Effect of surface layer depth on fatigue life of carburized steel and analysis of fracture proces

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Abstract Nowadays, it has been strongly required to extend the fatigue life of machine components and structures due to economic. To meet this demand, various surface refining processes have become major interest because they can provide additional surface properties such as high strength, thermal barrier, corrosion and wear resistance to structural materials. One of the most commonly used refining techniques is carburizing. The depth of carburized layer is one of the most important parameters determining fatigue endurance of machine components. This work deals with fatigue life dependence on carburized layer depth.

Introduction

In materials science, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the materials. Fatigue occurs when a material is subjected to repeated loading and unloading. If the loads are above a certain threshold, microscopic cracks will begin to form at the surface. Eventually a crack will reach a critical size, and the structure will suddenly fracture.

By changing surface layer properties of machinery parts it is possible to increase considerably their load-capacity. One of the ways to obtain high complex surface physical and mechanical properties of metallic materials such us hardness, wear resistance, contact fatigue and others are chemical heat treatment method as nitriding or carburizing [1-3]. Also, the carburizing is one of the basic methods for increasing fatigue strength of structural metallic materials [2-5]. Positive effect of carburized layer can be explained by increasing the compressive residual stresses in the surface.

Experimental material and carburizing technology

Two types of specimens with different geometry were used. The cylindrical specimens were subjected to torsion and bending fatigue tests. The flat samples were tested only in bending loading. The fatigue experiments were carried to the final fracture. The cylindrical specimens were made of the stainless steel with four different surface layer depths were obtained by two different carburizing temperetaures. The different carburizing temperatures caused different concentrations of C in

surface layers, this means that the layers with (roughly) same thickness differs in hardness.The flat sampes were made of the stainless steel with two different surface layer depths. The fatigue experiments were made at the room temperature. Geometry of both type of samples is shown in Fig. 1. The cylindrical specimens were made of the steel ČSN 41 4220 (equivalent to C15E EN 10084-94). The chemical composition of the materials is displayed in Table 1.

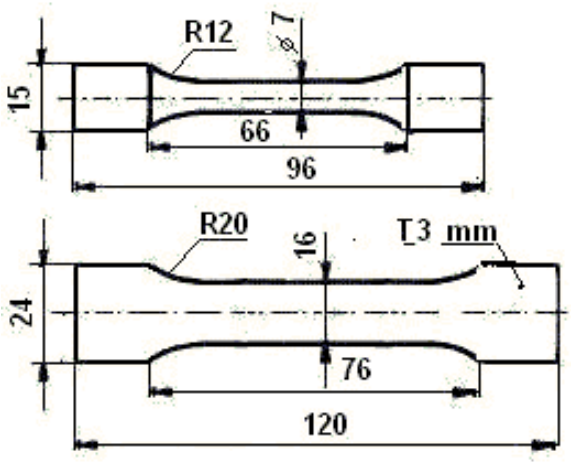

Fig.1. Specimens geometry. Thickness of plate specimen is T_S = 3 mm.

Table 1. The chemical composition of the steel ČSN 41 2122

chemical element [%] / According to	C	Mn	Si	P	S	Cr	Mo	V	Cu	Ni
Standard: ČSN EN 10 204	0.16	1.21	0.21	0.012	0.029	0.9			0.23	0.09
spectrometric measurements	0.13	1.25	0.15	0.01	0.002	1.02	0.05	0.03	0.22	0.05

The basic mechanical properties of the material are minimal yield strength $\sigma_{y,min}$= 588 MPa and ultimate strength S_u= 785 MPa. One of the surface treatment methods improving the some materials properties is carburizing. Chemical treatment is kind of surface hardering. Carburizing is a heat treatment process in which steel is heated in the presence of another material (most often in the range of 850 to 950 °C) which liberates carbon as it decomposes. Depending on the amount of time and temperature, the affected area can vary in carbon content. Longer carburizing times and higher temperatures lead to greater carbon diffusion into the part as well as increased depth of carbon diffusion. When the iron or steel is cooled rapidly by quenching, the higher carbon content on the outer surface becomes hard via the transformation from austenite to martensite, while the core remains soft and tough as a ferritic or pearlite microstructure.
In gas carburizing, commercially the most important variant of carburizing, the source of carbon is a carbon-rich furnace atmosphere produced either from gaseous hydrocarbons, for example, methane (CH_4), propane (C_3H_3), and butane (C_4H_{10}), or from vaporized hydrocarbon liquids. Parameters of gas-carbunizing process are displayed in Table.2. Test samples used for fatigue test were embedded in the activated carbon inside a steel pot which was then tightly sealed with clay cover to prevent the CO from escaping and prevent unwanted furnace gas from entering the steel pot during heating. The

