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Rolling contact fatigue of hot-deformed powder steels with calcium microadditives

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Abstract. Fatigue damage of the surface layers of metal is a characteristic cause of failure of rolling bearings, gears and a number of other machine parts operating under cyclically repeated contact loads. Resistivity to the development of contact damage of steels obtained by hot forging porous blanks is determined by the presence of cohesive bonds between the particles of the base powder, as well as by the presence of non-metallic inclusions and grain size. The possibility of increasing the contact endurance of hot-deformed powder steels due to micro-doping with calcium has been studied. Iron powders with various content of impurities, as well as atomized powder of low-alloyed chromium-molybdenum steel were used as the basis for preparation of the blends. Calcium was doped as calcium carbonate. Mixing was performed in a planetary centrifugal mill. Samples for mechanical testing were obtained by hot forging porous blanks. After hot forging the samples were carburized to compensate for the loss of carbon in the surface layer. It has been established that doping calcium microadditives is favourable for increasing the energy content of damage under the conditions of exposure to contact-fatigue and bending loads. This is due to a decrease in the size of austenite grains at the expense of inhibition of their growth during the adsorption of calcium at the grain boundaries. Microalloying with calcium changes the localization of seats of contact fatigue damage. In samples-witnesses without microadditives of calcium cracks originate near non-metallic inclusions of sharp-angled shape in the near-surface zone. In microalloyed specimens the cracks are located in the subsurface layer in the area of Hertz maximum shear stresses.

1. Introduction
Contact endurance of steel is largely determined by the presence of non-metallic inclusions and grain size [1]. Increasing contact endurance is provided by using various types of surface hardening: laser treatment, carbonitriding, nitriding, surface plastic deformation (SPD), etc. [2-7]. During the carburization residual compressive stresses (200–300 MPa) appear in the surface layer of the processed parts [8].

According to some authors the presence of a limited amount of retained austenite in the surface layer is desirable. The presence of retained austenite increases the impact strength and fracture toughness of steel. Inclusions of austenite promote relaxation of peak stresses and reduce the risk of brittle fracture [9, 10]. However, it should be noted that the formation of "soft" zones of retained austenite on the surface as a result of decarburization during heat treatment can lead to a decrease in contact endurance; therefore, the amount of retained austenite must be reduced [11]. An effective method of reducing the amount of retained austenite is the SPD, which ensures the formation of residual compressive stresses and dislocation substructure in the surface layer [5]. However, the use of SPD implies the need to include in the process an additional operation, which increases the cost of manufacturing products.

The resistivity to brittle fracture development (including when exposed to contact loads) of steels obtained by hot forging porous blanks (HFPB), in addition to these factors, is also determined by the presence of cohesive bonds between the base powder particles [12, 13]. Oxide films on the surface of particles prevent the formation of interparticle joining, which is one of the main reasons for limiting the use of HFPB in the manufacture of parts for rolling bearings [14, 15]. The presence of shear components during hot deformation of a porous preform (in particular, in the presence of extrusion elements) causes the fragmentation of surface films of impurities, which improves the quality of interparticle joining [16]. However, in the manufacture of structural products of various shapes it is not always possible to implement shear deformations during the performing hot repressing.

Microalloying is a promising method for improving the quality of interparticle joining and reducing the negative effect of impurities [17, 18]. The development of new lean steels and alloys containing microadditives of elements that enhance the mechanical and functional properties is a recent general trend [19]. In particular, the new prealloyed powder Astaloy CMN by Höganäs AB contains, wt. %: 0.5Cr; 0.1Mo; 0.5Ni and 0.2Mn. Values of hardness and strength of materials based on this powder are on par with materials based on the well-known Astaloy 85Mo powder containing 0.85 wt. % Mo.

When solving the problem of increasing the contact endurance of hot-deformed powder steels (HDPS), microalloying is promising not only in terms of the possibility of improving the quality of interparticle joining. No less important is its potential, which consists in the possibility of a significant reduction in grain size [20]. Reducing the grain size of austenite of nitrided steel causes an increase in the contact endurance of more than 3 times [4]. Doping vanadium microadditives to steel prevents abnormal growth of austenite grains during heat treatment [21]. A similar effect is observed when micro-doping with aluminum, nitrogen or niobium. Increased contact endurance of carburized surfaces during micro-doping is most pronounced when the main mechanism of failure is the propagation of cracks along the austenite grain boundaries [22, 23].

