Analysis of stress and temperature distribution of the exhaust valve made of titanium alloy Ti6Al4V

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Abstract

The paper presents analysis of the temperature and equivalent Huber-Mises stress distribution inside outlet valve during cold start of engine. Three various materials were taken into consideration, i.e. titanium alloy Ti6Al4V, commercially pure titanium Grade 2 and valve steel H9S2. The computations were carried out using ABAQUS Standard environment. Boundary conditions applied in the FEM simulation took into account gas temperature in the combustion chamber and outlet channel and temperature of valve socket and valve guide.

Introduction

Task of the engine valve is closing and opening in a given time of inlet and outlet channels of the combustion chamber. The valves consist of a spindle, the central part (spindle in the outlet channel) and the valve face. The task of the spindle is confirming of valve in the valve guide and the heat dissipation from a valve face. This component must comply with the many opposite requirements: have a low weight and sufficient strength, effectively draining the heat but at the same time have a small diameter to minimize disturbing of a gas flow. A typical diameter of the valve spindle is within the range from 15% to 30% of the effective valve diameter [1]. At the periphery of the face a valve seat is located. At a time when the valve is closed it is pressed into the socket, closing the combustion chamber. In addition, through contact between valve seat and socket follows the exchange of heat between the valve and the engine head. Highly heat-laden exhaust valves must meet the following requirements:

- high thermal conductivity,
- resistance to high temperatures,
- high resistance to shock loads,
- small coefficient of thermal expansion,
- high abrasion resistance,
- high resistance to corrosion.

The largest thermal load of valves occur during cold start of the engine. In the case when immediately after starting the vehicle engine is heavily loaded, very large temperature gradients which lead to the formation of strong internal stresses are present in his elements. After a given time working conditions stabilize, but the difference between the temperature in the combustion chamber, and thus the temperature of the surface of the valve face and valve spindle, cooled by a guide is still high. For this reason, it is desirable that the material from which engine valve is made must be been characterized by a good thermal conductivity. This makes easier to transport thermal energy flux from a valve face to the valve guide. Process of cooling of an engine parts is a lot slower than its warming up, therefore, do not arise so strong temperature gradients. Engine valves are exposed to two types of mechanical loads: the first one is related to the cycles of warming up and cooling of the engine, while the second is due to valve spring pressure. The frequency of latter type of load is very high, as the valve opens in each combustion cycle. As a result, the valve is exposed to several hundred to several thousands of cycles of load within minutes of engine operation. Both types of load can lead to the development of fatigue damage [2, 3].

Three types of steel are used for the structures of the engine valves, i.e. ferritic-perlitic, austenitic and silichroms [4-6]. The first type is characterized by a good thermal conductivity, high strength, low thermal expansion coefficient, good machinability, poor corrosion resistance and significant lowering of yield point under the influence of high temperature. Due to limited corrosion resistance and strength decrease at elevated temperatures (higher than 700°C) ferritic-perlitic steels applies mainly on the intake valves and spindle of exhaust valves.

The second group of steel has chrome-nickel austenitic structure. From the point of view of the design of the valves, the most important properties of this grade of are following: high hardness, strength, resistance to oxidation and corrosion resistance at high temperatures, low thermal conductivity and coefficient of thermal expansion.

Silicon-chromium steels with content of chromium from 8% to 12% and silicon from 2% to 4% are most commonly used for the exhaust valves. They are characterized by high durability, high impact resistance, good temperature resistance, low- and high-temperature corrosion resistance, high hardness at high temperatures, a low coefficient of thermal expansion and coefficient of thermal conductivity.

Currently, the development of the automotive industry is stimulated mainly by increasingly stringent standards, which limit the emission of harmful substances and carbon footprint in transport [7,8]. This effect can be achieved both by modifying the structure of the vehicle, which leads to reduce its weight, the use of hybrid or electric drive as well as the modification of the existing internal combustion engines. The last of these solutions is accomplished mainly by increasing the combustion temperature. This leads to an increase in the maximum temperature of exhaust gases from 600°C

