656. The influence of surface layer on the surface fatigue strength of cast iron EN-GJSF

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Abstract. This paper presents the results of the surface fatigue strength of cast iron EN-GJSF after grinding and burnishing with a force of P = 1000 N, 3000 N, 4000 N and 5000 N. In comparison to grinding, tests have revealed that burnishing increases the surface strength by about 140 – 170%. The research has demonstrated that the size of plastic deformation increases together with increasing strength. It was determined that the form of graphite and its distribution are essential to the development of fatigue cracks.

Keywords: spheroidal cast iron, surface layer, grinding, burnishing, surface fatigue strength.

1. Introduction

The elements of machines whose surfaces roll on each other (operate "in contact") are exposed to a specific type of surface fatigue wear. The elements exposed to surface fatigue wear include elements of rolling bearings, gears, cams, etc. The destruction mechanism for elements operating in contact is complex and depends on many factors. Research has demonstrated [1-4] that surface fatigue wear depends on stresses from the external load, the field of residual stresses, material hardness and structure, the surface free energy, the properties of lubricant, the geometry of rolling surfaces, surface geometric structure, and the defects of surface and surface layer.

Given the fact that the phenomena associated with surface fatigue strength occur on the surface or in the surface layers of machine elements, the condition of the surface layer is essential. The condition of the surface layer is formed in the technological process of element production, especially during final process operations, which are in the process of surface treatment such as thermal, thermo-chemical, shaving or plastic working.

One of the technological treatments of the deliberate shaping of the technological surface layer is burnishing, which involves the use of surface effects - local plastic deformations. After burnishing, as a result of local plastic deformations, the physical condition of the surface layer is changed, i.e. the surface smoothness and capacity improves, and the fragmented structure has a much higher hardness, a higher degree of deformation, and a favorable distribution of compressive residual stresses [6].

The tests indicate that the condition of the surface layer of cast iron determines the surface fatigue strength. The results of the tests are presented in this publication.

2. The goals and research methodology

The aim of this study was to assess the condition of the surface layer of cast iron EN-GJSF after grinding (a traditional method of finishing cast iron) and burnishing with the force of P = 1000 – 5000 N, with special emphasis on the influence of burnishing on the stereometric condition of the surface layer [6] and the contact-fatigue strength. Another important aspect was the analysis of the process of formation and growth of fatigue spalling.

2.1. Burnishing

Roller burnishing was carried out using a device of our own design mounted on a centre lathe. A diagram of rolling is shown in Figure 1.

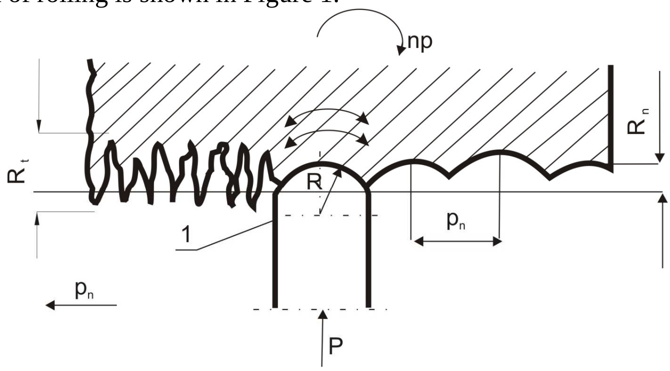

Fig. 1. Pressure rolling diagram

Pressure rolling (Fig. 1) is a static burnishing in which the burnishing force is constant and it acts on the object statically through the disk, which is in constant contact with the treated surface during processing. The figure shows that the effects of burnishing depend on the following technological parameters: force *P* with which a burnishing element is pressed onto the surface of the element, burnishing feed p_n, peripheral speed of the burnished element v_p, and the number of working passes.

The tool with the following parameters was used for the tests: disk diameter D_k = 60 mm, disk radius r_k = 20 mm, Rockwell hardness 60 HRC, and roughness Ra_k = 0,12 μm. The technological parameters of roller burnishing were as follows: variable burnishing force *P* = 1000 N, 3000 N, 4000 N, 5000N, feed f_n = 0.21 mm/r, speed *v* = 56 m/min, number of passes *i* = 1. During burnishing the surface was lubricated with machine oil (kinematic viscosity at 40° C is 16.5 mm^2/s, viscosity index is 60).

