



Impact of the cam and follower cooperation and of lubrication on the cam wear

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ABSTRACT

Purpose: The paper provides an analysis of the reasons for excessive wear of the cam/follower system components based on physical and mathematical models developed to describe the impact of selected material, technological and operational factors. Owing to the comparison between the calculation results obtained and the actual cam wear values, it was possible to assess the correctness of the wear models taken into consideration.

Design/methodology/approach: The research in question included preparation of a mathematical cam wear model developed by way of dimensional analysis as well as finite element (FEM) based structural models for a cam/follower system. The aforementioned FEM models were noted in a parametrical form using macro commands of the COSMOS/M system, and hence it was possible to analyse contact problems in various cam positions and change the selected analytical parameters (e.g. dimensions, material parameters).

Findings: The main reasons for excessive cam wear include inferior quality of the cam and follower frictional couple lubrication as well as edge-type cooperation between the cam and the cam follower. At the same time, a significant impact on the wear is exerted by hardness of the cam and its follower.

Research limitations/implications: Wear of cams and cam followers operating in timing gear systems of vehicle combustion engines takes place as an effect of friction occurring in presence of lubricant. During standard operation, components of the cam/follower system may be subject to an excessive or accelerated wear process. This study is an attempt to establish the reasons for this phenomenon to occur in order to control such cases.

Originality/value: In order to counteract the phenomenon of accelerated wear of cams, one should consider increasing the required hardness of their working surfaces.

Keywords: Cam; Cam follower; Wear

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

One of the systems exerting the most significant impact on a combustion engine's operation is the timing gear. A particularly

responsible function in this system is performed by a tribological couple of a cam and a cam follower. Components of this couple are usually subject to wear of small intensity and their service life is sufficiently long. However, it can happen that accelerated wear of cams and cam followers should occur during operation. In such

cases, those components may require replacement as soon as after merely several hundred kilometers of a car's mileage. It is particularly difficult to establish the reasons for this phenomenon. The paper provides an analysis of the reasons for excessive wear of the cam/follower system components based on physical and mathematical models developed to describe the impact of material, technological and operational factors. Owing to the comparison between the results obtained and the actual cam wear values, it was possible to assess the correctness of the wear models taken into consideration.

Durability of the cam/follower frictional couple components may be conditional to their wear. It is defined as a process of gradual deterioration understood as the components losing their operational properties. Material properties are very significant in such kind of processes, for example surface tension [8, 9] and quality of the process [11]. It is caused by input functions as well as physical and chemical factors affecting the components throughout their entire service life [1]. The notion of a wear process is also related to wear as such, being an outcome of the said process expressed in the appropriate units of measure, e.g. length (linear wear), volume (volumetric wear) or mass (mass wear) [2,10].

2. Wear of the cam/follower frictional couple components

Wear of cams and cam followers operating in timing gear systems of vehicle combustion engines takes place as an effect of friction occurring in presence of lubricant, namely engine oil. Durability of these components should match the engine's service life. Their wear should be little intense [3]. However, it turns out in practical operation that components of the cam/follower system may be subject to excessive wear [3-7] (Fig. 1). It may take place after the engine runs an insignificant mileage, i.e. from several to several hundred kilometers [5,7]. The excessive cam wear is also accompanied by accelerated wear of cam followers (Fig. 1b) [5].

The factors influencing excessive wear of the cam/follower system components may be divided into the categories of material related, technological and operational. The material factors include chemical composition, surface layer and core structure, surface layer hardness and quenched layer thickness. The surface layer properties depend on the graphite size and arrangement as well as the structure of the matrix usually composed of martensite and retained austenite. Fractions of these components are decisive for the surface layer hardness as well as the internal stresses which may contribute to the surface layer fatigue cracking by decreasing the number of cycles necessary for it to be initiated. In such a case, the fatigue wear intensity of a cam's surface layer may be considerably increased compared to its abrasive wear intensity, which may subsequently contribute to excessive cam wear and damaging of the cam/follower system. The technological reasons for excessive wear of the cam/follower frictional couple may result from an incorrect technological process (heat treatment), and particularly from inappropriate parameters of the cam induction quenching and tempering, poor mechanical working (grinding) or a failed choice of the engine's timing gear system components during assembly. Nonconformity with the required heat treatment parameters may cause a decrease