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to 1050°C [9] for spark ignition engines and up to 850°C [10] for diesel engines. In addition, the introduction of bio-components into mineral origin fuels induces faster corrosion of engine parts, including the valves. Therefore, there is lots of effort put in order to increase the resistance of currently used steel against high temperature corrosion. Mainly this is done by modifying the surfaces or inserting additional corrosion-resistant layer. At the Motor Transport Institute work is carried out on the possibility of the use of titanium alloy Ti6Al4V to fabricate exhaust valves. In addition, the surface of the valve will be covered with a layer of Graphene, which enables to increase the corrosion resistance of the material. TiAl6V4 alloy, also referred to as Grade 5, is the most widely used of the whole range of titanium alloys in aerospace, medicine, chemical and automotive industry. This material is characterized by high strength, while maintaining high strength-to-weight ratio of the element. Typical yield stress for TiAl6V4 alloy is equal to 830 MPa [11], tensile strength 900MPa, density 4420 kg/m^3, thermal conductivity 6.6 W/(mK) and coefficient of thermal expansion 9x10^{-6}/K. Because on the alloy surface tight layer of titanium oxide is quickly formed, items made from this material are resistant to corrosion. In the case even if the micro-damages are formed they are quickly filled by another layer of oxides protecting the surface from further corrosion. Despite the high prices TiAl6V4 alloy is relatively easily accessible in the form of rods and sheets.

The article presents also analysis of stress and temperature distribution inside the exhaust valve made of commercially pure titanium (CPT). The commercially pure titanium is produced in four variants, known as Grade 1 to Grade 4. With the increase in the index the strength of the material increases, while decreasing its susceptibility to machining and forming. The Grade 2 titanium used in this analysis have the following physical-chemical properties: yield point 275MPa-410MPa, tensile strength of 344MPa, density 4510 kg/m^3, thermal conductivity 16,4 W/(mK) and coefficient of thermal expansion, 8.6x10^{-6}/K. In comparison to the TiAl6V4 alloy CPT differs mainly in a strength and thermal conductivity, which may be very important for the construction of engine valves. Especially the second parameter may be crucial, because, as mentioned earlier, a large value of the coefficient of thermal conductivity is very desirable in the design of the engine valves. Despite the lower strength compared to the Ti6Al4V titanium alloy, CPT is also very often used, especially in applications requiring high chemical corrosion resistance and bio-compatibility. Examples of CPT applications are: medical implants, aircraft engine components, piping, heat exchangers, process chemistry apparatus elements.

Finite element method (FEM) is often used as a tool for analysis of the behavior of engine valves. This is because even in the laboratory conditions measurements of valves temperature and stress gradients occurring during engine start is impossible from technical reasons. Studies of carbon deposits impact on the exhaust valve temperature and heat exchange were carried using numerical computation [12, 13]. Developed model allows to investigate the valves in the transient and steady state analysis, with different variables of heat-exchange boundary conditions. A comprehensive analysis of the thermal loads of socket-valve pair of turbocharged engine, presented in the dissertation [1] took into account the influence of the technical parameters of the engine, such as its dimensions, the angle of the shaft or the amount of fuel supplied on the thermos-mechanical loads. Subsequently, analysis of heating process of socket-valve pair was carried out on the basis of calculation. Moreover, the temperature field inside valve and seat was determined.

The purpose of the research presented in this publication was to analyze the temperature distribution and equivalent Huber- Mises stresses inside the exhaust valve during a cold start of the engine.

Analysis methodology

The subject of conducted analysis was estimation of temperature and equivalent Huber-Mises stress distribution inside the exhaust valve during cold start of the engine. The engine rotational velocity was assumed to be equal to 3000 rpm. Boundary conditions used in the FEM simulation took into account gas properties in the combustion chamber and in the exhaust channel, as well as the temperature of the valve socket and guide. The data obtained from earlier works [1, 13] concerning heat transfer coefficient and temperatures were used in this simulation.

The quarter-symmetric numerical model applied in the simulation is shown in Fig. 1. Calculations have been carried out in ABAQUS Standard environment. The size of the grid element is assumed to be equal to 2 mm. The transient coupled thermal-displacement analysis were applied. Valve model was constrained at the end of the spindle in a longitudinal direction.

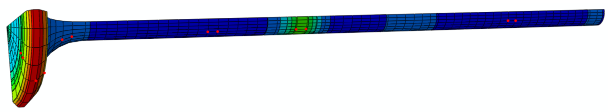

Fig.1. View of the valve model

Tests have been carried out for three types of materials: Ti6Al4V titanium alloy, CPT grade 2 and one of the modern silicon-chromium valve steel of H9S2 grade. The physical properties of the materials used in the simulation are presented in table 1.