The cast iron EN-GJSF with metallic ferritic matrix (Fe 94 P6) was the following chemical composition and mechanical properties were selected for the tests: *C* = 3.15%, *Mn* = 0.51%, *Si* = 3.47%, *P* = 0.10%, *S* = 0.1%, *HB* = 210, R_m = 436 Mpa.

2.2. Contact-fatigue strength tests

Contact-fatigue strength tests were carried out on a special test station of our own design, which had three rollers applying a load to the test samples. The diagram of loads on the test samples is illustrated in Fig. 2. The tests were carried out with variable clamping force of the frequency of 7410 cycles per minute (4.446 million cycles per 10 h) at the load *P* = 1425 N. In the area of contact between the sample and the disk of a hardness 60 HRC, a stream of machine oil was added. 10 fatigue spallings on the surface of the test samples sized Ø 36 x 10 mm were adopted as a failure criterion. Spallings were revealed by means of a vibration sensor as well as measuring and recording devices.

3. Test results and their analysis

The results of tests into the condition of the surface layer of the cast iron after grinding and burnishing with the force *P* = 1000 - 5000 N are shown in Table 1 [6]. These results indicate that the characteristic feature of the surface layer of the cast iron after burnishing is low roughness and a different geometric structure of the surface (Fig. 3). The value of surface roughness decreases when the burnishing force increases within the range of P = 1000 - 4000 N. At the burnishing force P = 5000 N, surface roughness increases again, which leads to the formation of microcracks and even surface flaking. The lowest surface roughness after burnishing R_a = 0.36 µm was obtained when the sample was burnished with the force P = 4000 N. With the increase in burnishing force from 1000 to 4000 N, the bearing surface increased, and at the burnishing force P = 4000 N, it was: G_{20} = 38% and G_{50} = 80%. Such a high bearing surface is connected with the shape of surface irregularities that are characterized by a large radius of the tops of irregularities.

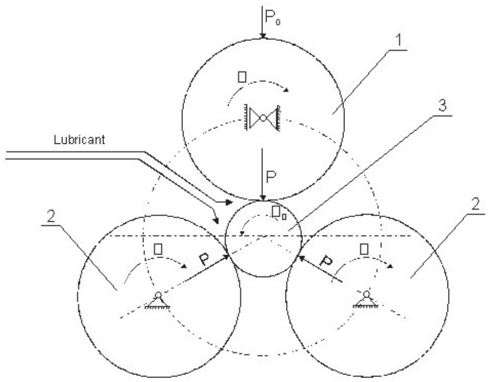

Fig. 2. Loads on samples to test surface fatigue strength: 1 – pressure roll, 2 – guide rolls, 3 – tested sample, P_0 – load, P – components of loads in contact points

The detailed analysis of the influence of burnishing force on the strengthening and the state of residual stresses is extremely difficult because of the heterogeneity of the material. The measurements are affected by significant errors, because there are large differences between the measurements on certain depths of the surface layer. However, it is concluded that the surface layer strengthens largely in the process of burnishing and the strengthening index rises to 66%.

A characteristic feature of residual stresses after burnishing is that they are compressive stresses, which might be an indication of the crucial role of plastic deformation of the material structure.

Table 1. The condition of the surface layer of the spheroidal ferritic cast iron EN-GJSF after grinding and burnishing

Working type	**Properties of the surface layer**				
	Ra [µm]	G_{20} [%]	G_{50} [%]	*U* [%]	$\delta_1 + \delta_2$ [MPa]
Burnishing P = 1000 N	0,51	14	43	5 - 21	- (289 - 667)
Burnishing P = 3000 N	0,46	21	62	30 - 55	- (269 - 969)
Burnishing P = 4000 N	0,36	38	80	33 - 66	- (316- 968)
Burnishing P = 5000 N	0,42	6	29	36 - 55	(342 – 1072)
Grinding	0,53	9	27	5 - 26	[289 - (-393)]