furnace temperature was adjusted to the required temperature T_C (860 and 940°C). The typical times of carburizing t_{TC} were: 3, 4, 5 and 6.5 hours at a temperature of 860 °C and 1, 2.5, 3.5 h and 4.5 hours at a temperature of 980 °C. In this case the application of the atmosphere composed of 23% CO, 36% H_2, 40% N_2, 2% CH_4 and 2% (CO_2 + H_2O). In the role of carburizing agents are in this case CO and CH_4. The time of cooling was t_{cl} = 2.5 hours for samples carburized at T_C = 860°C and for samples carburized at T_C = 940°C was used t_{cl} = 3.5 hours. After carburizing the samples were twice hardened, first at 990°C and again at 780°C. In both cases were endurance time at hardening temperature t_{eh} = 35 min and time of cooling t_{cool} = 3 min. As a cooling medium was used water solution with 10% NaOH. The specimens were tempered at 180°C (1.5 hours). The obtained depth of hardened layer and its parameters are shown in Table 2. The plate specimens are carburized only temperature T_C = 860°C and its surface layers are 0.65 and 0.45 mm.

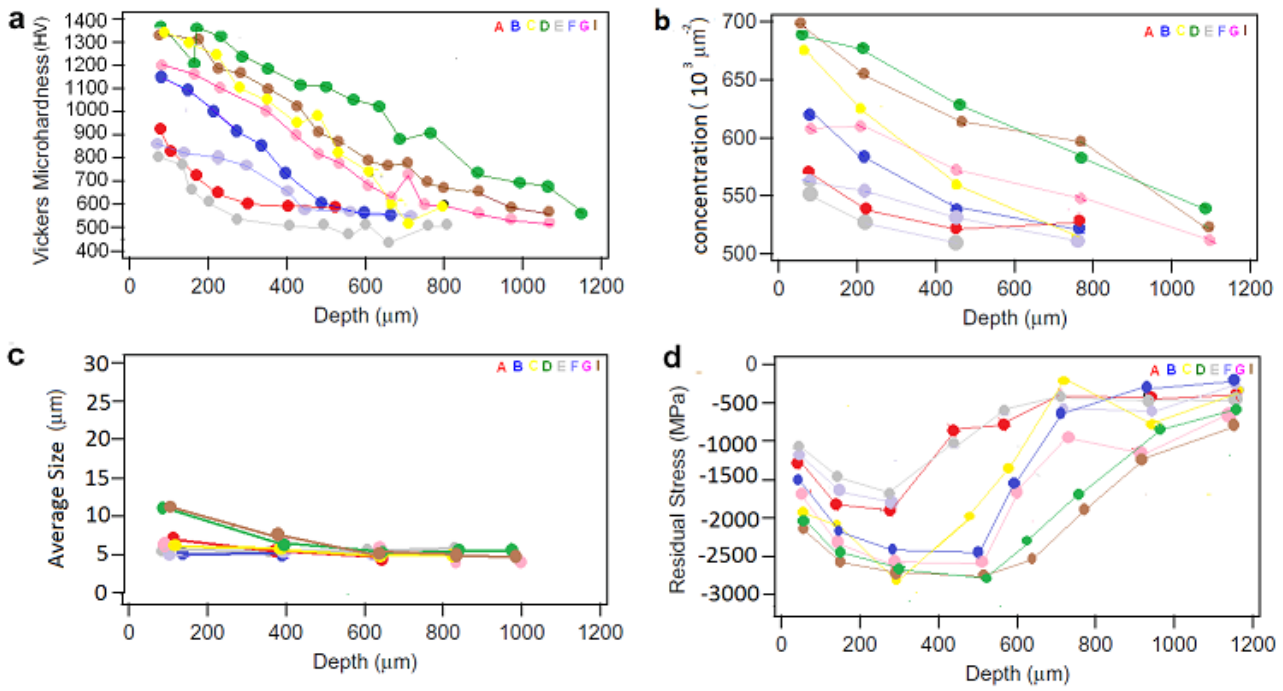

Fig.2. (a) microhardness to the depth, (b) microhardness to the grain concentration,

(c) average size D_A of carbide graine to the depth,

(d) distribution of residual stresses across the depth.