of the surface layer hardness and an increase of abrasive wear. Even more negative impact may be exerted by what is referred to as grinding cracks occurring during poor quality grinding. They can initiate fatigue cracks which, after a short period of propagation, cause rifts and excessive fatigue wear of cams. The operational reasons for excessive wear of the said frictional couple components may include inappropriate pressure forces and poor lubrication. Increased pressure forces are triggered by technological factors and an additional operational factor, namely an increased valve clearance. Deteriorated lubrication may be due to cams not being immersed in oil because of its low level or engine tilt, small oil pressure in the lubrication system and oil properties (e.g. too low viscosity). All these aspects can lead to excessive abrasive wear caused by an increase of pressure and friction forces as well as fatigue wear in the surface layer.

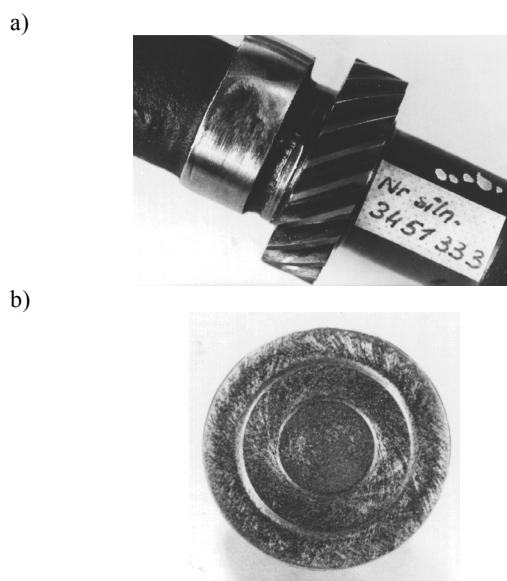


Fig. 1. Worn-out components of a cam/follower system (on car mileage of 154 km) [5]: a) timing gear cam, b) cam follower

To sum up the above consideration on the reasons for excessive wear of timing gear cams and cam followers, one may conclude that no single factor causing this kind of wear has been established in the literature of the subject. However, having analysed the related publications, the probable reasons for excessive wear of cams and cam followers can be systematised according to their priority. Authors of the related studies claim that the following factors matter:

- excessive pressure forces caused by edge-type cooperation between cams and cam followers,
- poor lubrication,
- cam and cam follower surface layer hardness.

3. Scope of research

The research consisted in testing of excessively worn-out components of a cam/follower system. The tests in question

comprised geometry measurements for worn-out camshaft cams from FIAT Cinquecento 700. They enabled determination of wear of these cams as well as its statistical description. Worn-out cams and cam followers were subject to metallographic tests using a light microscope and a scanning one in order to establish their material structures and wear mechanisms. The scanning microscope was used to examine the areas near the wear surface. The observations conducted proved that nearly in all cases, in the cams being examined, both excessively and properly worn-out, there were irregularities due to ridging and scratching accompanied by micro-cracking. Sample results of the metallographic tests of cams have been provided in Figures 2 and 3. An analysis conducted on the metallographic test results obtained enabled excluding certain possible reasons for the excessive wear of cams and cam followers, and proved the necessity of further laboratory and simulation tests.

