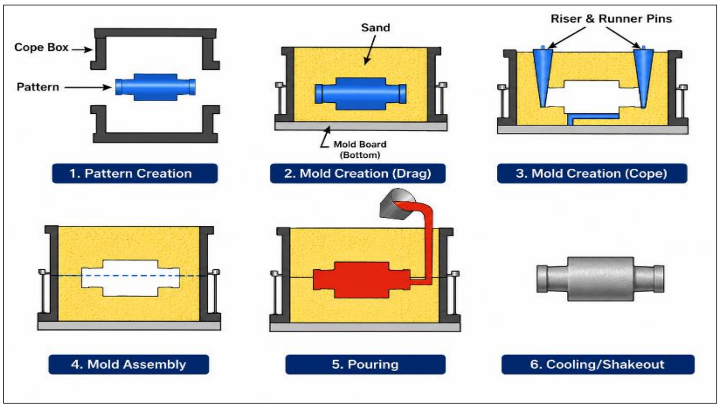

Fig. 1. Sand Casting Process

AA7075 aluminium alloy was first melted in the crucible furnace at 720 °C. After full melting, the SiC and FA reinforcements, which had been preheated, were slowly mixed into the melt using mechanical stirring until a homogeneous composition was achieved. The molten alloy slurry was maintained at the pouring temperature of 680 °C and then poured into the sand moulds that had been prepared. The resulting cast composites were taken out of the moulds and finished to the desired sizes of 180 mm × 20 mm.

Fabricated hybrid composites were analyzed through the conduct of various mechanical tests. UTS analysis was performed using RATNA K-210 Universal Testing Machine(UTM) based on the standards of ASTM E8/E8M and ASTM B557. In tensile testing, all samples showed brittle fracturing behavior. The IS was conducted using an Izod impact test in a Charpy impact testing machine based on IS 1598:1977 standards, and the sample size used was 12 mm x 12 mm x 55 mm with a 45° V-notch as per ASTM D256. Surface hardness was tested using a Micro Vickers Hardness Tester. For the purpose of measuring the hardness of the fabricated composites and the effect of reinforcement of SiC and FA, the MVH test was applied.

V. GRA Optimization

Grey Relational Analysis (GRA), which forms part of the Grey System Theory, has emerged as one of the most popular multi-attribute decision-making (MADM) methods used to solve optimization problems with multiple performance attributes. This methodology is especially useful when a number of output responses in varying units and scales are optimized concurrently. In the current study, GRA has been used to identify the optimal combination of reinforcements in the hybrid metal matrix composites based on AA7075 and reinforced by SiC and FA. The mechanical responses that have been optimized using GRA include UTS, IS, and MVH.

Normalization of the data from the experiment is the first stage of the GRA method. As larger values of UTS, IS, and MVH show better mechanical properties, the “higher-the-better” criteria were used for normalization. Normalization of the data for each response was performed by means of Equation (1):

$$Z'_i = \frac{Z_i - \min(Z_i)}{\max(Z_i) - \min(Z_i)} \qquad (1)$$

where Z_i is the original experimental value, while $\max(Z_i)$ and $\min(Z_i)$ represent maximum and minimum values, respectively, of the response for each experiment.

$$\Delta_i(k) = |Z'_0(k) - Z'_i(k)| \qquad (2)$$

where $Z'_0(k)$ is the ideal normalized reference sequence and $Z'_i(k)$ represents the normalized value of the i^{th} experimental specimen.

The Grey Relational Coefficient (GRC), representing how close an experimental result is to the ideal reference sequence, was computed using the following equation (3):

$$GRC_i = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_i + \zeta\Delta_{max}} \qquad (3)$$

where $\Delta_{\min}$ and $\Delta_{\max}$ are the smallest and largest deviations, respectively, and ζ is the distinguishing coefficient. The value of the discriminating coefficient adopted in this study is 0.5 since this is the value most often used in GRA.

