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Design and Analysis of an IC Engine Piston using Composite Material

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ABSTRACT

Piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of piston such as piston side wear, piston head cracks and so on. One of the design criteria is the endeavour to reduce the structural weight and thus to reduce fuel consumption. This has been made possible by improved engine design. These improvements include increased use of lightweight materials, such as advanced ultra-high tensile strength steels, aluminium and magnesium alloys, polymers, and carbon-fiber reinforced composite materials. Here the life of the piston is improved by means of introducing a new composite matrix of aluminum with particulates of silicon carbide which has the maximum wear factor and which has the same performance except a little bit variation in properties called Al 6061 alloy in reinforcement with Silicon carbide. The piston is designed and analyzed through aluminum and silicon carbide in the ratio 2:3. A parametric model of a piston is done in 3D modeling software Autodesk Inventor. Further, it is analyzed for its deformation characteristics through ANSYS Workbench software.

Keywords: Al 6061, Al SiC, Composite, Piston

INTRODUCTION

A piston is a component of reciprocating IC-engines [1]. It is the moving component that is contained in a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod [3]. Piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of the piston, such as piston side wear, piston head cracks and so on. So there is a need to optimize the design of piston by considering various parameters in this project the parameters selected are analysis of piston by applying pressure force acting at the top of the piston and thermal analysis of piston at various temperatures in various strokes [2]. Most of the pistons are made of an aluminium alloy which has thermal expansion coefficient, 80% higher than the cylinder bore material made of cast iron. This leads to some differences between running and the design clearances. Good sealing of the piston to the cylinder is the basic criteria to design of the piston. To allow for thermal expansion, the diameter of the piston must be smaller than that of the cylinder. The necessary clearance is calculated by estimating the temperature difference between piston and cylinder and considering the coefficient of thermal expansion of the piston.

The design of the piston is carried out using SOLIDWORKS software, thermal and stress analysis is performed using Finite Element Analysis (FEA). The best aluminum alloy material is selected based on thermal and stress analysis results. The analysis results are used to optimize the piston geometry of best aluminum alloy. In this paper the piston plays a major role in the performance of the engine performance, materials of the piston are made up of impacts the strength of the piston. In this paper the piston become optimized after the reducing the material of the piston, the mass and volume of the piston become reduced. The deformation also increased after the optimization which is responsible for the stress distribution on the piston head or piston crown. Design, Analysis and Optimization of Three Aluminium Piston and to select the best suited aluminium alloy using FEA. This paper describes the stress distribution and thermal stresses of three different aluminum alloy piston by using finite element method (FEM). The results predict the maximum stress and critical region on the different aluminum alloy pistons using FEA. Static and thermal stress analysis are performed by using ANSYS 12.1. The best aluminum alloy material is selected based on stress analysis results. The analysis results are used to optimize the piston geometry of best aluminum alloy.

The aim of this paper is to improve the reliability of piston made by matrix of aluminum with particulates of silicon carbide which has the maximum wear factor and which has the same performance except a little bit variation in properties called Al 6061 alloy in reinforcement with Silicon carbide.

Components of a Piston

The main components of the piston are as follows:

- Piston Crown- which carries gas pressure
- Skirt-which acts as a bearing against the side thrust of Connecting rod
- Piston Pin- Piston pins are used to connect the piston to the connecting rod. These pins are made from hardened steel alloy and have a finely polished surface. Most piston pins are hollow, to reduce weight
- Piston Rings- which seal the annular space between the cylinder wall and piston and scrap off the surplus oil on the cylinder.

Characteristics of a Piston

- Strength to resist gas pressure.
- Must have minimum weight.
- Must be able to reciprocate with minimum noise.
- Must have sufficient bearing area to prevent wear.
- Must seal the gas from the top and oil from the bottom.
- Must disperse the heat generated during combustion.
- Must have good resistance to distortion under heavy forces and heavy temperature.

MATERIAL SELECTION

Engine specification and material selection are given in Table 1-3. For IC engines the pistons are made of the materials such as cast iron, cast steel, forged steel, cast aluminium alloys and forged aluminium alloy. Here materials used for design and analysis are Aluminium (Al-6061) and Aluminium Silicon Carbide composite. The aluminium is selected for design based on the following reasons:

- It has thermal conductivity of approximately three times that of cast iron.
- Density of aluminium is about one- third that of cast iron.
- Therefore, the piston has less variation in temperature from the crown of piston rings.
- Light weight in construction and less inertia force.