Given the results of the tests into the influence of the burnishing force on the properties of the surface layer, one cannot determine which force is optimal, due to the contact–fatigue strength. Assuming that the preferred condition of the surface layer is characterized by low roughness, a high proportion of bearing surface, maximum strengthening and the occurrence of compressive residual stresses in the absence of decohesion, it can be assumed that the optimal force to burnish EN-GJSF is P = 4000 N. When the burnishing force is larger, strengthening and stresses have greater values, but the treated surfaces become clearly rougher and scaling increases, which is caused by exceeding the critical degree of deformation in the subsurface layer [6].

Fig. 4 presents the results of tests into the contact-fatigue strength of cast iron EN-GJSF after grinding and burnishing.

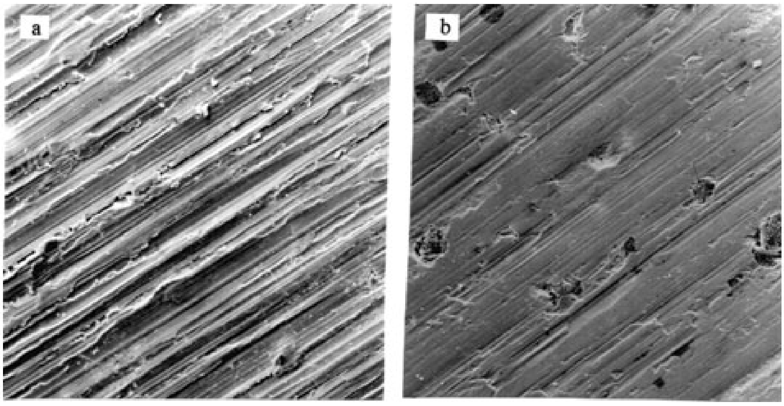

Fig. 3. Technological surface of cast iron EN-GJSF: a) after grinding, b) after burnishing with the force P = 4000 N. Enlargement 200 x

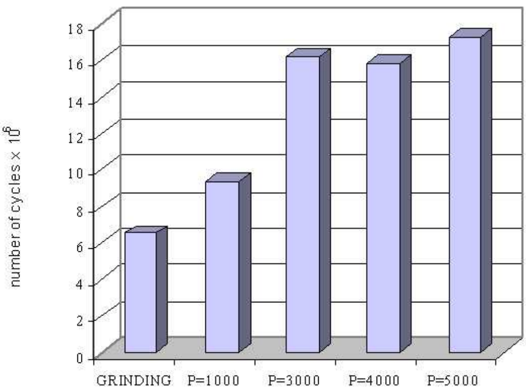

Fig. 4. Surface fatigue strength of cast iron EN-GJSF after grinding and burnishing

Comparing the changes in the surface contact–fatigue strength after grinding and burnishing (Fig. 4), the strength increased after burnishing for the whole range of the burnishing force. For the burnishing force P = 3000 - 5000 N, fatigue resistance increased from 145% to 170%, in comparison to the ground surface. It must be assumed that an increase in fatigue resistance after burnishing, compared with grinding, is connected with plastic deformation of the subsurface layer, which increases as burnishing forces increase in the process of burnishing. A decrease in surface roughness, an increase in bearing surface, as well as a substantial strengthening and formation of compressive stresses in the surface layer often accompany deformation of the subsurface layer.

As a result of burnishing, the homogenization of the surface geometric structure with mild forms of irregular cavities was obtained (Fig. 3), which is associated with a reduction of stress concentrators. A large bearing surface reduces the value of unit pressure, and thus improves the working conditions of elements.

