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Experimental investigations on wear process parameters optimization of Austempered Ductile Iron using Taguchi technique

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ABSTRACT: The influence of parameters like applied load, sliding speed and sliding distance on dry sliding wear rate of Ductile Iron (DI) / Austempered Ductile Iron (ADI) was investigated. The design of experiments (DOE) approach using Taguchi method was employed to analyze the wear behavior of Ductile Iron / Austempered Ductile Iron. Dry sliding wear tests were conducted using pin-on-disc wear testing machine. Signal-to-noise ratio and analysis of variance (ANOVA) were used to investigate the influence of parameters on the wear rate. It was determined that sliding distance was the most significant parameter influencing the wear rate of ADI followed by applied load and sliding speed. The mathematical model was obtained to determine the wear rate of DI / ADI. The confirmation tests were conducted to verify the experimental results foreseen from the mentioned correlations.

KEYWORDS: Dry sliding wear, Austempered Ductile Iron, Taguchi method, Signal to noise ratio, Analysis of variance, Multiple linear regression model.

I. INTRODUCTION

ADI is an acronym for Austempered Ductile Iron. It is a high strength material with superior ductility, toughness, hardness, fatigue and wear properties. It is 10% lighter than steel and can be manufactured at 20% less cost of steel. Because it is lighter and cheaper than steel, several steel parts (forgings, castings, assemblies) have been successfully replaced by ADI cast parts. While a majority of ADI application is in the automotive sector, other market distribution in railways, agriculture, mining and construction is quite significant. The excellent property combination of ADI has opened new horizons for cast iron to replace steel castings and forgings in many engineering applications with considerable cost benefits. New processing techniques have opened even more opportunities for this very prospective material to acquire better combinations of strength, ductility, toughness, wear resistance as well as machinability [1,2]. It is produced by austempering a ductile iron material to form a predominantly ausferritic matrix. Ausferrite consists of a combination of high carbon-stabilised austenite and acicular (needle-shaped) ferrite. It is this unique microstructure that is responsible for the remarkable combinations of strength, ductility, toughness and wear resistance that are exhibited by ADI. ADI refers to a family of heat-treated ductile iron. According to ASTM A897/897M-06 (2011), there are six different grades of ADI. The range of properties available for ADI is dependent on the choice of heat treatment parameters which will, in turn, determine the microstructural scale of the ausferrite as well as the relative amounts of austenite and ferrite within the ausferrite. [3]. Austempered ductile iron is produced by casting and heat treatment of common cast iron. Its microstructure is formed during casting, when special methods of metallurgical inoculation of molten metal ensure the formation of graphite in the form of nodules with a diameter of tens of micrometers, while the subsequent heat treatment shapes the matrix and changes it into a mixture of lamellar ferrite and austenite [4]. Austempered Ductile Iron is ferrous, cast material with a high strength to weight ratio and good dynamic properties. The austempering process is a high performance, isothermal heat treating process that imparts superior properties to ferrous materials. It was developed in the 1930's and, although in wide use, is familiar to only a fraction of the design

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community. Ductile iron or Spheroidal Graphite iron was developed in the 1940's. Ductile iron with its unique, spheroidal graphite morphology produces an iron that has tensile and impact properties sufficient for products as varied as brake calipers, pump impellers and steering knuckles. The application of the austempering process to ductile iron produces a material called Austempered Ductile Iron (ADI) that has strength to weight ratio that exceeds aluminium. ADI was commercialized beginning in the 1970's and has seen significant growth in the decades following [5].