To improve the quality of wrought steels microalloying with alkali and alkaline earth metals (AEM) is used. When microadditives of AEM are doped, impurities dissolved in the steel are bound to stable compounds, and nonmetallic inclusions are spheroidized [24]. The microalloying of iron powder with compounds of Na and Ca provided an improvement in the quality of interparticle joining due to the refinement of boundaries of grains and particles from segregations of harmful impurities [17, 25]. When concentrated on the grain boundaries, sodium and calcium reduce the level of boundary energy, which leads to a decrease in the tendency of the grain to grow and its size, as well as pushing off the atoms of the horophobic elements into the grain body and the formation of a homogeneous structure. This is accompanied by an increase in the diffusion mobility of carbon, which seems promising in terms of activating the process of carburizing HDPS.

The purpose of this work is to study the possibility of increasing the rolling contact fatigue live of HDPS due to micro-doping with calcium.

2. Experimental Procedure

Iron powders PZhV2.160.26 produced by Sulin Metallurgical Plant, as well as ABC100.30 and AstaloyCrM produced by Höganäs AB were used as the basis (table). Figure 1 shows the flow diagram for obtaining samples of HDPS. Pencil graphite GK-1 GOST 4404-78 was used as a carbon-bearing additive. Calcium was doped in the form of carbonate $CaCO_3$. Blending was performed in a planetary centrifugal mill SAND-1. In order to prevent segregation of components and improve compressibility, 1 wt. % of zinc stearate was added to the blends. The carbon content was constant and amounted to 1.0 wt. %, which, taking into account burnout when heated before hot forging (HF), provided for the production of steels of eutectoid composition. In order to minimize the conditions of surface porosity formation prior to HF die was heated to 600 ^{0}C (T_D = $600\ ^0C$).After HF samples were carburized to compensate for the decarburization of the surface layer.

Prismatic specimens of the size 10×10×55 mm to assess mechanical properties and to perform structural analysis were obtained. Contact endurance was studied using cylindrical specimens of ø26×6 mm. Tests for contact endurance were carried out on a LTM machine by rolling flat surfaces of cylindrical specimens with balls at contact stresses $\sigma_{zmax} = 5000MPa$. Tests were conducted before the appearance of fatigue spalling.

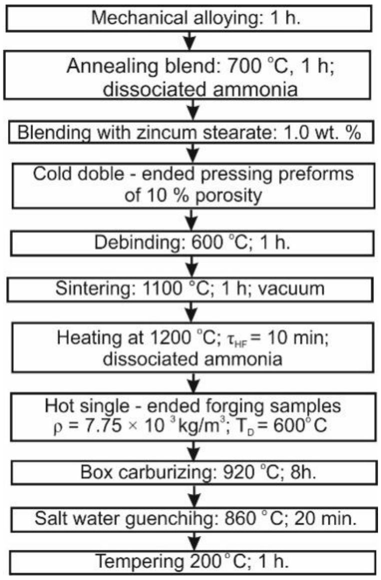

Figure 1. The flow diagram of specimen production.

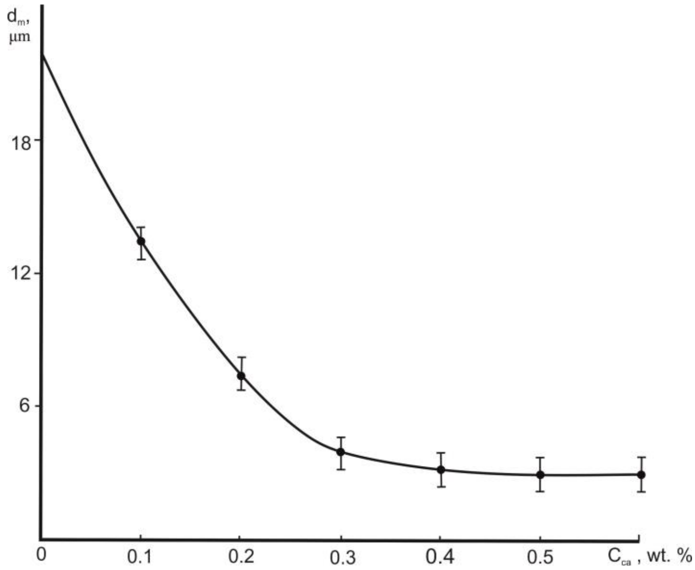

Figure 2. The median austenite grain size in the carburized layer of hot-deformed powder steel versus C_{Ca}.

The durability N_{90}, expressed in hours and corresponding to the probability of failure of 90% of the samples, served as characteristic of rolling contact fatigue live [2].

Table. Chemical composition of iron powders.