The scheme of valve with boundary conditions is shown in Fig. 2. The upper part of the valve spindle is placed in the valve guide. Its temperature during the heating of the engine grows according to the relationship:

$$T_P = 175\,[1 - \exp(\,0{,}05\,t)] \qquad (1)$$

The lower part of the valve spindle, and the upper part of the valve face are placed in the outlet channel, filled with the exhaust gas. Changes in the value of the heat transfer coefficient ("alpha 2") and the temperature of the exhaust gas (“Gas 2") are presented in Fig. 3. Changes in heat transfer coefficient and temperature in the subsequent four strokes of one combustion cycle of the engine were taken into account in the simulation. The rotational speed of engine was assumed to be 3000 rpm corresponding to the time of one full cycle equal to 0.08 s. When the valve is closed, the gas temperature at the outlet channel is fixed. When the valve is open the exhaust gas temperature becomes equal to the gas temperature in the combustion chamber. Therefore temperature and heat transfer coefficient are the same for the range of time from 0.06 s to 0.08 s. For the closed valve the temperature of valve seat is equal to those of socket and rise according to the relationship:

$$T_G = 350[1 - \exp(0{,}05t)] \qquad (2)$$

During the exhaust stroke the valve opens and boundary conditions for valve seat changes. The valve is no longer in contact with the socket, and begins to come into contact with the exhaust gases from the combustion chamber. Thus the boundary conditions for the valve seat for the time from 0.06 s to 0.08 s are described by “Gas 1” properties, corresponding to the “alfa 1” and “Gaz 1” in Fig. 3. The lower part of the valve face is located in the combustion chamber, therefore the boundary conditions estimated for the combustion chamber "Gaz 1" and "alfa 1" were used. It is worth noting that at the beginning of the combustion cycle there is a sharp increase in temperature up to 2700°C and heat transfer coefficient up to $3000 Wm^{-2}K^{-1}$ which is associated with the combustion of the mixture in the engine.

Results

Temperature for valves made of the test materials is shown in Figs 4-6. The values were obtained after 180 seconds, from engine start. The temperature of the upper part of the spindle is equal to the temperature of the valve guide. The highest temperature region is located near the bottom of the valve face. For valve made of TiAl6V4 alloy the maximum temperature is equal to 900°C, while for the other materials equal to700°C.

Table 1. Material properties

Material	Thermal cond. $[Wm^{-1}K^{-1}]$	Density $[kg/m^3]$	Young’s modulus [GPa]	Poisson’s ratio	CTE 10^{-6}/K			Specific heat cap. $[Jkg^{-1}°C^{-1}]$
					20°C	250°C	500°C	
TiAl6V4	6,7	4430	114	0,33	8,6	9,2	9,7	526
CPT	16,4	4510	105	0,37	8,6	9,2	9,7	523
Valve steel H9S2	25	7800	200	0,33	10	10	10	460

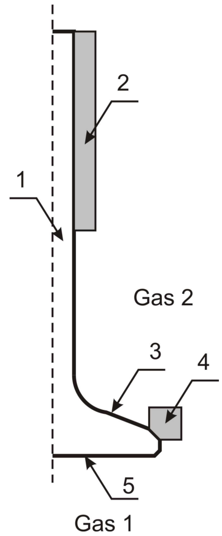

Fig. 2. View of the valve including boundary conditions: 1 – valve spindle, 2 – guide, 3 – spindle in the outlet channel, 4 – valve seat, 5 – valve face.