U. Ritha Kumari et al., [6] studied the influence of austempering temperature on the wear behaviour of austempered ductile iron. At high austempering temperature large amounts of austenite was instrumental in improving the wear resistance through formation of deformation induced martensite. A.S.M.A. Haseeb et al., [7] compared the tribological behaviour of ductile iron heat-treated by quenching, tempering, and austempering to an identical matrix hardness of 445 BHN. Austempered ductile iron exhibited a better wear resistance than quenched and tempered ductile iron, although both have an identical chemical composition and matrix hardness. Uma Batra et al., [8] investigated to examine the influence of structural and mechanical properties on wear behavior of austempered ductile iron (ADI). ADI developed at higher austempering temperature has large amounts of austenite, which contribute toward improvement in the wear resistance through stress-induced martensitic transformation, and strain hardening of austenite. Amar Kumar Das et al., [9] carried out austempering for three different grades of ductile iron and studied variation in mechanical properties. With increasing austempering time, hardness, tensile strength and elongation are increasing but with increasing austempering temperature hardness and tensile strength are decreasing and elongation increasing. Austempered ductile iron with alloying element (Cu or Ni) has shown some improved mechanical properties such that: higher strength, hardness and lower elongation, than the unalloyed austempered ductile iron. Y. S. Lerner et al., [10] reviewed Austempered Ductile Iron as an alternative to steels, alloyed and white irons, bronzes, and other competitive materials. In the wear study quenched DI with a fully martensitic matrix slightly outperformed ADI. H. B. Bhaskar et al., [11] studied the influence of wear parameters like sliding speed, applied load and sliding distance on the dry sliding wear of aluminium metal matrix composites. The design of experiment approach was employed to acquire data in controlled way using Taguchi method. An orthogonal array, signal-to-noise ratio and analysis of variance were employed to investigate the wear behavior of aluminium and its composite. The mathematical model was obtained to determine the wear rate of the aluminium and its composite. The confirmation tests were conducted to verify the experimental results. Wear is one of the most commonly encountered industrial problems. Wear is defined as progressive loss of material from a surface as a result of relative motion between the surface and another. Wear contributes to the diminished usefulness of an item through changes in dimension, appearance or structural integrity [12].

II. MATERIALS AND METHODS

2.1 Material

Austempered ductile iron is used in the present experimental investigation. The chemical composition of ductile iron from which ADI is produced is shown in Table 1.

Table 1: Chemical composition of ductile iron

Element	Ceq	C	Si	Mn	P	S	Cr
Wt %	4.36	3.52	2.50	0.161	0.037	0.014	0.027
Element	Ni	Mo	Al	Cu	Ti	Mg	Fe
Wt %	0.151	0.421	0.017	0.78	0.026	0.054	92.2

2.2 Preparation of the material

Ductile iron castings were produced in a metal casting foundry using 500kg medium frequency induction furnace. Pig iron, mild steel, S. G. iron and return risers were used as the charge materials. The melt from the furnace was poured into the shell mould at 1420ºC to cast the sample test bar and is shown in figure 1. The samples for the experimental work were then machined to the required size of ϕ10mm and 30 mm length as shown in figure 2.

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Figure 1. Ductile Iron test bar

Figure 2. Test specimen

The test samples thus prepared were heated to austenization temperature of 870ºC in a furnace with heating rate of 180ºC / hour and solutionised for 90 minutes. The samples were then suddenly quenched into the salt bath designated as hisalt 1150 maintained at temperature 345ºC and soaked for 150 minutes. The samples were then air cooled. The ADI thus prepared has a hardness of 363 BHN.

2.3 Experimental set up and procedure

DUCOM pin-on-disc wear testing machine (Figure 3) was used to evaluate the dry sliding wear characteristics of the austempered ductile iron. The dry sliding wear tests were conducted as per ASTM G99-95a standards. The pin was cleaned with acetone and its initial mass was measured using a digital weigh scale with least count 0.0001g. The pin was then held pressed against the rotating EN-32 steel disc (counterface) with a hardness of 65 HRC during the test. The tests were conducted as per the run order generated by Taguchi method. At the end of each test, the pin was again cleaned with acetone and its final mass was measured. The difference between the initial and final mass of the pin gave the mass loss due to sliding wear. The volume loss due to wear was calculated by the use of corresponding density values of the pin. The wear rate of the ADI pins was then calculated.

Figure 3. DUCOM pin-on-disc wear testing machine

2.4 Plan of experiments

The experimental plan was generated considering three parameters and three levels based on the Taguchi technique. The three independent process variables considered for the experimental study were load, sliding speed and sliding distance. Parameters and their levels are represented in Table 2.