In order to present contact-fatigue resistance, microscopic observations of the surface and the cross-section perpendicular to this surface in the place where fatigue spalling appeared were carried out (Figs. 5-8). Fig. 5 presents a typical picture of a pitting breach formed on the surface in the place where graphite is liberated. A general view of the surface after pitting tests is shown in Fig. 6a. It shows a gap situated in the central part of the picture and the grid of microcracks all over the surface. The magnified image of the breach is presented in Fig. 6a. Figs. 6 b, c, d and 7a show the area of changes occurring in the process of pitting. Fig. 7b illustrates fatigue spalling and the net of microcracks propagating from the central part of the spalling. Inside the spalling, there are products of the subsurface layer destruction. They are in the form of debris (layered plates) - Figs. 6c, 7a, and 7b. Probably, there are also wear products in a form of rotational lumps ("eggs"), which are empty inside - Figure 7c and 7d. In Fig. 8a there are also visible wear products in a form of "an empty egg" and lumps consisting of two joint "eggs."

Cracks initiated in spallings spread on the surface and deep into the surface layer - Fig. 8b.

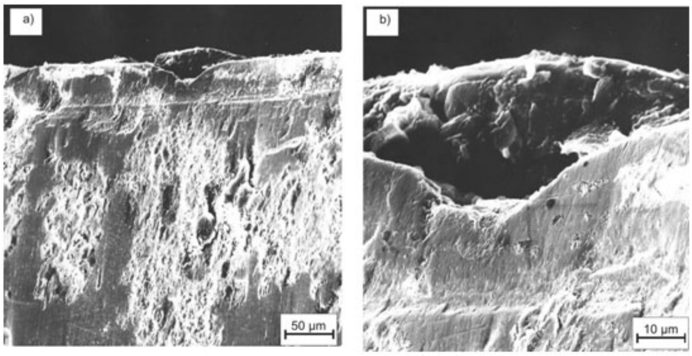

Fig. 5. Microstructure of the surface layer after testing contact-fatigue strength of cast iron EN-GJSF burnished with the force of P = 4000 N

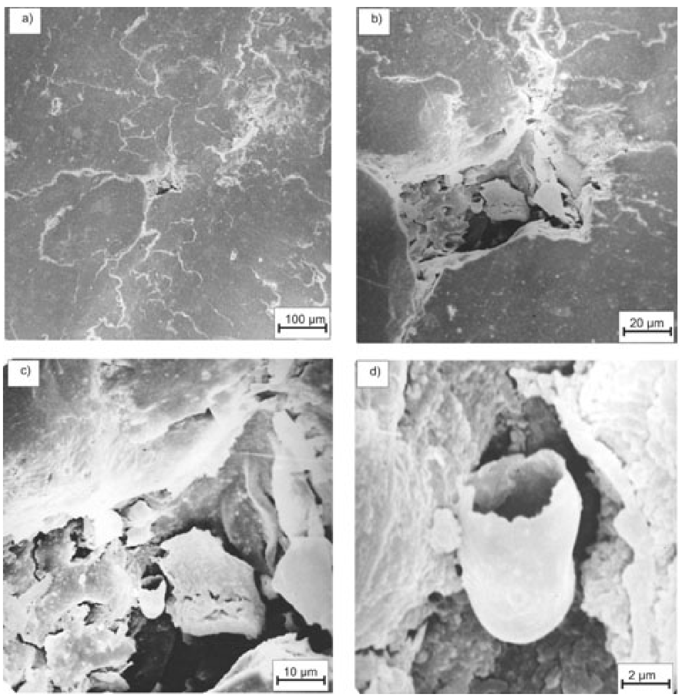

Fig. 6. General view of the surface of a pitting breach after testing contact-fatigue strength of cast iron EN-GJSF roller burnished with the force P = 4000 N

