International Journal of Scientific Engineering and Research (IJSER)
ISSN (Online): 2347-3878
Impact Factor (2020): 6.733

Static and Thermal Analysis of a Piston with Different Thermal Barrier Coatings

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Abstract: ***The design of engine pistons is one of the most complicated in automobile engines it is subjected to extremely high temperatures and high pressures resulting in high thermal stresses and thermal strains. Several investigators had carried out different research works wherein some of them addressed this issue by proposing new geometrical shapes of the piston and some others stressed the use of new materials like various alloys to ensure that their pistons meet the design requirements following operating performance improved during the engine operation in the present work both experimental &numerical investigation has been carried out on piston i.e. static analysis and thermal analysis on a 4-stoke gasoline engine piston using various metals used for construction manufacture of the piston such as aluminum -silica alloy and (AA4032) the piston was modeled using CATIA V5 R20soft ware followed by meshing and analysis with the help of ABAQUS CAE software. The static analysis was carried out by applying different static loads i.e., 2mpa and 4mpa to predict and evaluate deformation and stresses. The thermal analysis was also carried out. The results obtained for the above analysis were stress distribution, displacement distribution, and temperature distribution contours from their results it was observed the best material is AA4032 as it is found to have the lowest deformation at all pressures as improved temperature distribution and also the life of piston used for gasoline engine higher as observed comparatively static and thermal conditions for thermal barrier coated piston and then normal piston .when also tested as well as practical applications in the hero 100cc bike engine.***

Keywords: Piston, Automobile, Ansys, ABAQUSCAE

1. Introduction

1.1 Materials for piston:

Aluminum alloy is the most common material utilized. Cast or forged aluminum pistons are available. Pistons are also made of cast iron. Because of its superior wear properties, coefficient of expansion, and overall adaptability in manufacturing, cast iron was nearly universally used for pistons in the early years. However, because aluminum was required for the piston, a thicker metal was required to achieve the same strength; the light metal's advantage was lost. Aluminum has lesser strength and wears resistance than cast iron, and its greater coefficient of expansion needs additional cylinder clearance to prevent seizure. An aluminum alloy piston may function at substantially lower temperatures than just a cast-iron cylinder (200°C to 250°C vs. 400°C to 450°C) due to aluminum’s heat conductivity being roughly three times that of cast iron, as well as the higher thickness necessary for strength. Therefore, carbonized oil does not accumulate on the bottom of the piston, and the crankcase stays cleaner. Aluminum's cold-running properties are now recognized as useful as its lightweight; in fact, cylinders are routinely made thicker than required for durability to offer greater cooling. Because there is a high chance of seizure at temperature applications if the "cold clearance" is managed to keep just adequate, if the cold clearance is managed to keep large, this same engine understands or slaps once cold, an essential drawback of using metal alloy cylinders for cast iron coils is their inequitable co-efficient of expansion, that also creates engine slap.

The following are some Piston Material Alloys

Piston material	Al-Si-Alloy	AA4032
Density (kg/m^3)	2770	2.69
Elastic modulus (GPa)	71	70
Poisson ratio	0.33	0.33
Thermal conductivity (W/m-K)	174.15	155

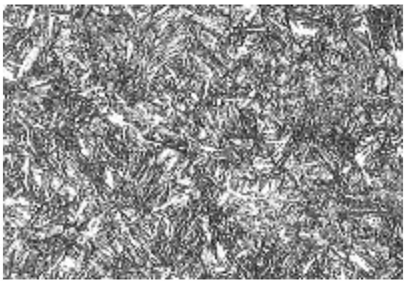
a) AL-SI- ALLOY:

AL-SI alloys are one of the most used alloys in car engine cylinders, cylinder heads, cylinder liners, and pistons. Corrosion resistance, superior wear resistance, low density, low coefficient of thermal expansion, high specific strength, and many other features contribute to this. C, Mn, Si, P, S, Cr, Ni, Mo, and other alloying elements can be used to improve the qualities of AISI alloys.

AL-SI alloys are widely utilized materials in the automotive industry, accounting for 85 percent to 90 percent of all aluminium cast parts produced. Because the tensile and fatigue strengths of A1-Si alloys are insufficient in the temperature range of 260°C to 370°C, they are not suitable for high-temperature applications.