Table 2: Parameters and their levels

Level	Load, L (N)	Sliding speed, S (m/s)	Sliding distance, D (m)
1	19.62	1.047	1257
2	29.43	2.095	2514
3	39.24	3.142	3770

In the present investigation an L_9 orthogonal array was selected, which has 9 rows and three columns. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than or equal to, the sum of the variables [13]. The selection of orthogonal array depends on number of factors and their interactions, number of levels for the factors, the desired experimental resolution or cost limitations. The response variable studied was wear rate. The experiments were conducted based on the run order generated by Taguchi model and the results were obtained. The analysis of the experimental data was carried out using MINITAB 15 software, specially designed for DOE applications.

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III. TAGUCHI METHOD

Essentially, traditional experimental design procedures are too complicated and not easy to use. A large number of experimental works have to be carried out when the number of process parameters increase. To solve this problem, the Design of Experiments (DOE) approach using Taguchi technique has been successfully used by researchers in the study of wear behavior of tribological materials. Taguchi method is a powerful tool for the design of high quality systems [13, 14]. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. The Taguchi approach to experimentation provides an orderly way to collect data and to analyze the effects of parameters over some specific response. The method combines experimental and analytical concepts to determine the parameter with the strongest influence on the resulting response for a significant improvement in the overall performance. The plan of experiments is generated in Taguchi method by the use of standard orthogonal arrays. The experimental results are then analyzed by using analysis of mean and analysis of variance (ANOVA) of the influencing factors [15, 16].
The steps applied for Taguchi optimization in this experimental study are as follows. [17]

- Select noise and control factors
- Select Taguchi orthogonal array
- Conduct Experiments
- Wear rate measurement
- Analyze results (Signal-to-noise ratio)
- Predict optimum performance
- Confirmation experiment

IV. RESULTS AND DISCUSSION

Table 3 shows the experimental results of wear rate. The wear rate is expressed as volume loss per unit sliding distance in m^3/m.

Table 3: Orthogonal array of Taguchi for wear rate and experimental results

Experiment no.	Load, L (N)	Speed, S (m/s)	Sliding distance, D (m)	Wear rate of DI (m^3/m) $x10^{-12}$	Wear rate of ADI (m^3/m) $x10^{-12}$
1	19.62	1.047	1257	0.12325	0.10084
2	19.62	2.095	2514	0.02801	0.06163
3	19.62	3.142	3770	0.03736	0.01494
4	29.43	1.047	2514	0.30813	0.15687
5	29.43	2.095	3770	0.08219	0.05978
6	29.43	3.142	1257	0.14566	0.08964
7	39.24	1.047	3770	0.41840	0.06351
8	39.24	2.095	1257	0.16807	0.14566
9	39.24	3.142	2514	0.08964	0.11205

4.1 S/N ratio analysis

S/N ratio response analysis was used to evaluate the influence of control parameters such as load (L), sliding speed (S) and sliding distance (D) on wear rate. Process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance. The sliding wear quality characteristic selected was smaller is the better type and same type of response was used for signal to noise ratio which is given below.

$$\eta = -10\log_{10}\{\frac{1}{n} \sum_{i=1}^{n} y_i^2\} \text{---------------(1)}$$

The S/N ratio response was analysed using equation (1) for all nine tests and presented in Table 4.

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Table 4: S/N ratios for DI and ADI material

L_9 test	S/N ratio for DI (db)	S/N ratio for ADI (db)
1	18.1843	19.9273
2	31.0537	24.2042
3	28.5519	36.5130
4	10.2253	16.0892
5	21.7036	24.4689
6	16.7332	20.9500
7	7.56820	23.9432
8	15.4902	16.7332
9	20.9500	19.0118

The S/N ratio response analysis for DI presented in table 5 shows that among all the factors, load is the most influential and significant parameter followed by sliding speed and sliding distance.

Table 5: Response table of DI for S/N ratios - smaller is better (wear rate)

Level	Load (N)	Speed (m/s)	Sliding distance (m)
1	25.93	11.99	16.80
2	16.22	22.75	20.74
3	14.67	22.08	19.27
Delta	11.26	10.76	3.94
Rank	1	2	3

Figure 4 shows the mean of S/N ratios of DI for wear rate graphically and figure 5 depicts the main effects plot for mean wear rate.