Table -1 Engine Specification

Parameters	Values
Engine type	4 stroke, petrol engine
Number of cylinders	single cylinder
Bore	39mm
Stroke	50mm
Maximum Power	6.03KW at 7500 rpm
Maximum Torque	8.05N/m at 5500 rpm
Compression ratio	8.4
Calorific value of petrol	47000 kJ/kg

Table -2 Chemical Composition of %Al 6061 grade

Al	97.6
Si	0.68
Fe	0.61
Cu	0.021
Ti	0.053
Mg	0.92
Mn	0.044
Zn	0.072
Cr	0.005

Table -3 Mechanical Properties of Al 6061

Parameters	Al 6061
Elastic modulus (GPa)	68.9
Ultimate tensile stress (Mpa)	260
0.2% yield stress (Mpa)	240
Poisson ratio	0.33
Thermal conductivity (W/m.K)	173
Coefficient of thermal expansion (m/degree Celsius)	23.5×10^{-6}
Density (kg/ m^3)	2700

Table -4 Mechanical Properties of Al SiC Composite

Parameters	Al SiC(40-60) %
Young's modulus	230 GPa
Poison ratio	0.24
Density	2937kg/ m^3
Thermal conductivity	197W/m.°C
Specific gravity	894 J/kg.°C

Reasons for Selecting Al 6061 Grade

- It has a high magnesium content in its composition next to the aluminium
- It is one of the aluminium grade, which is used for high with-standing loads and temperatures
- It reduces corrosion and wear at a considerable level

Advantages of Al6061

- They have greater strength when compared to other grades.
- They have a high durability.
- It balances ductility and strength with good wear resistance.

Reasons for selecting AlSiC Composite

- Ultra high strength
- Excellent temperature stability
- High fatigue strength

Advantages of AlSiC Composite

- Tailor-made coefficient of thermal expansion.
- High thermal conductivity
- Conducts heat almost like aluminium
- Light weight and strong
- Precision surface treatment
- Cost effective production

METHODOLOGY

- First of all, the piston is designed based on the available specification using Autodesk inventor software.
- Then it is analyzed through the ANSYS Workbench Software by both structural and thermal based.
- Then some manual calculation was done on the analysis in order to verify and deliver the conclusions based on the calculations.

DESIGN PROCEDURE

Let,
IP = indicated power produced inside the cylinder (W)
η = mechanical efficiency
n = number of working strokes per minute
= N/2 (for four stroke engine)
N = engine speed (rpm)
L = length of stroke (mm)
A = cross-section area of cylinder (mm^2)
r = crank radius (mm)
l_c = length of connecting rod (mm)
a = acceleration of the reciprocating part (m/s^2)
m_p = mass of the piston (Kg)
V = volume of the piston (mm^3)
T_h = thickness of piston head (mm)
D = cylinder bore (mm)
p_{max}= maximum gas pressure or explosion pressure (MPa)
σ_t = allowable tensile strength (MPa)
σ_{ut}= ultimate tensile strength (MPa)
F.O.S = Factor of Safety
K = thermal conductivity (W/m K)
T_c= temperature at the center of the piston head (K)
T_e= temperature at the edge of the piston head (K)
HCV = Higher Calorific Value of fuel
BP = brake power of the engine per cylinder (KW)
m = mass of fuel used per brake power per second (kg/KW s)
C = ratio of heat absorbed by the piston to the total heat developed in the cylinder.
b = radial width of ring (mm)
P_w= allowable radial pressure on cylinder wall (N/mm^2)
σ_p = permissible tensile strength for ring material (N/mm^2)
h = axial thickness of piston ring (mm)
h_1 = width of top lands (mm)
h_2 = width of ring lands (mm)
t_1 = thickness of piston barrel at the top end (mm)
t_2 = thickness of piston barrel at the open end (mm)
l_s = length of skirt (mm)
μ = coefficient of friction (0.01)
l_1 = length of piston pin in the bush of the small end of the connecting rod (mm)
d_o = outer diameter of piston pin(mm)