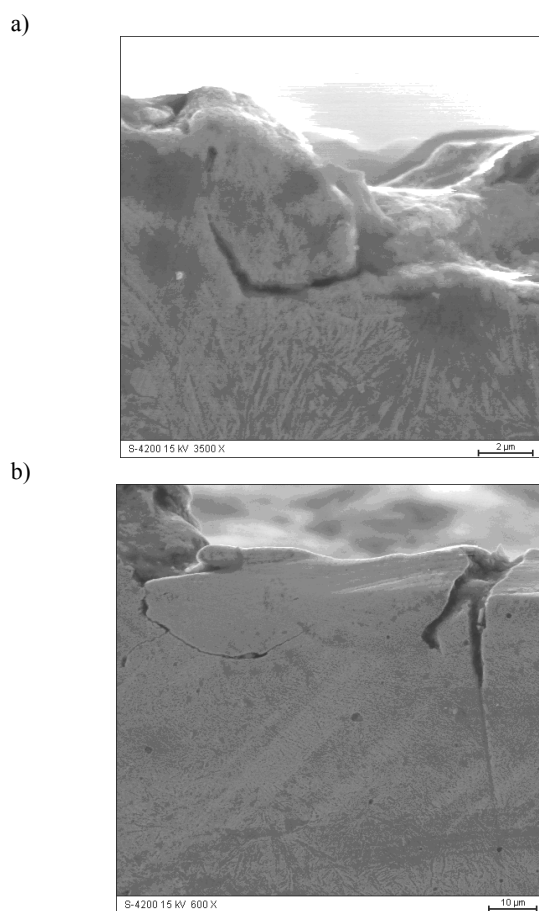


Fig. 2. a) visible ridges, scratches and micro-cracks near the wear surface (correct cam, nital etching, magnification of 3500x), b) visible micro-cracks near the wear surface (damaged cam, nital etching, magnification of 600x)

The laboratory studies comprised testing of abrasive and fatigue wear as well as metallographic assessment of wear mechanisms. The laboratory tests of abrasive wear of specimens conducted at a T-01M station in a mandrel and disk system were

performed in order to establish the wear and durability dependence on material parameters of a cam and a cam follower, and on the values being characteristic of the frictional couple cooperation. These dependences enabled calculations of wear and durability of cams which made it possible to analyse the reasons for their excessive wear. The calculations in question were verified by comparing their results with the results of tests concerning wear of camshaft cams.

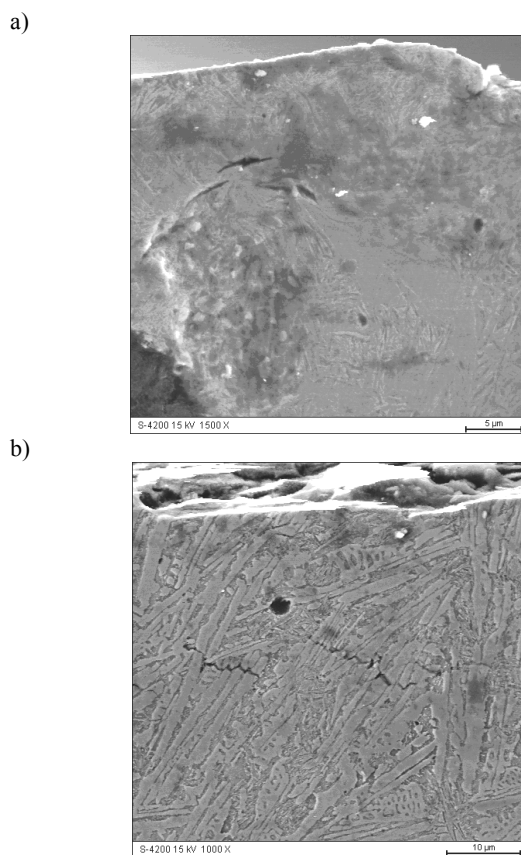


Fig. 3. a) near-surface micro-cracks in the modular graphite zone (correct cam, nital etching, magnification of 1500x), b) near-surface micro-cracks in the eutectic structure (damaged cam, nital etching, magnification of 1000x)

The first group of model calculations, closely linked with the laboratory studies, was conducted using a mathematical model of cam wear previously developed for the sake of a dimensional analysis of the factors decisive for the wear and its intensity. It enabled determination of the cam wear intensity on preset material properties of the friction node components and conditions of the couple's operation. This model entails numerical coefficients established based on results of laboratory studies of abrasive wear. Using this model in cam wear calculations requires establishing their operating conditions for the purpose of which numerical examinations were conducted by application of the finite element method (FEM) enabling the stresses occurring between the cam and the cam follower to be determined.

Based on an analysis of the results of wear intensity calculations obtained as a result of the geometry measurements for excessively worn-out camshaft cams, one could conclude that the most probable reasons for excessive wear of cams and cam followers included inferior lubrication quality resulting from too low oil viscosity, too high oil temperature or low pressure in the lubrication system which may be accompanied by edge-type cam and follower cooperation.