Composition:

Element	Weight%
C	0.38 – 0.43
Mn	0.60 – 0.80
Si	0.15 – 0.30
P	0.035 Max
S	0.04 Max
Cr	0.70 – 0.90
Ni	1.65 – 2.00
Mo	0.20 – 0.30



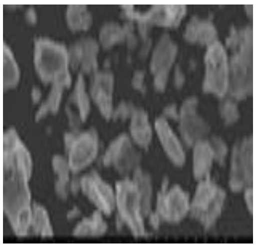
Microstructure of AL-SI Alloy

b) AA4032 ALLOY:

One of the most well-known qualities of aluminum is its lightness, with a density of 2.7 kg/m3 (one-third that of steel). Aluminum is lightweight due to its low density; however, this has no bearing on its strength. Tensile strengths of 70 to 700 MPa are common in aluminum alloys. Extrusion alloys have a strong range of 150 to 300 MPa. At low temperatures, unlike most steel grades, aluminum does not become brittle. Its strength, on the other hand, grows. Aluminium's strength deteriorates at elevated temperatures. When temperatures are consistently above 100°C, strength is weakened to the point that it must be considered. Aluminum is an extreme heat and electrical conductor. A copper conductor with the same conductivity weighs about half as much as an aluminum conductor. In neutral and slightly acidic situations, aluminum is exceedingly robust. Corrosion occurs quickly in situations with strong acidity or basicity.

Composition:

Element	Weight%
Al	85
Si	12.2
Cu	0.9
Mg	1
Ni	0.9



Microstructure of AA4032 Alloy

1.2 Discuss about thermal barrier coatings

Thermal interface coating (TBC) is a sophisticated materials solution that is typically put to metallic surfaces operating at severe temperatures, such as jet engine or aero-engine components, as a kind of exhaust heat control. By adopting thermally insulated substances that can withstand a substantial temperature difference between both the pile metal and the coating surfaces, these 100m to 2mm coatings can safeguard components from severe and persistent heat loads. These coatings may extend part life by minimizing oxidation or thermal fatigue while allowing for better-operating temperatures and less heat exposure to structural components. TBCs permit working fluid temperatures greater than the melting point of a metal air foil in some turbine applications when used in conjunction with active film cooling. There is a significant drive to decarbonize due to the increased need for greater engine operation (efficiency grows at higher temperatures), better sturdiness, and thin coatings to minimize the paralic mass of rotating/moving components.

1.3 Coating material selection:

Thermal barrier coatings are used to keep heat from flowing through a surface. Thermal barrier coatings (TBC) play a critical role in insulating components such as gas turbine and aero-engine parts when they are exposed to high temperatures. The best TBC material is chosen using the weighted residual approach once a shortlist of TBC materials is created. In terms of low heat conductivity and high young's modulus, bond bonded ceramic is unrivaled.

Ceramic:

The ceramic coat is a thin film coating applied on the top surface of the piston. With a thermal barrier coating, it is utilized to insulate the top of the piston (TBC). Because the ceramic limits the heat flow through it to the metal surface, it will reduce the heat entering the metal. The metal can transfer heat to the rings. Because ceramic has a smaller heat capacity than metal, there is a complicated heat flux balance to contend with.

Bond coating:

The thermal barrier coating's bond coat (TBC). Between the substrate and the coating layer, these materials will form a strong connection. This material's desirable coating characteristics are adhesion strength and usage within working temperature restrictions.

Investigated coated thicknesses and width

Ceramic coated (Mgzro3) thickness	Bond coat (NicrAl) thickness	Total coating (mm)	Coating width W (mm)
0.05	0.15	0.2	9.2,11.2
0.15	0.15	0.3	9.2,11.2

2. Experimental Procedure

CATIA V5 R20 is seeing ever more application in the development and design of gasoline engines as the processing capability of current computers increases. This chapter mostly covered the CATIA V5 R20 SOFTWARE description, applications, design data, and piston model creation in CATIA V5, which was subsequently transferred into Abaqus CAE Software.

2.1 Piston Design

The piston data is acquired from the machine design and data handbook according to the procedure and specification. Pressure on the piston head, temperatures in various parts of the piston, heat flow, tensions, strains, length, the diameter of the piston and hole, thicknesses, and other characteristics are all considered.