Piston Specifications

Table -5 Specifications of a Piston

Parameters	Values
Length (L)	39mm
Bore diameter(D)	50mm
Allowable radial pressure(P_w)	0.025Mpa
Permissible tensile Strength(σ_p)	110N/mm^2
Brake Power(BP)	6.2KW
Mechanical Efficiency(η)	80% or 0.8
Ratio of heat absorbed to heat de-veloped(C)	0.05 or 5%
Calorific value of fuel(HCV)	47000kJ/kg
Mass of fuel(m)	34.45×10^{-3}kg/KW s
Factor of Safety(F.O.S)	3

Width of Top Land and Ring Lands

Width of top land; $h_1 = (t_h \text{to} 1.2\ t_h)$=4mm
Width of ring land; h_2 = (0.75 h to h) =0.75mm
Piston barrel
Thickness of barrel at top end; t_1 =0.03D + b+ 4.9 =0.03×39+1.02+4.9=7.09mm
Thickness of the barrel at the open end; t_2 = (0.25 t_1 to 0.35 t_1) =0.25×7.09 =1.77 mm =2mm (assume)

Length of Skirt

l_s= (0.6 D to 0.8 D) = 0.6× 39 = 23.4 mm
Length of piston pin in the connecting rod bushing
l_1 =45% of piston diameter =0.45×39 =17.55mm
Piston pin diameter d_0 = (0.28D to 0.38D) =0.28×39 =10.92 mm.
The center of the piston pin should be 0.02D to 0.04D above the center of the skirt.

CAD Model of Piston

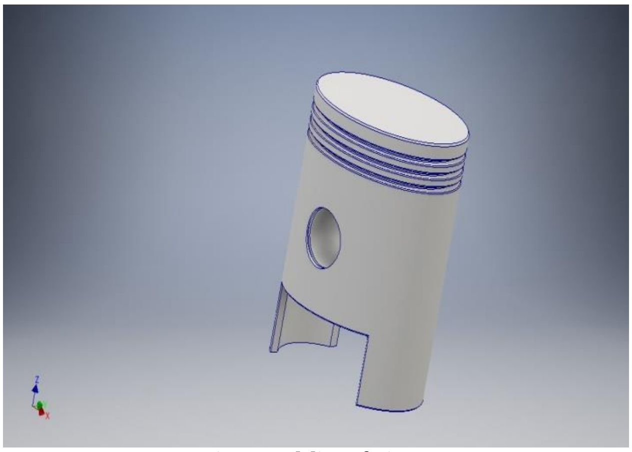

Fig. 1 Modeling of Piston

ANALYSIS OF PISTON

First of all, the piston was designed using Autodesk Inventor software. Then the model is converted to IGES format. Then it is imported to the ANSYS Workbench software for analysis. For structural and thermal analysis, the following boundary conditions are used:

- Pressure- 30Mpa
- Temperature- 500℃
- Film co-efficient- 22℃
- Ambient temperature- 24℃

Procedure for Analysis

- The imported piston is meshed using mesh tool
- The material properties are applied to the piston such as young's modulus, Poisson ratio and density of the material such as Al 6061 and Al SiC composite by creating new materials in engineering data sources section under workbench software.
- Then it is subjected to addition of frictionless constraint over the cylindrical portion.
- Fixed constraint is applied to the hole portion i.e., the piston pin portion
- After that, pressure load of 30Mpa is applied to the crown portion of the piston
- It is stimulated for deformation, Equivalent stress and strain values
- If it is a thermal analysis means the thermal conductivity values of the materials are applied respectively
- Temperature value of 500℃ is applied to the center of the piston crown
- Film co-efficient and ambient temperature values are applied
- Finally, it is stimulated for heat flux and maximum temperature
- Finally, the results of both static structural and thermal analysis values are tabulated.

STATIC STRUCTURAL ANALYSIS

The static structural analysis like total deformation, equivalent elastic strain and equivalent stress was carried out for alloy and composite.(aluminium 6061 and aluminium silicon carbide). The Fig. 2-4 shows the static structural analysis of aluminium 6061.