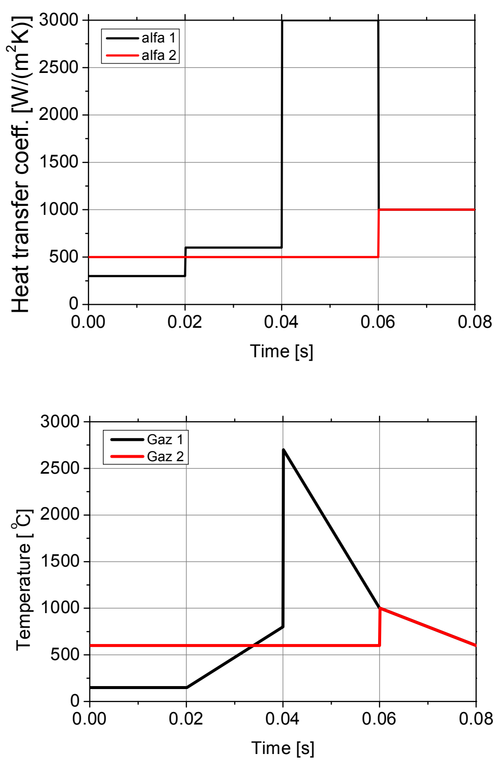

Fig. 3. Boundary conditions for heat exchange at valve surface: a) heat transfer coefficient, b) temperature

Analyzing results presented in Figs 4-6 it can be seen that the valve seat has a lower temperature compared to the rest of the valve face. This is because the heat is conducted from the bottom of a face to the parts of valve with temperature. The heat flux is transferred outside of valve thru contacts between valve seat - socket and spindle – valve guide. Despite that the temperature of socket is equal to 350°C the temperature of valve seat is higher (500°C). It may be concluded that not all heat flux may be conducted thru this contact. The remaining part of the thermal energy is drained through a spindle to the valve guide.

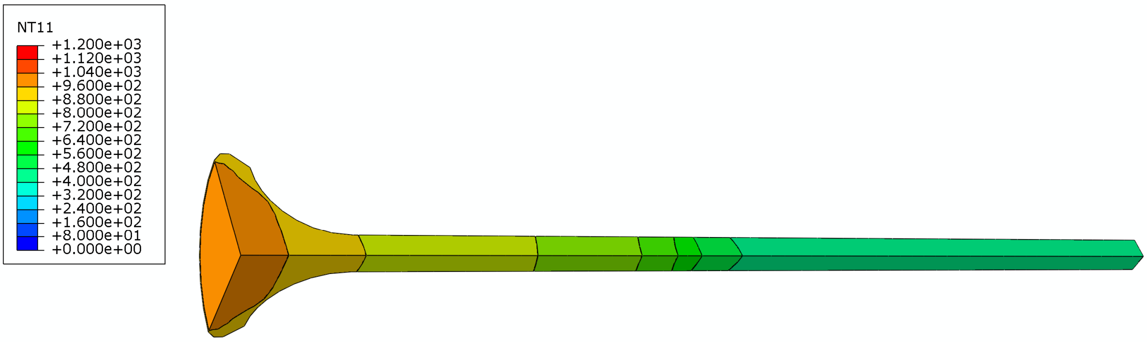

Fig. 4. Distribution of temperature [K] inside exhaust valve made of H9S2 steel for pre-heated engine

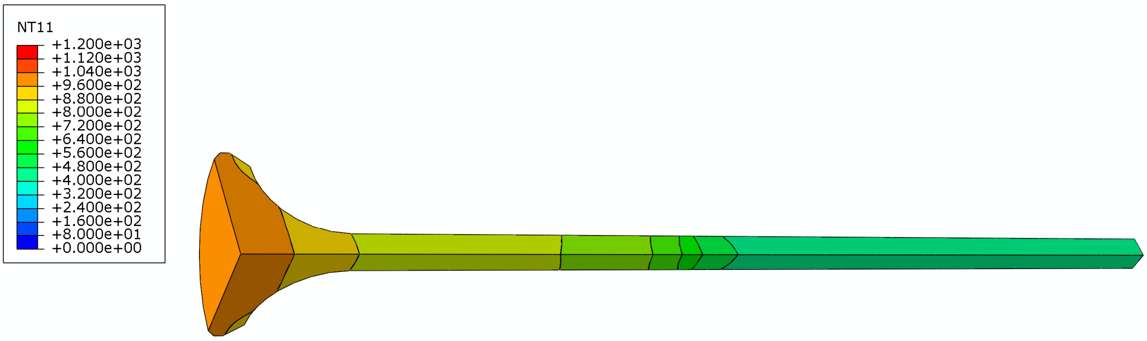

Fig. 5. Distribution of temperature [K] inside exhaust valve made of CPT for pre-heated engine