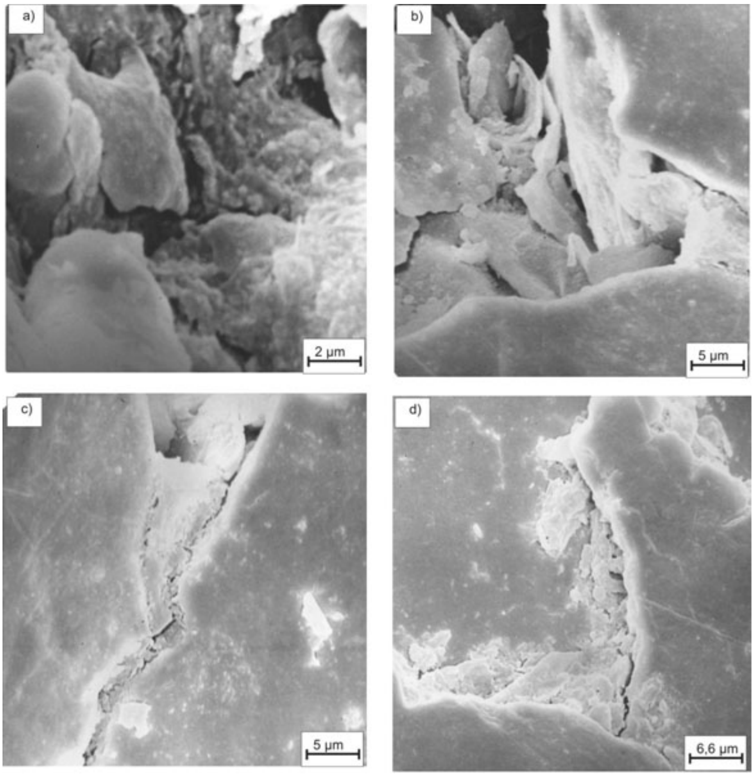

Fig. 7. Surface after testing contact-fatigue strength of cast iron EN-GJSF roller burnished with the force *P* = 4000 N

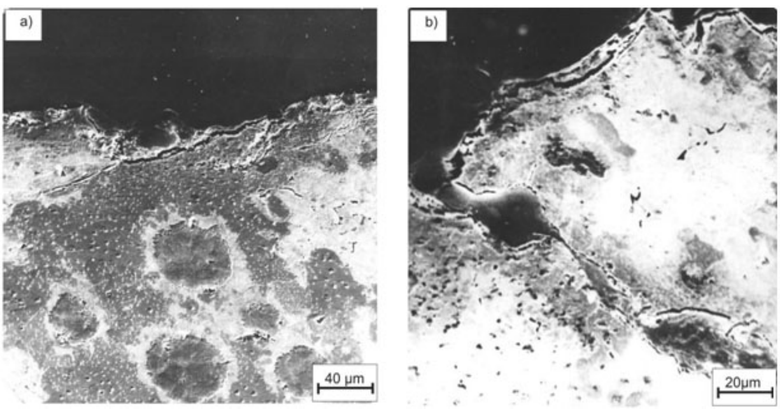

Fig. 8. Microstructure of the surface layer after testing contact-fatigue strength of cast iron EN-GJSF roller burnished with the force *P* = 4000 N

The microscopic observations of the surface and surface layer show that, apart from the condition of the surface layer, the distribution of graphite in the subsurface layer determines the fatigue resistance of cast iron EN-GJSF. If the liberation of graphite is located near the surface and in the vicinity, there is not an additional liberation of graphite and a spalling is quite small. However, if there is another liberation of graphite nearby, a crack propagates into the depth of the surface layer to the next graphite liberation along the particle border - Figure 8b. A uniform distribution of graphite in the surface layer is conducive to a high resistance to surface fatigue of cast iron, irrespective of the type of treatment (grinding or burnishing). As it is observed in Fig. 8a, cracks initiated by pitting breaches propagate inside the surface layer up to the grain boundary.

Conclusion

1. The tests have revealed that burnishing modifies the properties of the surface layer of the cast iron, in particular, it changes the formation of the surface geometric structure, which is characteristic of this kind of treatment. Physical and mechanical properties of the surface layer are modified as well including the fragmentation and homogenization of microstructure as well as strengthening and formation of compressive residual stress.
2. Compared to grinding, burnishing increases the contact-fatigue strength. This is mainly caused by lower surface roughness (in the process of burnishing micro-cracks are "rolled" as potential stress concentrators), a larger bearing surface, and the intensification and occurrence of compressive residual stress.
3. One of the most important factors determining the contact-fatigue strength of cast iron is the even distribution of graphite in the subsurface layer. The more evenly the graphite is distributed, the greater the contact-fatigue strength.

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