Total DeformationEquivalent-Elastic Strain

Equivalent-Stress

The static structural analysis was carried out for aluminium silicon carbide. The Fig. 5 -7 shows the static structural analysis of aluminium silicon carbide.

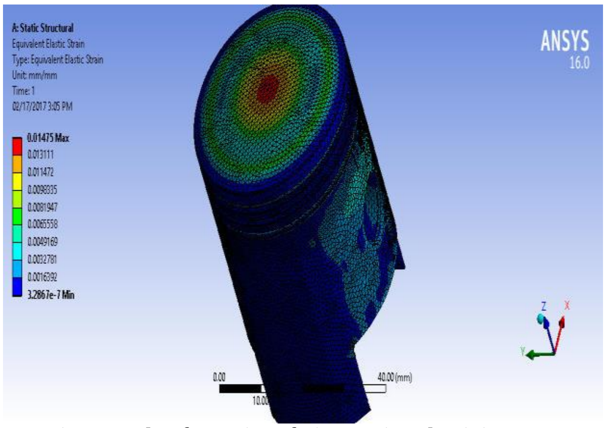

Fig. 2 Total Deformation of Piston using aluminium6061

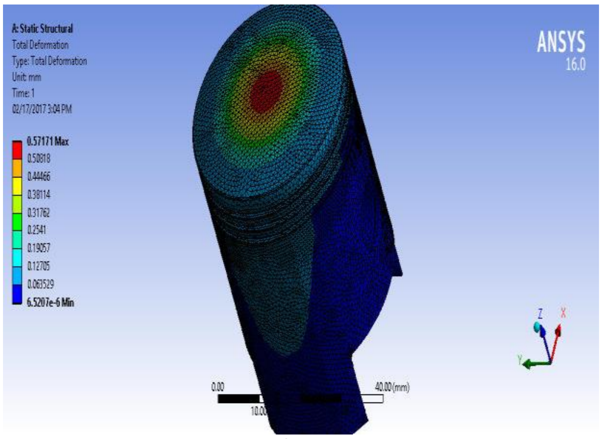

Fig. 3 Equivalent strain of Piston using aluminium6061

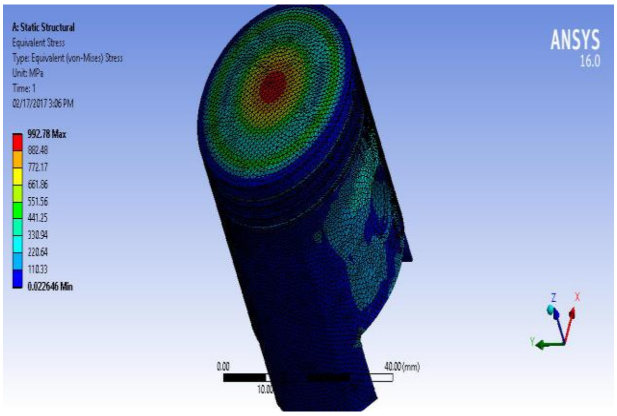

Fig. 4 Equivalent stress of Piston using Aluminium6061

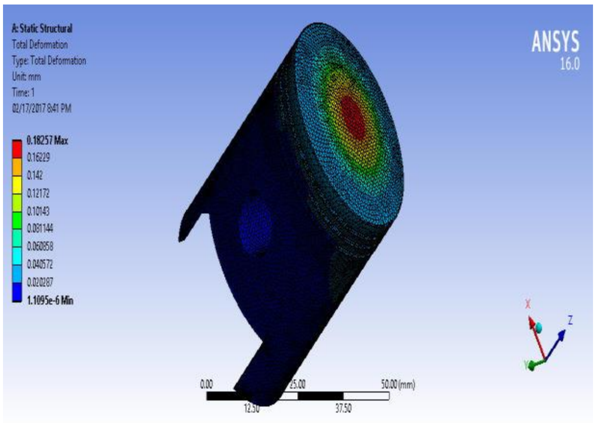

Fig. 5 Total Deformation of Piston using Al SiC

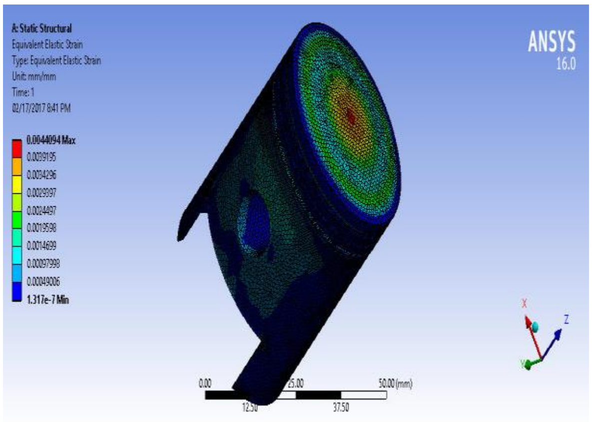

Fig. 6 Equivalent strain of Piston using AlSiC

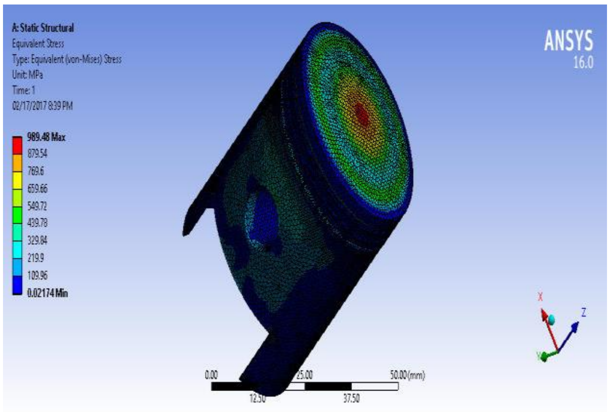

Fig. 7 Equivalent stress of Piston using Al SiC

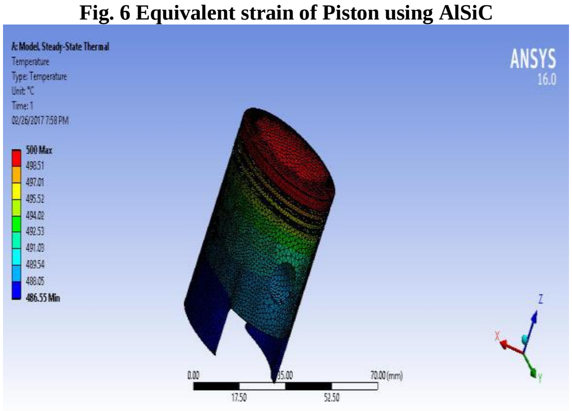

Fig. 8 Temperature distribution of Piston using aluminium6061

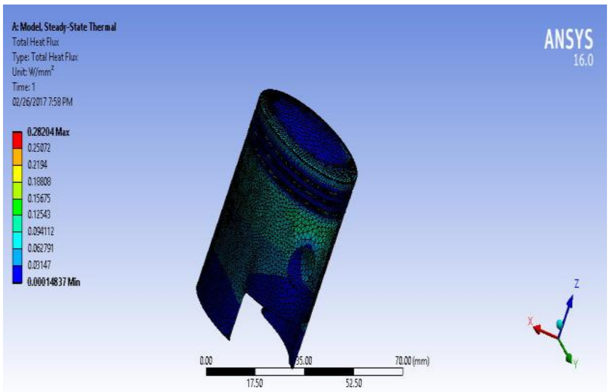

Fig. 9 Total heat flux of Piston using aluminium6061

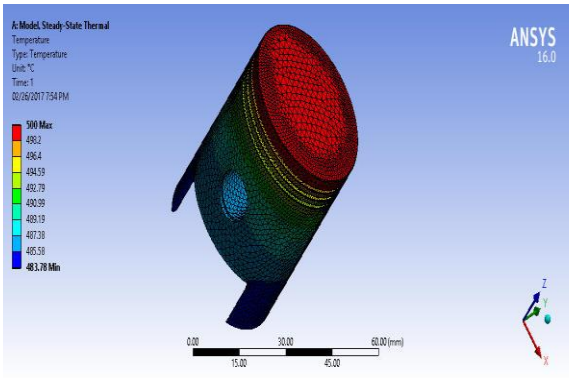

Fig. 10 Temperature distribution of Piston using Al SiC

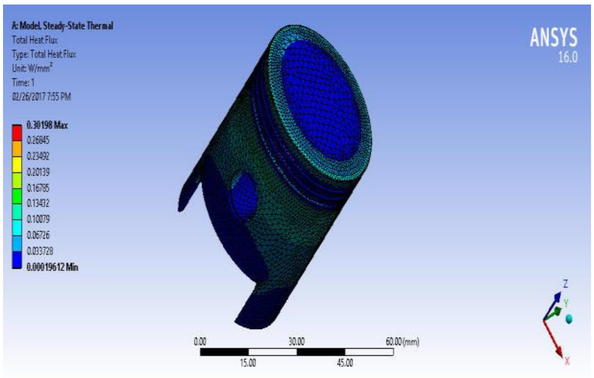

Fig. 11 Total heat flux of Piston using Al SiC

STEADY-STATE THERMAL ANALYSIS

The steady state thermal analysis was carried out for aluminium 6061.The Fig. 8-9 shows the temperature and total heat flux analysis using ANSYS Workbench.

TemperatureTotal Heat Flux