Finally, the overall Grey Relational Grade (GRG) for each composite was obtained by averaging the GRC_i values corresponding to all performance characteristics, as expressed in Equation (4):

$$GRG_i = \frac{1}{n}\sum_{k=1}^{n} GRC_{ik} \qquad (4)$$

where n is the total number of experiments considered. A superior GRG indicates that the composite exhibits mechanical properties closer to the ideal performance, thereby representing the optimum reinforcement combination among the investigated specimens.

VI. Results and Discussions

Ten metal matrix composite (MMC) specimens, using AA7075 as base alloy and reinforcing agents such as SiC and FA, were manufactured at different weight percentage ratios (from 0 to 9 wt.%) of the composites. The mechanical behavior of the manufactured composites was investigated in terms of UTS, IS, and MVH.

A tensile test was performed using the ASTM E8/E8M standard. The obtained values of UTS range between 163.56 and 218.08 MPa. This shows that the composition has a substantial effect on the loading capacity. The values of IS were calculated using the Izod impact test, which had a value range of 31.35 to 90.25 J, showing that the energy-absorbing capacity of different compositions of composites varies. MVH was done using the Vickers hardness test method, and the hardness values range from 79.61 to 93.18 kgf/mm².

It can be seen from the experimental results that the mechanical properties depend greatly on the proportion of SiC and FA particles used in the AA7075. A proper ratio of the reinforcing particles has improved the tensile strength, impact strength, and hardness of the composite materials due to the enhanced load transfer and particle reinforcement technique. The total experimental data obtained from the fabrication of different samples have been provided in Table 3 below, while Figs. 2-5 show the variation of UTS, IS, MVH, and their comparative values of all three mechanical properties.