Powder grade	Chemical composition (wt. %)								
	Mn	Si	Cr	Mo	P	S	O	C	Fe
PZhV2.160.26	0.36	0.13	–	–	0.01	0.02	0.33	0.03	bal.
ABC100.30	–	–	–	–	–	–	0.04	< 0.01	bal.
AstaloyCrM	–	–	3.0	0.5	–	–	0.21	< 0.01	bal.

Metallographic investigations were performed using an AltamiMET-1M optical microscope (Altami Ltd., Russia) on etched and unetched slices. Etching was performed in 3% nital. Fractures of specimens obtained during the rolling contact fatigue (RCF) tests were studied on a Quanta 200 i 3D scanning electron microscope-microanalyzer. The size of austenite grain in the surface layer was determined by the cementite network on the as-carburized samples.

3. Results and Discussion

Doping calcium microadditives caused a decrease in the size of austenite grain (d_m) in samples of HDPS (figure 2). As the calcium content in the composition of initial blend (C_{Ca}) increases, the $d_m$values decrease monotonically due to the inhibition of grain growth by calcium adsorbed at the grain boundaries [17].

The decrease in grain size in the surface layer led to a decrease in the thickness of the filament of cementite network. In the as-carburized samples-witnesses without calcium microadditives the thickness

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of the filament is 8–11 μm. In microalloyed steels with $C_{Ca} = 0.3\ wt.\%$ excessive cementite in the surface layer has the form of rounded and scattered inclusions of 2–3 μm in size, which do not cause such a fragility of the layer as in the presence of a carbide mesh. The remainders of the carbide mesh correspond to grade 4–5 on the scale number 4 GOST 801-78. In the structure of micro-doped samples after heat treatment the carbide mesh is not observed (grade 1), and in the samples-witnesses its residues corresponding to grades 2–3 are fixed.

The core structure of as-carburized micro-doped specimens is fine-grained pearlite (grade 3–4 on the scale number 2 GOST 8233-56; HV 310–330). Point and very fine-grained pearlite is observed in the surface layer (grade 1–2; HV 350–400). Doping calcium micro-additives is favourable to the spheroidizing non-metallic inclusions, which is most clearly seen in the structure of steel based on the reduced powder PZhV2.160.26 with relatively high impurity content.

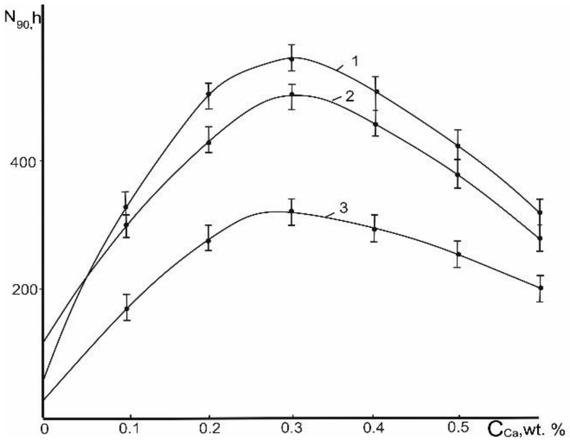

Figure 3. Rolling contact fatigue live of hot-deformed powder steels versus C_{Ca}.

$C_{Cb} = 1.0\ wt.\%$. Base powder: AstaloyCrM (1); ABC100.30 (2); PZhV2.160.26 (3).

The structure of fine and medium needle-type martensite (grade 4–5 on the scale number 3 GOST 8233-56; HV 710–740) is formed in the core of samples on the basis of all powders studied as the result of heat treatment. The structure of surface layer is determined by the type of base powder. In the surface layer of samples based on the chrome-molybdenum powder AstaloyCrM and the unalloyed powder ABC100.30 with a low content of impurities cryptocrystalline martensite is observed (grade 1 on the scale number 3 GOST 8233-56; HV 820–850). In the samples based on the powder PZhV2.160.26 very fine needle-type martensite is fixed (grade 2; HV 780–810).

Doping calcium micro-additives was favourable for increasing the contact endurance of steels. However, the C_{Ca}-dependencies of the rolling contact fatigue live shown in figure 3 are non-monotonic. The increase inC_{Ca} in the range from 0 to 3 wt. % leads to an increase in N_{90} values, which is associated with the prevailing the factor of reducing the size of grains and other components of the structure. With further gain in C_{Ca} the contact endurance of the samples decreases as a result of the formation of large clusters of second phase particles, which cause the material to soften.

In samples-witnesses contact-fatigue destruction cracks originate in the areas of positioning non-metallic inclusions of acute-angular shape. On the surface of the samples there are holes of fatigue flaking. The size of the cleavage facets depends on the type of the initial powder and is 18–24, 22–25 and 50–75 μm for samples based on powders AstaloyCrM, ABC100.30 and PZhV2.160.26, respectively.