The steady state thermal analysis was carried out for aluminium silicon carbide.The Fig.10&11 shows the temperature and total heat flux analysis using ANSYS Workbench.

RESULTS AND COMPARISONS

The comparison of structural analysis of Al 6061 and Al SiC was tabulated in Table -6. The comparison of thermal analysis of Al 6061 and Al SiC was tabulated in table -7.

Table -6 Structural Analysis Results

Materials	Total Deformation		Equivalent Strain		Equivalent Stress	
	Min (mm)	Max (mm)	Min	Max	Min (MPa)	Max (MPa)
Al 6061	6.52×10-6	0.57	3.29×10^{-7}	0.01	0.02	992.8
Al SiC	1.11×10-6	0.18	1.32×10^{-7}	4.4×10^{-3}	0.02	989.5

Table -7 Thermal Analysis Results

Materials	Temperature		Total Heat Flux	
	Min (°C)	Max (°C)	Min (W/mm^2)	Max (W/mm^2)
Al 6061	486.55	500	1.5×10^{-4}	0.2820
Al SiC	483.78	500	2.0×10^{-4}	0.3020

MANUAL ANALYSIS FOR VALIDATION

The analysis was further verified using theoretical calculations for structural analysis of aluminium 6061.The procedure for the theoretical calculation as follows.

Procedure
Considering manual analysis of aluminium 6061

Data;
Allowable stress for Al 6061= 35ksi (241.3165MPa); which is referred through aluminium construction manual (specification for aluminium structures)
Safety factor as assumed =4
Elastic modulus= 69 GPa
Length of piston= 50mm
Thus the maximum ranges of deformation, stress and strain values for aluminium 6061 is considered.

Steps;
Allowable stress= maximum stress/factor of safety
Maximum stress, σ_{max}= allowable stress× safety factor =241.3165×4 =965.266MPa.