2.2 Design Considerations for a Piston

1) When building a cylinder for an engine, the following elements should be considered:
2) It must be exceedingly sturdy to withstand the huge pressure.
3) To endure inertia forces, it is as light as feasible.
4) It should form an effective oil seal in the cylinder.
5) It must have a sufficient bearing surface to avoid excessive wear.
6) It must be willing to reciprocate quickly without creating any noise.
7) It should be made of materials that can withstand heat & mechanical deformation.
8) It must be robust enough to hold the piston pin in place.

2.3 Procedure for Piston Design

The procedure for piston designs consists of the following steps:
1) The thickness of the piston head (t_H)
2) Heat flows through the piston head (H)
3) The radial thickness of the ring (t_1)
4) Axial thickness of the ring (t_2)
5) Width of the top land (b_1)
6) Width of other ring lands (b_2)

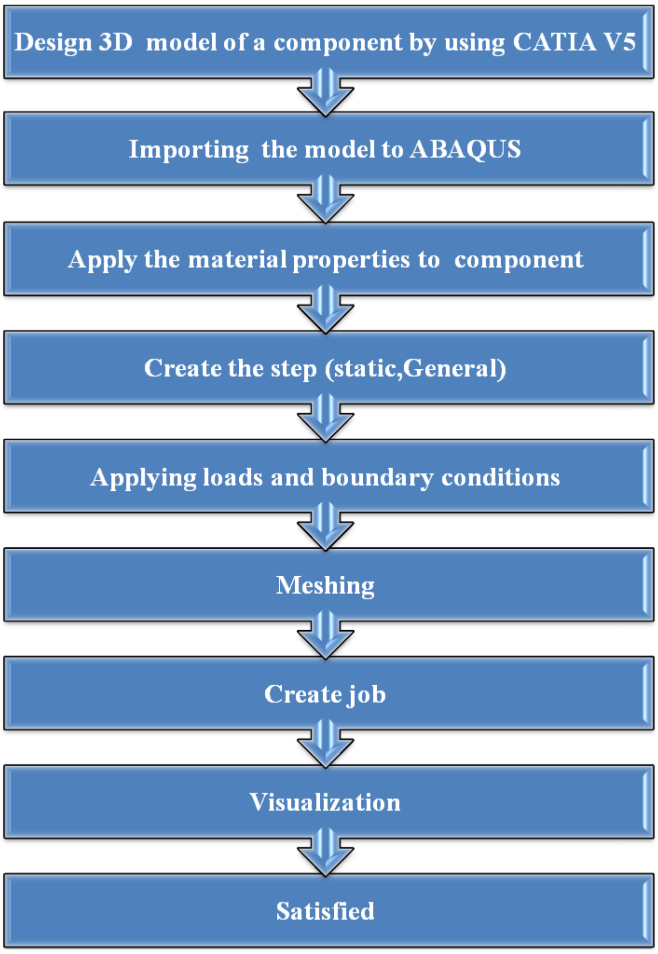
2.4 Specification:

- Length of the Piston=37 mm
- Cylinder bore/outside diameter of the piston (D) -49.5 mm
- The thickness of the piston head (t_H) – is 6.65mm
- The radial thickness of the ring (t_1) – is 2.01 mm
- Axial thickness of the ring (t_2) -2mm
- Width of the top land (b_1) –6.78mm
- The thickness of the barrel (t3) -is 12.7mms