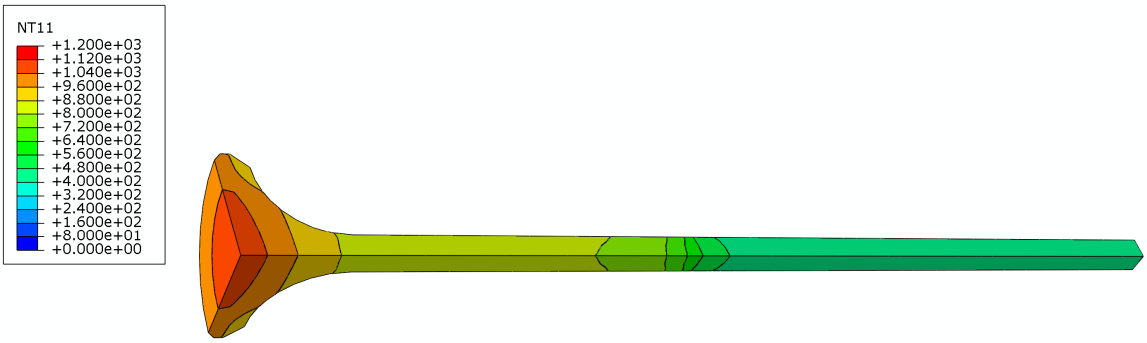

Fig. 6. Distribution of temperature [K] inside exhaust valve made of Ti6Al4V titanium alloy for pre-heated engine

Distribution of equivalent Huber-Mises stress inside the valves made of different materials is shown in Figs. 7-9. Internal stress observed in the engine valves is caused by thermal expansion of the material from which they are made. As it was mentioned before, due to the different boundary conditions, various parts of the valve heat up to different temperatures. At regions where temperature gradients have a high value large internal stresses are induced. Although the coefficient of thermal expansion for all analyzed materials, i.e. valve steel, CPT and TiAl6V4 titanium alloy is similar (from $8.4x10^{-6}$/K to $10x10^{-6}$/K) differences in the distribution of internal stress for valve made of particular material may be observed. The most significant internal stress is present inside the valve face. The reason of such behavior is following: the bottom of valve face is imposed to hot gases with average temperature equal to 1000^{o}C, top of the face is located in the outlet channel where average temperature is equal to 600^{o}C, the valve seat is in contact with socket which temperature is equal to 350^{o}C and the middle part of face is cool down by heat transfer to the valve guide. The internal stress distribution is determined by temperature gradients, coefficient of thermal expansion, thermal conductivity, Young’s modulus. The lowest internal stress inside valve face equal to 20 MPa is present for the valve made of CPT (Fig. 8). For the valve made of H9S2 steel the stress is higher (equal to 40 MPa). The highest stress values equal to 70 MPa were found in the valve made of Ti6Al4V titanium alloy. The basic difference between CPT and titanium alloy from point of view of physical properties is in the thermal conductivity value, which is 2.5 times higher for the CPT than for alloy. The other properties are very close. Therefore it may be concluded that thermal conductivity value is most important for lowering of internal stresses in the valve. The differences of temperature in particular valve regions are quickly lowered due to high capability to transfer a heat flux. It makes possible to reduce temperature gradients and as a consequence internal stress. Despite the fact that valve steel is characterized by even higher thermal coefficient than CPT alloy the internal stress is more significant than for CPT. This behavior is related to value of coefficient of thermal expansion which is higher for steel than for CPT.