This theoretical value is **nearer** to the value analyzed through ANSYS (992.8MPa).

By Hooke's law, stress, σ= elastic modulus (E) × strain
Strain, e = stress/elastic modulus =965.266×10^6 Pa/69×10^9 Pa = 0.01399.
This theoretical value is **very close** to the value analyzed through ANSYS (0.01).

Strain, e = change in length (dl) /original length (l)
Deformation, dl= e × l =0.01399×50 = 0.69 mm.

This theoretical value is **exactly** to the value analyzed through Ansys (0.57mm).
Hence, the analysis is said to be in safe and verified.
This method is applicable for both materials and hence thus analysis is validated.

CONCLUSION

Thus the piston made up of aluminium 6061 and aluminium silicon carbide is modeled and analyzed successfully. The stress reduction is a very important factor which is responsible for the design of pistol crown or piston head. From the analysis Al SiC produces less stress concentration as compared to Al 6061, for the same load condition. Al SiC has a three-time lesser deformation than Al6061.Hence the reliability is higher for Al SiC as compared to aluminium 6061. The composite piston is capable of withstanding heavy loads under very severe environments. It also offers high strength retention on ageing. Both the pistons have a good temperature distribution under heavy loads.The Al SiC piston is more preferable because of cost effective and lower stress concentration and deformation.

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