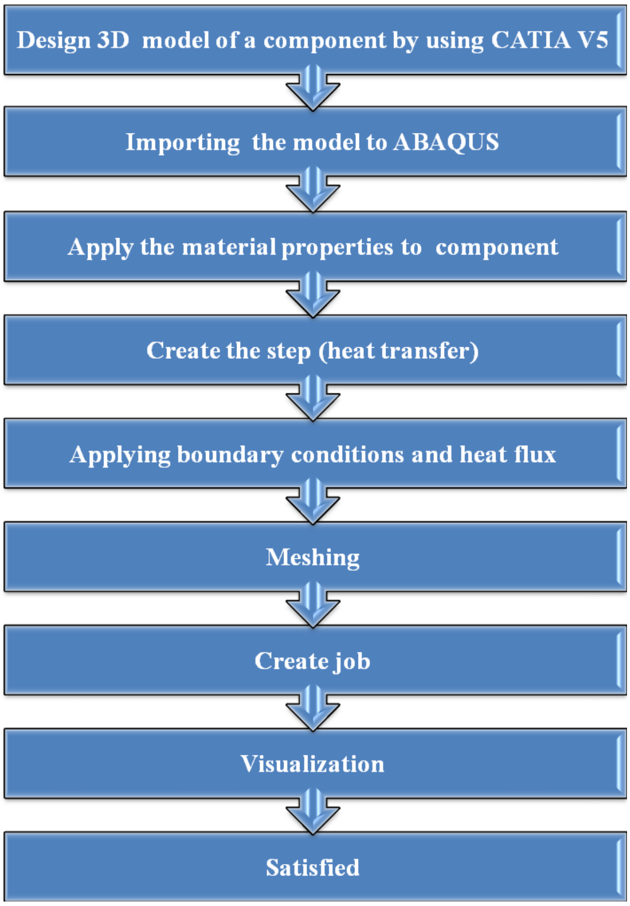
2.5 The analysis of piston

The static and thermal analysis

1) Procedure for static analysis:



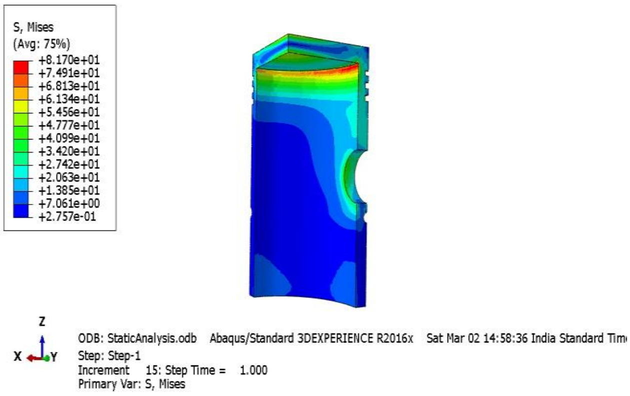
2) Procedure for Thermal Analysis:



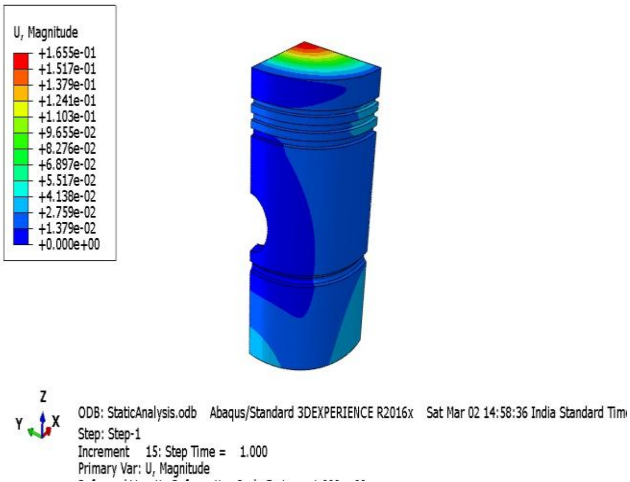
a) AT 2MPA LOAD

AL-SI ALLOY:

The stress distribution contours and displacement distribution contours for the alloy of Al-Si Aluminum material at 2Mpa injection pressure are given in the figure below. The maximum stress is 81.7Mpa, with a maximum displacement of 0.1655 mm.



The stress distribution for Al-Si Aluminum alloy materials at 2Mpa

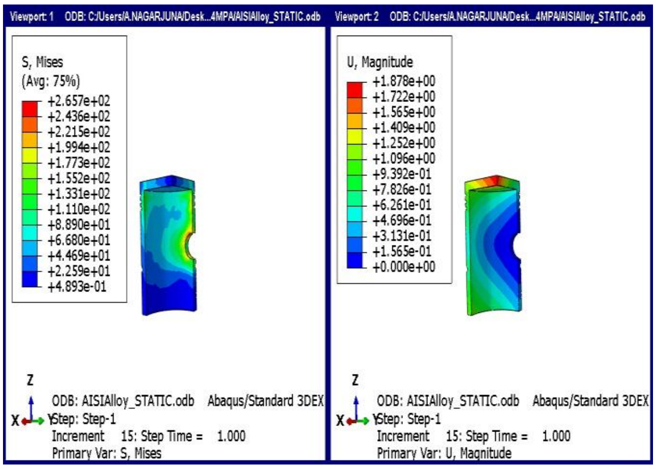


The displacement distribution contours for Al-Si alloy material at 2Mpa

b) At 4MPA Load

Static Analysis for AL-SI Alloy:

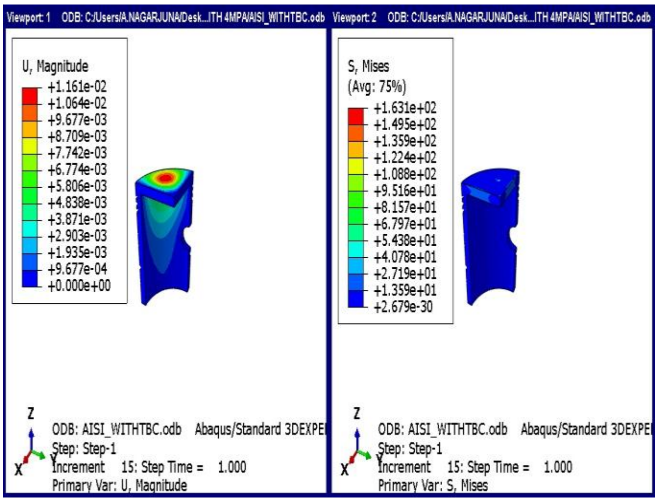
The stress distribution contours and displacement distribution contours for the alloy of Al-Si Aluminum material at 4Mpa injection pressure are given in the figure below. The maximum stress is 265.7Mpa, with a maximum displacement of 1.878mm.



The Stress Displacement Distribution Contour for Al-Si Alloy at 4Mpa

Thermal barrier coated piston for Al-Si alloy:

The stress distribution contours and displacement distribution contours for the alloy of Al-Si Alloy material at 4Mpa injection pressure are presented in the figure below. The maximum stress is 163.1Mpa, with a maximum displacement of 0.0161 mm.



The Stress and Displacement distribution contours for material Al-Si at 4Mpa

3. Results & Discussions

The results show Von – Misses stress, displacement, and temperature distribution on four-stroke gasoline engine pistons for various materials (AA4032, AL-SI alloy), as well as Von – Misses stress, displacement, and temperature distribution on four-stroke gasoline engine pistons after applying thermal barrier coatings at different pressures (2Mpa and 4Mpa). The findings of the static, thermal analysis is presented below.

3.1 Analysis Results

1) Static analysis

Static analysis results of gasoline piston at 2mpa and 4mpa

Static analysis			Gasoline bare piston		Thermal Coated Piston	
S. no.	Materials	Applied pressure (Mpa)	Von misses stress (Mpa)	Displacement (mm)	Von misses stress (Mpa)	Displacement (mm)
1	AL-SI Alloy	2	81.7	0.1655	80.96	0.1652
		4	265.7	1.878	163.1	0.0161
2	AA4032 Alloy	2	133	1.179	44.2	0.06286
		4	265.7	1.905	164.7	0.0117

2) Thermal analysis:

a) Thermal analysis results of gasoline piston at 2mpa

Thermal analysis			Gasoline piston
S. No	Material	Heat flux distribution	Temperature distribution (k)
1	Al-Si Alloy	2.372	253.8
2	AA4032 Alloy	2.21	253.8

b) In Practical Application:

- **AL-Si Alloy Coated piston**
- **AA4032 Alloy Coated Piston**

S/NO	Load (kg)	Torque (NM)	BP (KW)	N (B.th%)	Bsfc (kg/kwh)
1	1	1.26	0.12	2.26	3.31
2	2	2.67	0.14	2.50	3.300
3	3	4.11	0.16	3.49	2.11
4	4	5.68	0.22	4.50	1.81
5	5	6.81	0.25	5.21	1.42
6	6	8.30	0.27	4.41	1.01
7	7	9.65	0.30	12.08	0.61
8	8	11.06	0.32	16.28	0.53