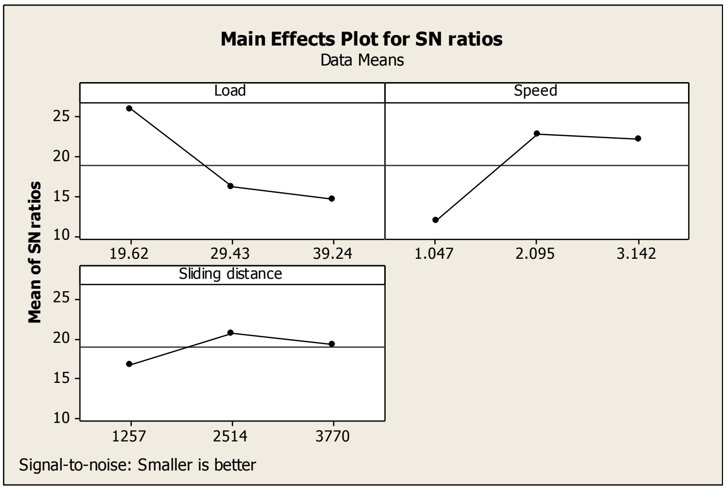

Figure 4. Main effects plot of DI for S/N ratios – Wear rate

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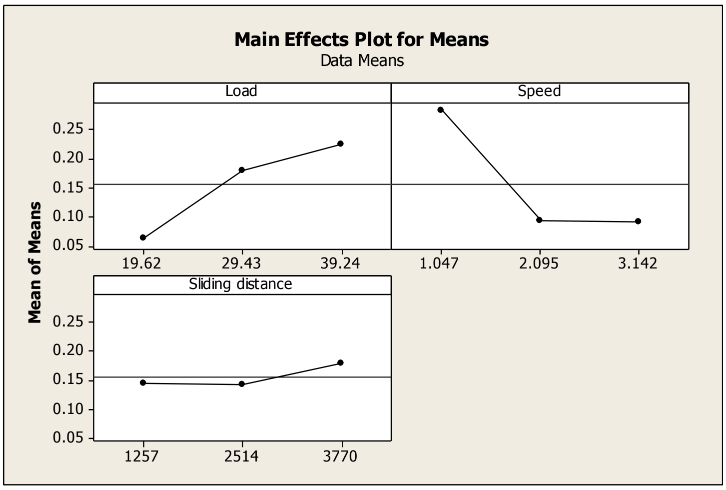

Figure 5: Main effects plot of DI for Means - wear rate

The S/N ratio response analysis for ADI presented in table 6 shows that among all the factors, sliding distance is the most influential and significant parameter followed by load and speed.

Table 6: Response table of ADI for S/N ratios - smaller is better (wear rate)

Level	Load (N)	Speed (m/s)	Sliding distance (m)
1	26.88	19.99	19.20
2	20.50	21.80	19.77
3	19.90	25.49	28.31
Delta	6.99	5.51	9.10
Rank	2	3	1

Figure 6 shows the mean of S/N ratios of ADI for wear rate graphically and figure 7 depicts the main effects plot for mean wear rate. From the analysis of these results , it can be inferred that parameter combination of L = 19.62N, S = 2.095m/s and D = 2514m gave the minimum wear rate for the range of parameters tested for DI. For ADI, the parameter combination of L = 19.62N, S = 3.142m/s and D = 3770m gave the minimum wear rate for the range of parameters tested.