4. Cam wear model

In the course of the laboratory studies of abrasive wear, linear wear intensity of specimens made of nodular cast iron was determined for different operating conditions and material hardness values. The results obtained enable establishing the dependence between wear intensity and the factors altered while testing. One of the solutions to determine these dependences recommended in literature is to use a wear model developed through dimensional analysis [2]. According to these recommendations, the following mathematical form of linear wear intensity was assumed:

$$\frac{Z}{l} = a_0 \left(\frac{p_0}{H_1} \right)^{a_1} \left(\frac{H_2}{H_1} \right)^{a_2} \mu^{a_3} \quad (1)$$

where: Z - linear wear being a liner decrement of the specimen (i.e. cam) dimension [m], p_0 - maximum Hertz pressure at the contact surface [Pa], H_1 , H_2 - hardness of frictional couple components (the examined and the cooperating one accordingly) [HB], l - friction distance [m], μ - friction coefficient, a_0 , a_1 , a_2 , a_3 - coefficients established by regression of the laboratory wear test results.

The above function was transformed into a linear function by finding logarithms for both sides of the equation (1). It enabled using the linear regression to determine coefficients a_i . Average values of these coefficients along with standard deviations have been provided in Table 1. The quality of the regression performed was determined using a square of the R^2 correlation coefficient. The R^2 value obtained came to 0.8 (see Table 1) which implied good correlation of results of the model calculations and the laboratory tests.

Sample calculation results obtained by application of the cam wear model have been provided in Figures 4 and 5. The wear model coefficients provided in Table 1 for equation (1) were established for pressure p_0 expressed in MPa and hardness H_1 and H_2 expressed in HB. The wear intensity calculated based on the model is then expressed in mm of linear wear for mm of friction distance, and hence relatively small values are assumed. As shown in Figures 2 and 3, it was converted to mm/km of friction distance multiplying it by 10^6 .

The dependences obtained by application of the wear model imply that the factors the model takes into consideration exert impact on the wear of both specimens and cams in operation. The largest impact on wear intensity is exerted by the friction coefficient (Fig. 5). Therefore, it is probable that the reason for

excessive wear of camshaft cams is poor lubrication causing the said coefficient to increase. Wear intensity also depends on pressure force (Figs. 4 and 5). Hence increased pressures between a cam and a cam follower due to edge-type cooperation between these components may also accelerate their wear. Consequently, the calculations based on the wear model enable assessment of the cam wear and the impact exerted by the individual factors on the possibility of its excessive wear. However, a prerequisite for those calculations to be conducted is knowing the cam and the cam follower operating conditions. For that purpose, a finite element based model of a cam/follower system was developed and subsequently used to establish the pressures occurring between these components.

Table 1.
Wear model coefficients

Coefficient	Average value	Standard deviation
a_i		
$\ln a_0$	-11.39	0.36
a_0	$1.13 \cdot 10^{-5}$	-
a_1	1.00	0.11
a_2	2.69	0.42
a_3	3.23	0.13
R^2	0.80	-

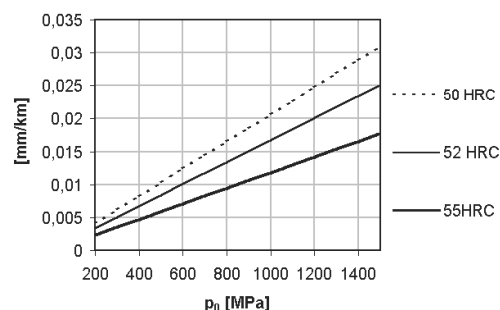


Fig. 4. Dependence between a cam's linear wear intensity and pressure force as well as its hardness on friction in presence of oil ($\mu = 0.1$)

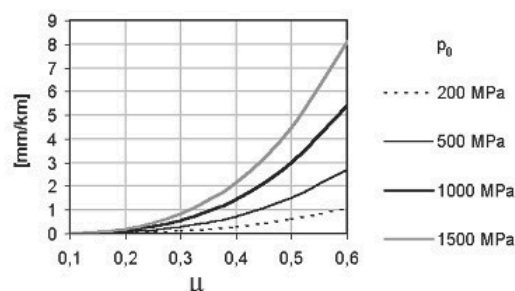


Fig. 5. Dependence of linear wear intensity of a cam of the hardness of 55 HRC on friction coefficient and pressure assuming the cam follower hardness of 59 HRC

5. FEM analysis of a cam/follower system

The structural FEM models developed for a cam/follower system have been illustrated in Figure 6. Figure 6a provides a detailed image of the cam and follower model, and Figure 6b shows a simplified model. The fact that a simplified model was assumed for the sake of calculations resulted from the fact that the detailed model was too large and the results obtained in the contact zone inaccurate compared to the results established for the Hertz model. In order to obtain accurate results for the contact zone one should first appropriately compact the elements of the contact zone between the cam and the cam follower (Fig. 6b).