Fig. 2(a). show microhardness measurements on the cases of the specimens. The micro-hardness profile measurements of the carburized case were performed using 9.81 N loads in Vickers hardness scale, and the effective case depth was defined as the distance below the surface where the hardness was equal to 500 HV. Fig.2 (b). shows relationship between microhardness and density (on the plane) of carbide particles. Fig.2(c) shows relationship between average size of carbide particles and depth for different carburizing temeprature and time. Fig.2 (d). shows distribution of residual stresses across the depth. The residual stresse were measured by X-ray diffraction method. The effect of an increased strengthening with decreasing grain size d is described by the well known Hall–Petch equiton:

$$\sigma_Y = \sigma_0 + k\frac{1}{\sqrt{d}}, \qquad (1)$$

where σ_y is the yield stress, σ_0 the 'friction stress' and k is the Hall–Petch factor which depends on the material and measures the relative hardening contribution of grain boundaries/interfaces. The difference between the average size of carbid grain (for different heat treatments) is not significant, but occurrence of extremely large grains grow with, see Fig. 3. From Fig. 2 and 3 is clear that, due to growth in the number of particles of all sizes average particle size remains approximately the same. Most of the particles are lamellar, lamellar ratio is L_V = 0.25 - 0.40.

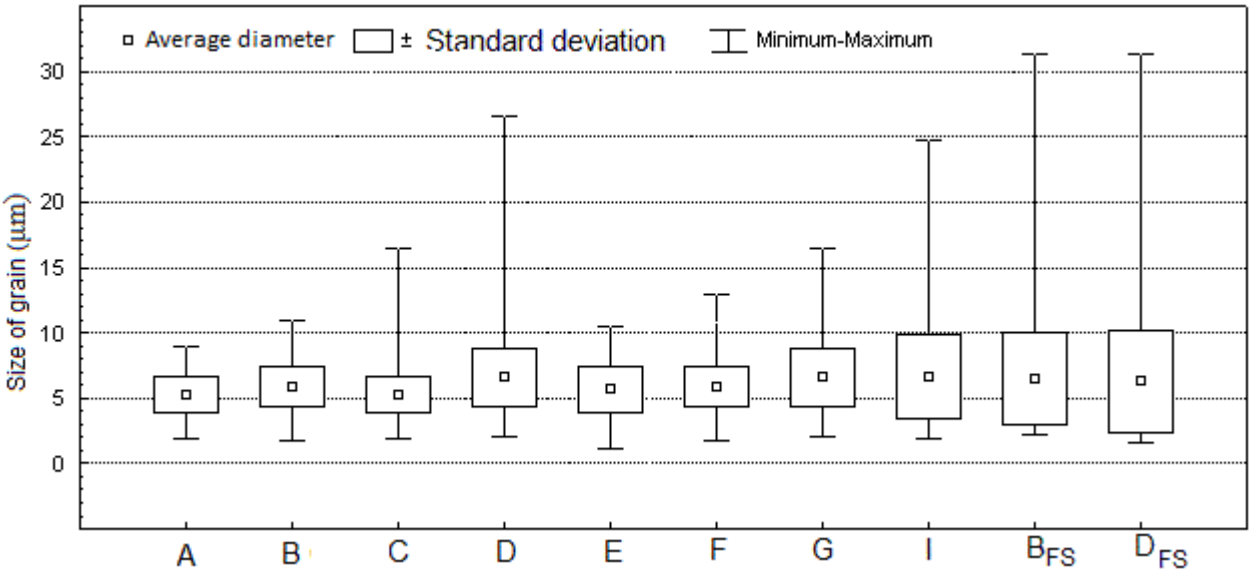

Fig.3. Size of carbide grains (subscription FS means flat samples).