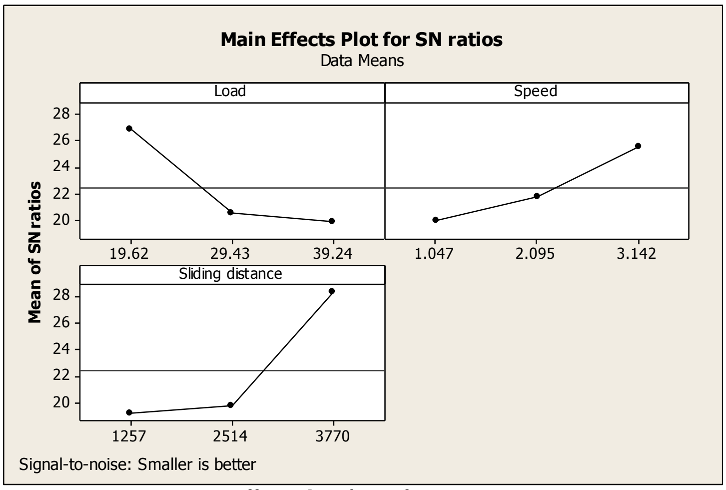

Figure 6. Main effects plot of ADI for S/N ratios – Wear rate

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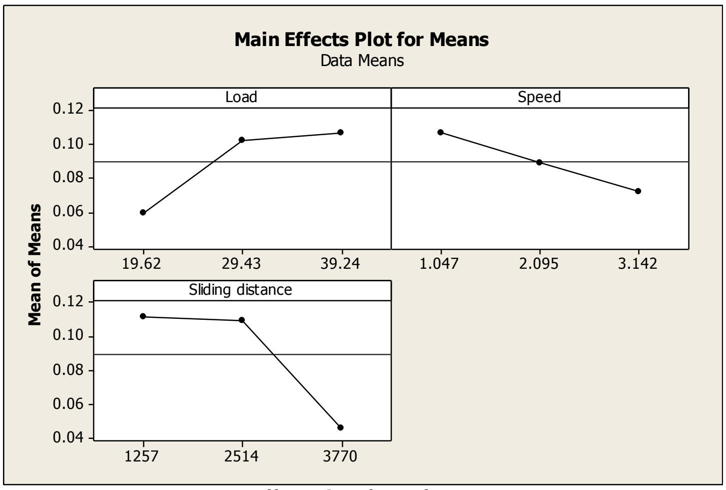

Figure 7: Main effects plot of ADI for Means - wear rate

4.2. Analysis of Variance results for wear test

The experimental results were analyzed with Analysis of Variance (ANOVA), which is used to investigate the influence of parameters considered for the study. This analysis was evaluated for a confidence level of 95%, that is for significance level of α=0.05. Tables 7 and 8 show the results of ANOVA for wear rate of DI and ADI. The last column of the tables indicates the percentage of contribution (P %) of each parameter on the response, indicating the degree of influence on the result.

Table 7: Analysis of Variance for S/N ratios - wear rate (DI)

Source	DOF	Seq SS	Adj SS	Adj MS	F-test	P-value	Percentage Contribution (%)
Load	2	223.475	223.475	111.737	27.03	0.036	47.20
Speed	2	217.877	217.877	108.939	26.35	0.037	46.02
Sliding distance	2	23.794	23.794	11.897	2.88	0.258	5.06
Error	2	8.268	8.268	4.134			1.72
Total	8	473.415					100

Notes: DOF, Degrees of Freedom; Seq SS, Sequential sum of squares; Adj SS, Adjusted sum of squares; Adj MS, Adjusted mean squares.

It can be observed from the results that, for DI, Load L (47.20%) and Speed S (46.02%) have the highest influence on wear rate. However, Sliding distance D (5.06%) has the least influence.

For ADI, Sliding distance D (51.92%) has the highest influence on wear rate followed by Load L (29.88%) and Speed S (15.70%).

Table 8: Analysis of Variance for S/N ratios - wear rate (ADI)

Source	DOF	Seq SS	Adj SS	Adj MS	F-test	P-value	Percentage Contribution (%)
Load	2	89.854	89.854	44.927	11.97	0.077	29.88
Speed	2	47.214	47.214	23.607	6.29	0.137	15.70
Sliding distance	2	156.148	156.148	78.074	20.80	0.046	51.92
Error	2	7.057	7.057	3.753			2.50
Total	8	300.722					100

The coefficient of determination (R^2) is defined as the ratio of the explained variation to the total variation. It is a measure of the degree of fit. When R^2 approaches unity, a better response model results and it fits the actual data. The value of R^2 calculated for this model was 0.975 that is reasonably close to unity and thus acceptable. It demonstrates that 97.5% of the variability in the data can be explained by this model. Thus it is confirmed that this model provides reasonably good explanation of the relationship between the independent factors and the response.