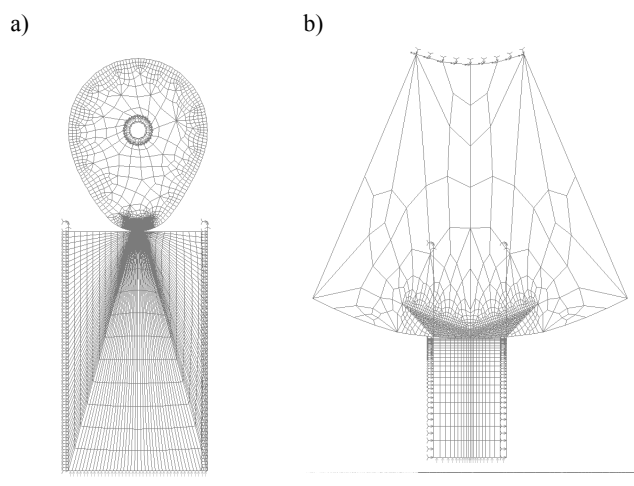


Fig. 6. The cam and follower model: a) detailed, b) simplified

The grid of finite elements was generated using the measurement data describing a lift of a new reference cam. The cam support used enables simulation of its slight rotation. The cam follower is pressed by the pressure generated by a force depending on the cam position, and it can move vertically. The said model was noted in a parametrical form using macro commands of the COSMOS/M system, and hence it allowed for analysing contact tasks in various cam positions and changing the selected analytical parameters (e.g. dimensions, material parameters etc.). Sample maps of stresses occurring in the cam and cam follower contact zone have been provided in Figure 7.

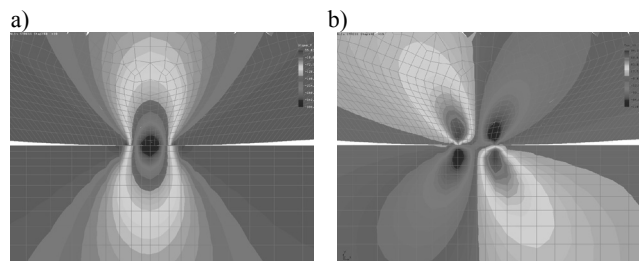


Fig. 7. Map of stresses in the cam and cam follower contact zone: a) normal, b) tangential

The values of normal and tangential stresses obtained for the contact zone match the values established based on the Hertz equations well.

6. Impact of the cam and follower cooperation and of lubrication on the cam wear

The wear model and the FEM model which allow for determination of the stresses occurring in a cam/follower system enable analysis of the reasons for excessive wear of cams by establishing the impact exerted by the most significant material, technological and operational factors on the wear and durability of cams. The study in question entailed the dependence of wear and durability on edge-type cooperation between a cam and a cam follower (modelled through a decreased contact width) and lubrication quality (determined by application of the friction coefficient). In order to determine whether the edge-type cooperation between the cam and the cam follower may cause excessive wear of cams, using the FEM model of the cam/follower system, the Hertz pressures were established on different contact widths b . Next, by inserting those stresses into equation (1), the linear wear intensity in the function of cam's angle α was established. The linear wear intensity calculated based on the wear model determines the wear (in mm) per 1 km of friction distance. Whereas in the tests of worn-out camshaft cams, a different wear intensity was established, namely the operational one expressed as a relationship between cams' linear wear and car mileage. In order to be able to compare the results of wear model calculations with the results of cam tests, the friction distance was converted into car mileage. The calculation results obtained with regard to relative operational wear intensity of a cam conditional to angle α on different widths b of the contact between the cam and the cam follower have been depicted in Figure 8. The wear in question is the largest on angle $\alpha = 36.5^\circ$ regardless of the friction coefficient value or the contact width. Therefore it is decisive for durability of cams. A comparison of the model calculation results and the actual state of matters has been provided in Figure 9 which depicts a median of the relative operational wear intensity of cams obtained based on measurements of worn-out cams (marked as "Exp") collated with the curves obtained in the calculations illustrated in Figure 8b. Having analysed the curves depicted in Figure 9, one may claim that the curves are qualitatively similar. All graphs have two maxima. Angles α , on which the maxima occur, are similar. The shape differences for the curves being analysed result from the impact of wear, changing the cam profile, exerted on the pressures and the contact dimensions being decisive for further wear of cams. As a result of what is referred to as "feedback", the operation curve becomes a little smoother, and the wear intensity maxima are slightly shifted towards smaller angles. For the first maximum, on angle $\alpha = -40^\circ$, the shift does not exceed 5° being a value exactly corresponding to the operational measurements. For the maximum decisive for the cam durability, the difference comes to ca. 6.5° .