Table 2. Parameters of basic carburizing technology

Sample	Surface layer depth h[mm]	Time t_{cl}[h]	T_C [°C]	Hardness [HV]	hardening		t_{eh} [min]	t_{cool} [min]
					T_{ch1}[°C]	T_{ch2}[°C]		
A	0.3	3	860	920	990	780	35	3
B	0.45	4	860	1150	990	780	35	3
C	0.7	5	860	1350	990	780	35	3
D	1.15	6.5	860	1370	990	780	35	3
E	0.25	1	940	800	990	780	35	3
F	0.4	2.5	940	850	990	780	35	3
G	0.65	3.5	940	1190	990	780	35	3
I	1.0	4.5	940	1340	990	780	35	3

A very important factor, influencing fatigue life of specimens, is the depth of surface film of carbides deposited onto the surface layer. A heterogeneous compound layer is often a site of an early fracture initiation. This was approved also in experiments, where the compound layer was mechanically removed by fine grinding [1,7]. It completely changed the type of fracture initiation particularly at high levels of loadings. Before this operation, fracture started from the specimen surface inside the compound layer. After the process of grinding, the epicentre of fracture transferred out of the diffusion layer into the specimen core. This alteration in fracture mode was accompanied by a significant increase in the fatigue life.

Fatigue tests and discusion

The cylindrical specimens were subjected to torsion and bending fatigue tests. The flat samples were tested only in bending loading. All tests were carried out to the final fracture of loaded specimen. S-N curves were drawn, see Fig. 4, 5 and 6. Vertical lines separate the region of crack initiation on the surface and the region where is typical subsurface crack initiation.

The comparison between carburized samples and tempered samples showed considerably higher fatigue resistence of carburized material. The long life of carburized specimens corresponds to the fracture initiation below the surface layer. Long life fractures usually reveal crack nucleation on the inclusion, but contrary to the nitrided specimen (see [1,8]) cracks do not have the characteristic shape of "fish eyes" with exactly with identifiable boundary between different crack growth ways (crack growth in a vacuum/ crack growth with oxidation). In the case of the thicker case depth exhibited a higher internal oxidation depth and amount at the surface. The subsurface oxide on the grain boundaries are most often crack initiation sites (about 60%). The crack initiation on non-metalic (oxide/ sulfide) inclusions is typical for all thicknesses of surface layers. Samples with a higher incidence of large grains of carbides, however, have a lower resistance in the low-cycle (samples D, I). The creation of subsurface cracks on inclusion can be explained as the result of the presence of residual stress in the surface layer. Residual stress prevents cracks on the surface of the sample. The value $K_{I,max}$ of the stress intensity factor on the surface of an ellipsoidal inclusion can be expressed as [1,8,9]:

$$K_{I,\max} \approx 0.65\sigma\sqrt{\pi\sqrt{A_P}}\ , \qquad (2)$$

where A_P is the area of a cross-section of the inclusion [9]. The square root of A_P corresponds to the effective inclusion diameter a_{ef} . In the case of D and I are present carbide particles larger than (sulfide/oxide) inclusions on which the cracks initiate in other cases.