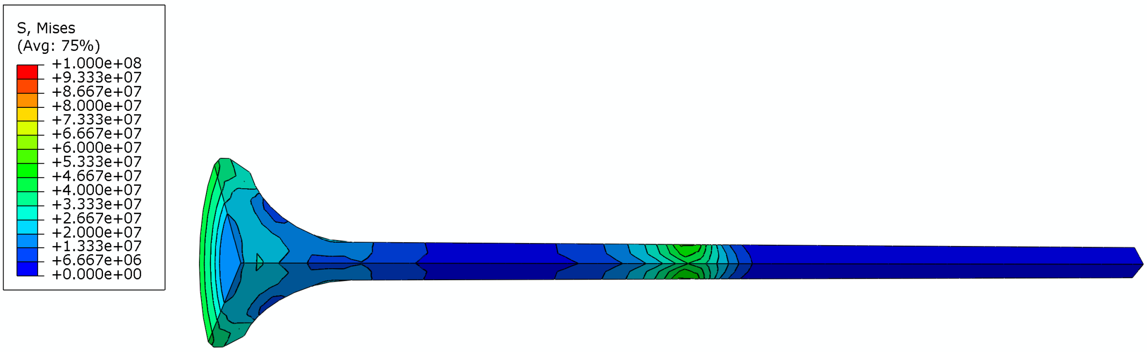

Fig. 7. Distribution of Hubera-Mises equivalent stress due to thermo-mechanical loadings inside exhaust valve made of H9S2 steel for pre-heated engine

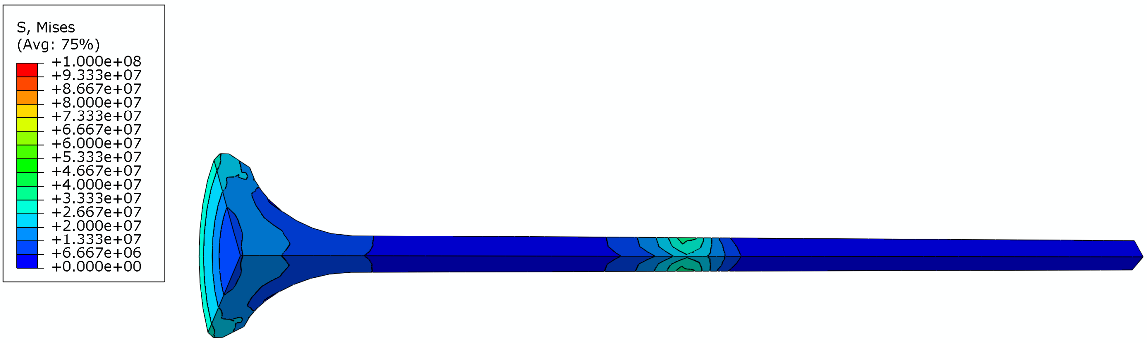

Fig. 8. Distribution of Hubera-Mises equivalent stress due to thermo-mechanical loadings inside exhaust valve made of CPT for pre-heated engine

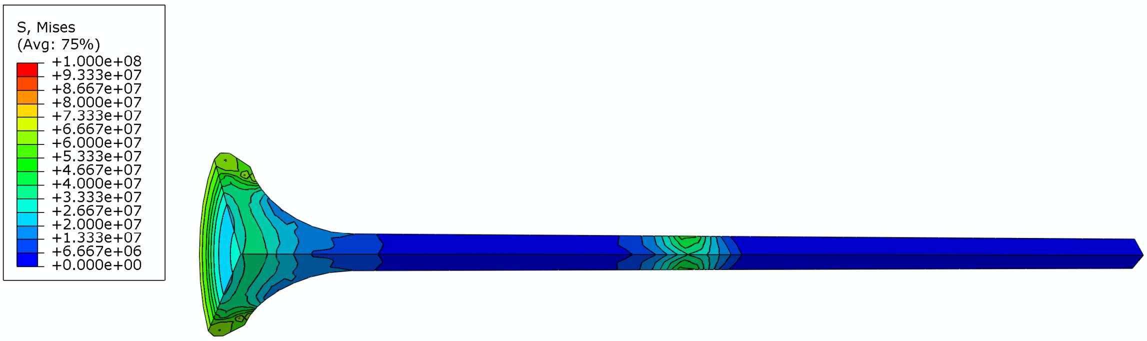

Fig. 9. Distribution of Hubera-Mises equivalent stress due to thermo-mechanical loadings inside exhaust valve made of Ti6Al4V titanium alloy for pre-heated engine

Summary

The difference of the thermal conductivity of H9S2 valve steel, CPT and Ti6Al4V titanium alloy induces various temperature distribution inside valve made of particular material despite the fact that the same boundary conditions were applied. The highest temperature reaching 900^{o}C was found in the valve face region for valve made of Ti6Al4V titanium alloy. For other materials the maximum temperature was equal to 700^{o}C. On the basis of simulation it was determined, that highest internal stress were present in the valve made of Ti6Al4V titanium alloy, whereas the lowest internal stress were predicted for CPT.

Acknowledgements

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