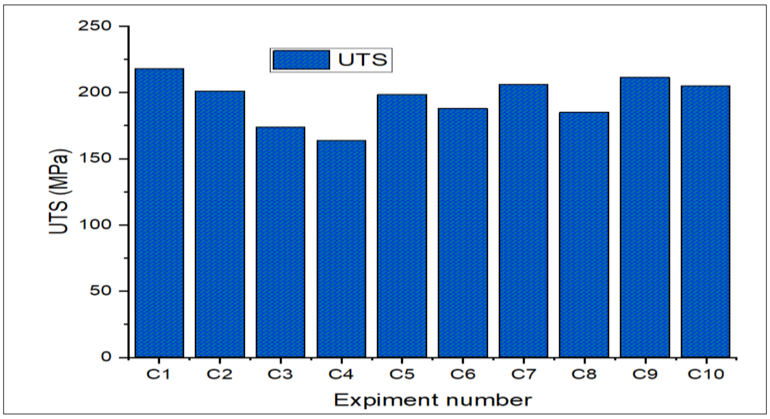

Fig. 2. UTS comparison

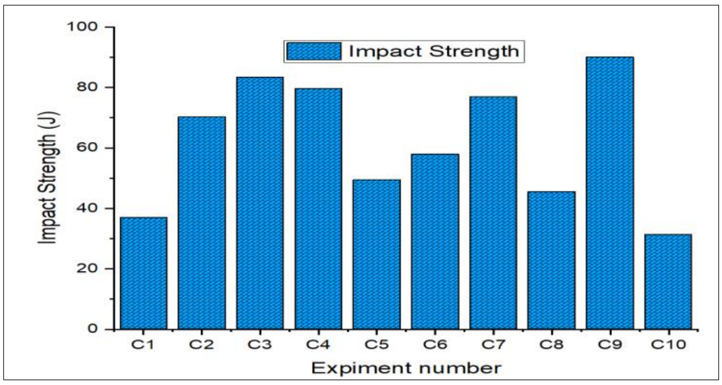

Fig. 3. Impact Strength comparison

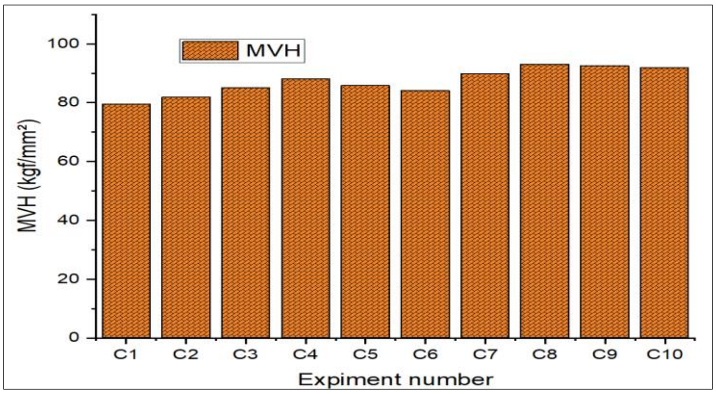

Fig. 4. MVH comparison

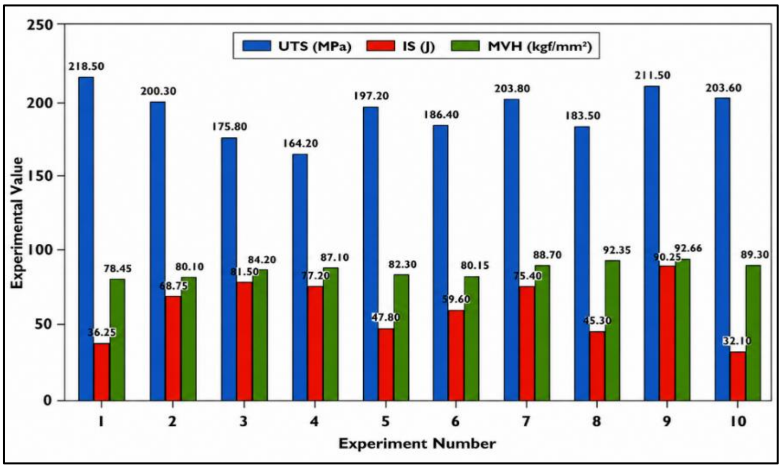

Fig. 5. Combined property chart representing UTS, IS, MVH values.

In order to evaluate the general performance of the produced hybrid composites, GRA was utilized as an effective multi-objective optimization approach. As the response variables considered, UTS, IS, and MVH have dissimilar units of measurement and orders of magnitude, the experimental data were first normalized in order to overcome the dimensionality issue and compare the responses. As the aim of this work is to obtain the highest possible values of all three mechanical responses, the higher-the-better normalization criteria were applied to UTS, IS, and MVH. Normalization yielded the experimental data to be converted into dimensionless numbers in the range between 0 and 1, with a value of unity corresponding to better performance. The normalized data were then used in the calculation of the deviation sequences, GRC, and GRG.

Table 4: Normalized matrix and Deviation Sequence.

NORMALISED MATRIX				DEVIATION SEQUENCE			
S.NO	UTS	IS	MVH	S.NO	UTS	IS	MVH
Units	MPa	J	Kgf	Units	Mpa	J	Kgf
C1	1.000	0.097	0.000	C1	0.000	0.903	1.000
C2	0.690	0.661	0.173	C2	0.310	0.339	0.827
C3	0.190	0.887	0.404	C3	0.810	0.113	0.596
C4	0.000	0.823	0.628	C4	1.000	0.177	0.372
C5	0.638	0.306	0.462	C5	0.362	0.694	0.538
C6	0.448	0.452	0.340	C6	0.552	0.548	0.660
C7	0.776	0.774	0.763	C7	0.224	0.226	0.237
C8	0.397	0.242	1.000	C8	0.603	0.758	0.000
C9	0.879	1.000	0.962	C9	0.121	0.000	0.038
C10	0.759	0.000	0.917	C10	0.241	1.000	0.083

The deviation sequence was obtained from the normalized experimental values and the best sequence by taking the absolute difference between the two sequences. The deviation sequence is an indicator of how close an experimental response is to the ideal reference, whereby the lesser the deviation, the more the experimental response correlates with the ideal reference sequence. From the deviation sequences, the GRC for each specimen is then obtained as an indicator of the strength of correlation between the experimental sample and the ideal reference. Higher GRC indicates more correlation and hence better performance. Lastly, the GRG for each composite specimen is obtained by taking the average of the GRC of each performance parameter. GRG is an integrated performance index incorporating UTS, IS, and MVH. The composite specimens are ranked depending on the GRG values, whereby the composite specimen having the highest GRG value is the optimal composite specimen.