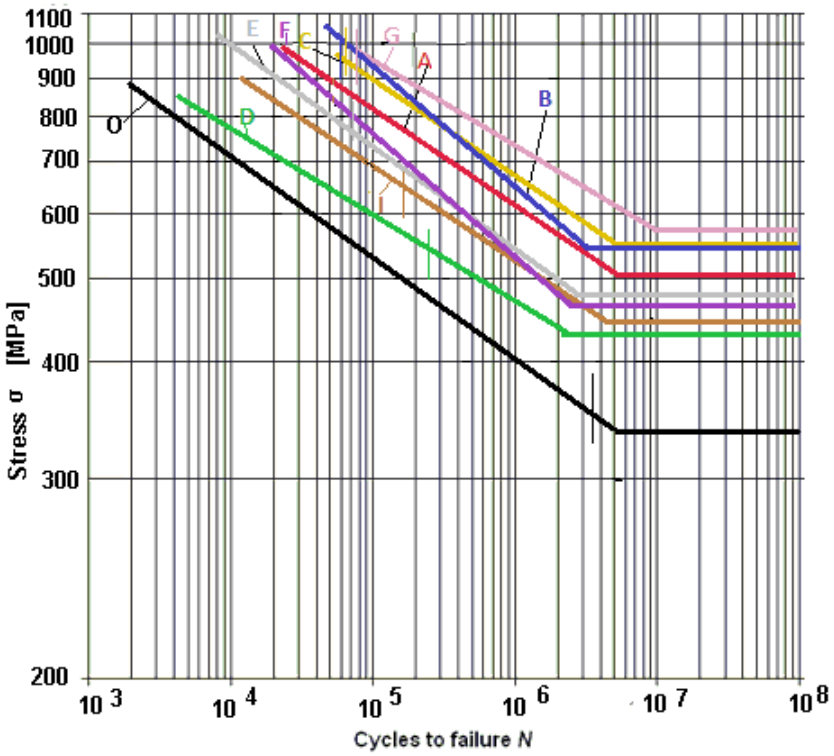

Fig.4. Wöhler curves for virgin (O) and carburized (A-I) specimens – bending.

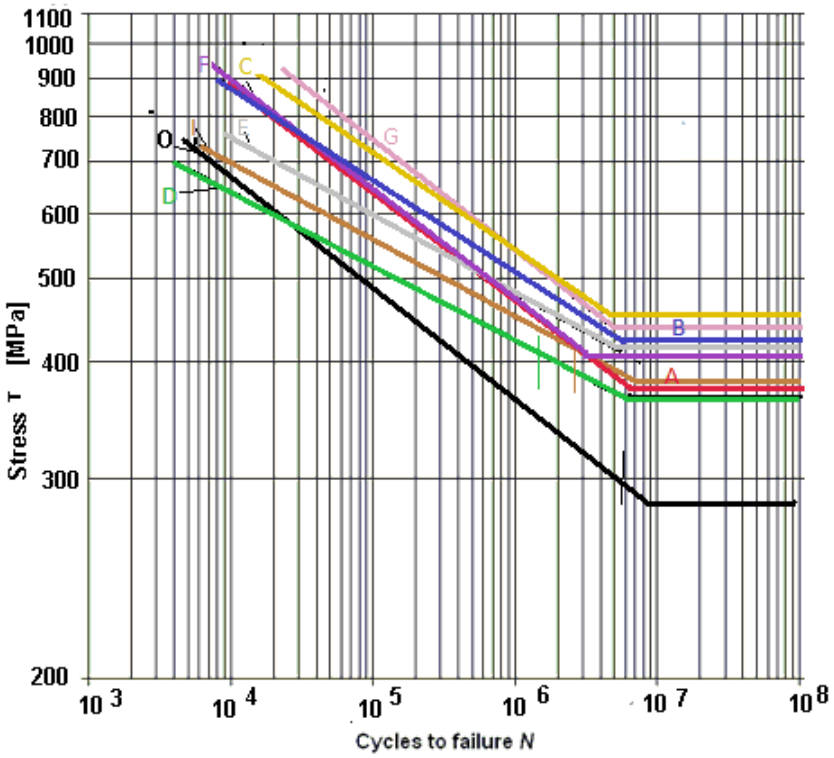

Fig.5. Wöhler curves for virgin (O) and carburized (A-I) specimens – torsion.