By applying a ceramic coating to the piston, the mass of fuel consumption is reduced by 3.11 percent as compared to a piston without a coating. By applying a ceramic coating to the piston, the braking thermal efficiency is boosted by 10% when compared to a piston without a coating. By applying a ceramic coating to the piston, the brake-specific fuel consumption is reduced by 2.56% as compared to a piston without the coating. By covering the piston with ceramic material as opposed to a non-coated piston, the emission of carbon or hydrocarbon in the exhaust gases is decreased. When compared to a regular piston, a ceramic thermal barrier coating improves the performance of an internal combustion engine.

c) The Hero 100CCC Bike Engine in 500 KM

- **AA4032 (Aluminum wrought alloy)**

Parameter	Calculated Values	Actual Values	Difference
Piston Length	36.16mm	37 mm	0.84 mm
Piston Diameter	50 mm	49.5 mm	0.5 mm
Pin hole external diameter	13 mm	12.7 mm	0.3 mm
Pin hole internal diameter	8 mm	6.6 mm	1.4 mm
Piston ring axial thickness	1.05 mm	0.8 mm	2.25 mm
Radial thickness of ring	1.62 mm	2 mm	0.3 mm
Depth of ring groove	2.02 mm	2.01 mm	0.01 mm
Gap between the rings	2.75 mm	2.6 mm	0.15 mm
Top land thickness	7.3 mm	5.6 mm	1.7 mm
Thickness of piston at the top	7.05 mm	6.65 mm	0.4 mm
Thickness of piston at open end	1.76 mm	1.64 mm	.12 mm

- **Aluminum silica Alloy**

Parameter	Calculated Values	Actual Values	Difference
Piston Length	36.12 mm	37 mm	0.88 mm
Piston Diameter	50.08 mm	49.5 mm	0.58 mm
Pin hole external diameter	13 mm	12.7 mm	0.3 mm
Pin hole internal diameter	7.9 mm	6.6 mm	1.3 mm
Piston ring axial thickness	1.32 mm	0.8 mm	2.52 mm
Radial thickness of ring	1.21 mm	2 mm	0.79 mm
Depth of ring groove	2.04 mm	2.01 mm	0.03 mm
Gap between the rings	2.81 mm	2.6 mm	0.21 mm
Top land thickness	7.12 mm	5.6 mm	1.52 mm
Thickness of piston at the top	7.18 mm	6.65 mm	0.53 mm
Thickness of piston at open end	1.76 mm	1.64 mm	.12 mm

The results were first computed using the methods described in the study and then compared to the size of the real pistons used for the hero splendor motorcycles.

4. Conclusion

The experimental investigation and numerical analysis were carried out for different piston materials with fuel injection pressure 2mpa and 4mpa. The performance of gasoline engines was tested for different pistons with the details given below.

From the Analysis:

Static Analysis:

The static analysis for 2mpa the observation in von misses' stress for uncoated piston (or)AL-Sl alloy piston 80.96mpa and (AA4032) alloy coated piston von misses stress is 44.2mpa will obtained. The displacement is 0.1652mm and AA4032 alloy displacement is 0.06286mm. The static analysis for 4mpa the observation in von misses' stress for uncoated piston (or)AL-Sl alloy piston 163.1Mpa and (AA4032) alloy coated piston von misses stress is 164.7mpa will obtain. The displacement is 0.0161mm and AA4032 alloy displacement is 0.0117mm. From the above observation piston withAA4032 alloy as lowest von misses stress 44.2mpa and with the lowest displacement of 0.06286mpa

Thermal Analysis

The heat flux distribution for AL-SI alloy is 2.372 and AA4032 alloy 2.21. The corresponding temperature distribution in AL-SL alloy is 253.8 in the AA4032 alloy is 253.8. It can be concluded that piston coated with AA4032 alloy has the best performance with the values. this can be attributed to the coating as played the role of insulator thereby shielding the piston from elevated temperature and pressure that has resulted in the lowest heat flux distribution near constant.

Thermal Analysis

The thermal analysis result of AL-SI material is shown below. The maximum heat flux distribution is found to be 2.372. The greatest temperature is 650 degrees Fahrenheit. The maximum stress is 185.6 MPa, with a maximum displacement of 1.149 mm. The thermal analysis result for AA4032 material is shown below. The maximal heat flow distribution is found to be 2.371 w/m2. The maximum temperature was 2.539 degrees Celsius. For the AI-SI and AA4032 materials. In comparison to AI-SI Alloy, we found that AA4032 is the optimum material for putting thermal barrier coatings.

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