In microalloyed specimens cracks originate at a depth of ~ 0.5 mm in the zone of the Hertz maximum shear stress (figure 4, a). Cleavage facets have a developed microrelief, and their size is 3-5 μm (figure 4, b).

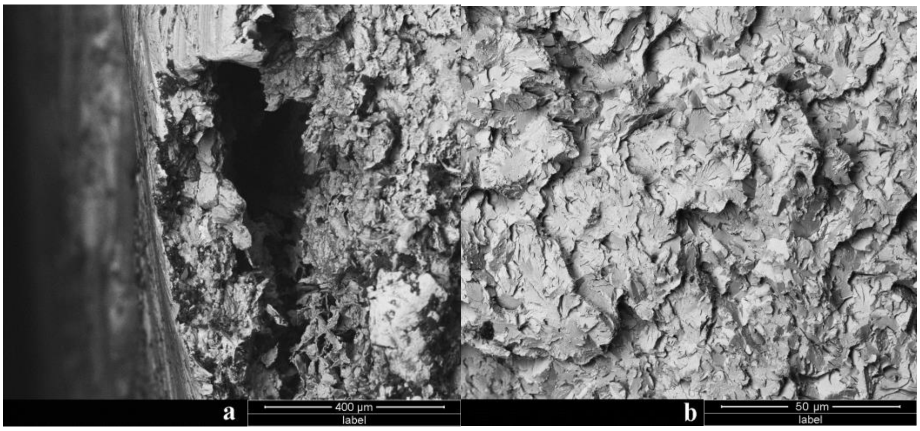

Figure 4. Contact fatigue failure in the surface layer of powder steel with a micro-additive of 0.3 wt. % of calcium. Base powder: PZhV2.160.26.

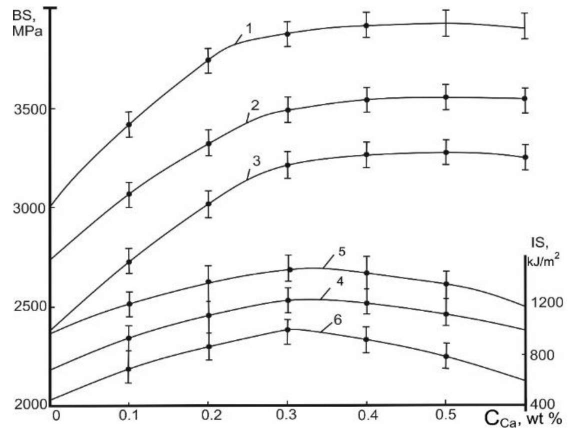

Figure 5. Mechanical properties of hot-deformed powder steels versus C_{Ca}.

$C_{Cb} = 1.0\ wt.\%$. Base powder: AstaloyCrM (1, 4); ABC100.30 (2, 5); PZhV2.160.26 (3, 6). BS (1 – 3); IS (4 – 6).

The results indicate that doping calcium microadditives was favourable for reduction in size of grains and cleavage facets. This caused increasing the energy content not only of contact-fatigue fracture, but also of fracture that develops under the conditions of the bending tests. As the calcium content in the composition of initial blend increases, the bending strength (BS) of the samples increases (figure 5, plots 1–3). The highest BS values are observed on samples of chromium-molybdenum steels. Samples based on the powder PZhV2.160.26 demonstrate the lowest strength, which is associated with a relatively high content of impurities (table). The C_{Ca}-dependencies of impact strength (IS) are non-monotonic (figure 5, plots 4–6). The reasons for the non-monotonic C_{Ca}-dependencies of IS are similar to those described above for the $N_{90}(C_{Ca})$.

4. Conclusions

1. Doping calcium micro-additives increases the energy content of destruction under the conditions of contact-fatigue and bending loads, which is caused by a decrease in austenite grain sizes due to inhibition of their growth during calcium absorption at grain boundaries.

2. The maximum values of rolling contact fatigue live and bending strength are observed on samples of chromium-molybdenum steels containing 0.3 wt. % of calcium. The highest impact strength was demonstrated by samples based on powder ABC100.30 with a low content of impurities.

3. Microalloying with calcium changes the localization of seats of contact fatigue damage. In samples-witnesses without microadditives of calcium, cracks originate near non-metallic inclusions of an acute-angular shape in the near-surface zone. In microalloyed specimens, the cracks are located in the subsurface layer in the area of the Hertz maximum shear stress.

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