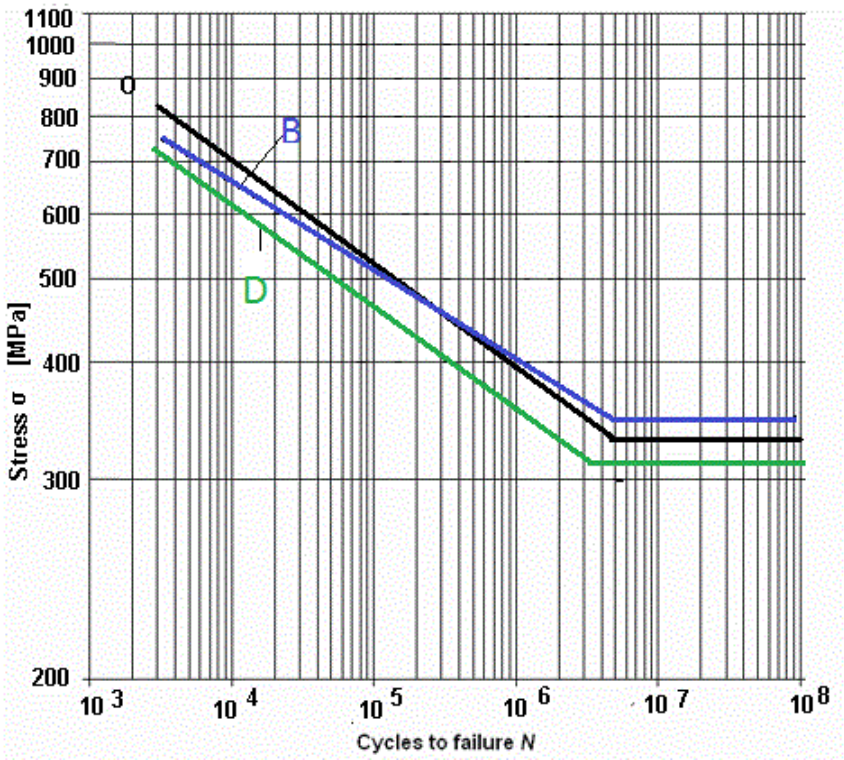

Fig.6. Wöhler curves for virgin (O) and carburized (A and C) specimens – bending, flat sample.

The specific problem is the flat samples. These samples are characterized by uneven coating. Diffusion of carbon ions in the thin edges is very intensive, in the edges is high concentration of carbides particles. In the thin sides of the flat sample is presence of great particles (diameter higher then critical) 100x higher than the broad side of the specimen surfaces. On these particles initiated cracks. This effect leads to a decline of fatigue life. Estimated optimal depth of the carburized layer is 0.55, see Fig.5.

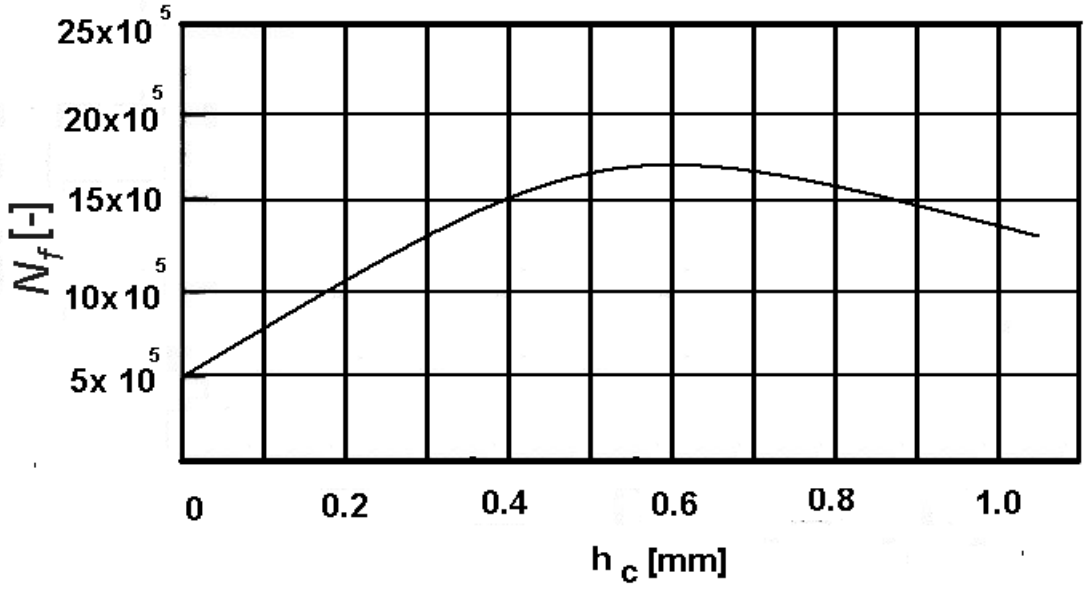

Fig.4. Dependence of the fatigue life on the layer depth.

Summary

The carburized steel showed considerably higher fatigue strenght compared with the untreated material. A fractography study revealed that different fatigue crack initiation mechanisms are active. Fatigue cracks initiated at a early stage of fatigue life near the boundary between the carburized layer and the core material. In the case of flat specimens the cracks initiated often narrow gauge edges of the sample. This fact can be explained by different thickness of surface layer at the edge of a flat sample.

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