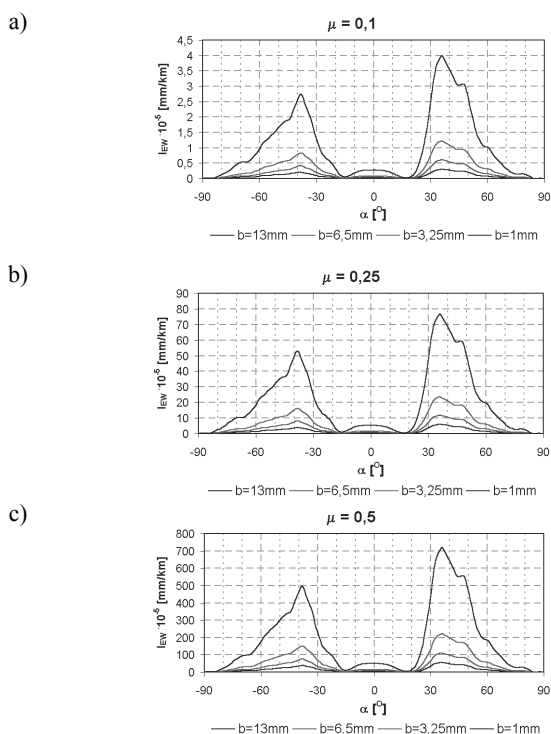


Fig. 8. Dependence of cam's operational wear intensity I_{EW} on angle α on different values of width b of the cam and cam follower contact (cam hardness of 55 HRC and cam follower hardness of 59 HRC) for the friction coefficient equalling: a) 0.1; b) 0.25; c) 0.5

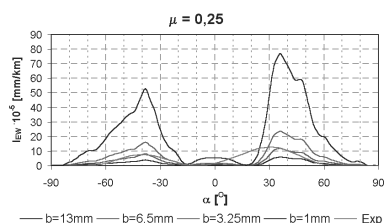


Fig. 9. Operational dependence of cam's relative wear intensity I_{EW} on angle α calculated based on the model for the friction coefficient of 0.25 and based on the operation ("Exp")

7. Conclusions

Wear intensity and durability of cams are strongly dependent on the value of friction coefficient (lubrication). An increase of the friction coefficient from 0.1 (lubricated contact) to 0.5 (dry friction) reduces the cam durability by two orders of magnitude (Fig. 8). Also the contact width (edge-type cooperation between a cam and a cam follower) exerts a significant impact on durability of cams. An increase in this width from 1 to 13 mm increases the durability by more than a dozen times (Figs. 8 and 9). Furthermore, the cam durability is considerably affected by the material the cam and the cam follower are made of. Raising the cam hardness from 50 to 55

HRC increases its durability (Fig. 4). A similar effect is observed when the cam follower hardness is reduced from 59 to 53 HRC. By comparing the model calculation results with the actual state of matters, one could draw the following conclusions pertaining to the reasons for excessive wear of cams.

1. The main reason for excessive cam wear is inferior quality of the cam and follower frictional couple lubrication which manifests itself in an increase of the coefficient of friction between these components. At the same time, one can observe a considerable impact of the contact width as well as the hardness of cams and cam followers on their wear.
2. In order to counteract the phenomenon of accelerated wear of cams, one should consider increasing the required hardness of their working surfaces.

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