Table 5: GRA Ranking

GREY RELATION COEFFICIENT				GREY RELATION GRADE		
S.NO	UTS	IS	MVH	S.NO	GRG	RANK
	Mpa	J	Kgf			
C1	1.000	0.356	0.333	C1	0.563	5
C2	0.617	0.596	0.377	C2	0.530	8
C3	0.382	0.816	0.456	C3	0.551	6
C4	0.333	0.739	0.573	C4	0.548	7
C5	0.580	0.419	0.482	C5	0.494	9
C6	0.475	0.477	0.431	C6	0.461	10
C7	0.691	0.689	0.678	C7	0.686	2
C8	0.453	0.397	1.000	C8	0.617	4
C9	0.805	1.000	0.929	C9	0.912	1
C10	0.675	0.333	0.858	C10	0.622	3

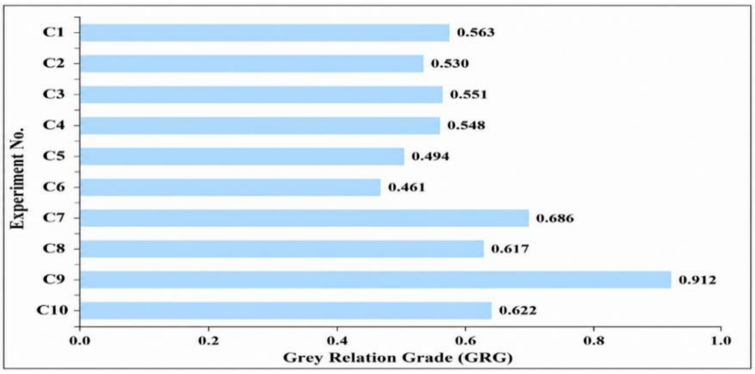

Fig. 6. Ranking of the composite's performance based on GRG value

VII. Conclusion

Composites based on AA7075 alloy reinforced with SiC and FA were successfully developed using the sand-casting method. A total of ten different compositions of the composite were manufactured by altering the weight percent of both reinforcing materials, which were then cut into required sizes for mechanical testing. The mechanical characteristics of the composites were determined using UTS, IS, and MVH tests. GRA was used as a multi-objective optimization technique to optimize all three mechanical responses at once. The normalized values of the experiments were obtained using higher-the-better normalization criteria, after which deviation series, GRC, and GRG were calculated. The sample C9 (AA7075+9 wt.% SiC + 3 wt.% FA) obtained the best GRG = 0.912 and was found to be the best one due to its highest strength, impact strength, and hardness combination. The IS of the C9 composite was the highest (90.25 J), while this composite possessed high values of Ultimate Tensile Strength (218.08 MPa) and Micro Vickers Hardness (93.177 kgf/mm^2). The results of the present investigation have demonstrated that the combination of 9 wt.% SiC and 3 wt.% FA has improved the mechanical properties of the hybrid metal matrix composites due to the increased load transfer capability and reinforcement effect. Thus, GRA turned out to be a good multi-response optimization method to find the optimal reinforcement combination in metal matrix hybrid composites. The optimized AA7075/9 wt.% SiC/3 wt.% FA composite can be considered as a prospective material for structural, automotive, and aerospace engineering. Further research may involve a more detailed investigation into the microstructure to understand more about the strengthening mechanisms that have led to the resulting mechanical behavior.

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Conflict of Interest:

The authors declare that there was no relevant conflict of interest regarding this paper.

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