4.3. Multiple Linear Regression Model

A multiple linear regression analysis attempts to model the relationship between two or more predictor variables and a response variable by fitting a linear equation to the observed data [18, 19]. Based on the experimental results a

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multiple linear regression model was developed using MINITAB 15. A regression equation thus generated establishes correlation between the significant terms obtained from ANOVA, namely, load, sliding speed and sliding distance. The regression equations developed for DI and ADI are as follows.

Wear rate (DI) = 0.0706 + 0.008282 L - 0.09184 S + 0.00001339 D-------------------- (2)

Wear rate (ADI) = 0.11837 + 0.002443 - 0.01664 S - 0.00002625 D-------------------- (3)

The above equations can be used to predict the wear rate of Ductile Iron and Austempered Ductile Iron. The constant in the equation is the residue. The regression coefficient obtained for the model was 0.975 and this indicates that wear data was not scattered. From the above regression equations for wear rate, we found that wear rate of DI is directly proportional to the load (L) and sliding distance (D) and inversely proportional to the sliding speed (S) and wear rate of ADI is directly proportional to the load (L) and inversely proportional to the sliding speed (S) and sliding distance (D). The wear rate associated with load (L) in the regression equations (2) and (3) is positive and it indicates that as the load increases, wear rate also increases for DI and ADI. Similar results have been observed in the study of dry sliding wear behavior of Al-2219/SiC [20].

4.4. Confirmation Test

In order to validate the regression model, confirmation wear tests were conducted with parameter levels that were different from those used for analysis. The different parameter levels chosen for the confirmation tests are shown in table 9.

Table 9: Parameters used in the confirmation wear test

Test no.	Load L, (N)	Sliding speed S, (m/s)	Sliding Distance D, (m)
1	9.81	1.31	1571
2	29.43	2.62	3142
3	49.05	3.93	4713

The results of the confirmation test were obtained and a comparison was made between the experimental wear rate values and the computed values obtained from the regression model (table 10). The error between the experimental values and the computed values from the regression model for ADI was less than 6%. Hence, the regression model developed demonstrated a feasible and effective way to predict the wear rate of ADI. Similar results were obtained in the study of dry sliding wear behavior of HMMCs [21].

Table 10**:** Confirmation wear test results and their comparison with regression model

Test no.	Experimental wear rate (m^3/m) x 10^{-12}	Regression model – predicted wear rate (m^3/m) x 10^{-12}	Error (%)
1	0.08211	0.07930	3.42
2	0.10265	0.10543	2.64
3	0.05202	0.04909	5.63

V. CONCLUSION

Taguchi's method is used to find the optimum conditions for dry sliding wear of Austempered Ductile Iron. The following are the conclusions drawn from the present study.

1. Optimum wear rate was obtained from the experimental results using Taguchi method.
2. The wear rate of Austempered Ductile Iron is dominated by different parameters in the order of sliding distance, load and sliding speed. It is concluded from the ANOVA test that as sliding distance increases the wear rate also increases significantly.
3. Applied load, L = 19.62N, sliding speed, S = 3.142m/s and Sliding distance, D = 3770m are the optimum conditions for wear rate.
4. The parameter sliding distance (51.92%) has the highest influence on the dry sliding wear rate of ADI than the other parameters applied load (29.88%) and sliding speed (15.70%).
5. From the regression equation for wear rate of ADI, it is found that wear rate is directly proportional to the applied load and inversely proportional to the sliding speed and sliding distance.
6. From confirmation tests, it is found that the errors associated with wear rate calculations ranges between 2.64% to 5.63%. Hence it can be concluded that design of experiments by Taguchi method is a powerful technique for calculating wear rate from the regression equation.

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7. Austempering heat treatment increased the wear resistance of Ductile Iron.

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