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RESEARCH

Wear of Machine Elements Made from Powder Metallurgical Tool Steels

The contacts of machine elements, such as gears and rolling bearings, are exposed to high pressure and, in many cases, to high slide-to-roll ratio as well. They operate in the mixed or even boundary lubrication regime and therefore their wear is often their load limiting factor. In order to increase the load carrying capacity of such machine elements, one could consider the applicability of powder metallurgical steels, which are commonly used for cold work applications. They offer very high adhesive wear and galling resistance. In this paper the main characteristics of three commercially available powder steels are described at first. Afterwards, the experimental setup and the experiments that were carried out in order to evaluate the wear resistance of the considered powder steels in reference to 100Cr6 through hardened steel are outlined. The main measured parameters such as mass loss, friction and normal force, surface roughness, surface temperature near contact and surface photos are presented. Finally, comparative charts of running-in wear rate, wear rate after running-in and friction coefficient and additional charts of temperature, surface roughness measurements and photos are given and discussed.

Keywords: powder steels, wear, friction coefficient, running-in, surface roughness

1. INTRODUCTION

Severe operating conditions are met at the operation of the machine elements, such as gears and rolling bearings. High contact pressure and high slide-to-roll ratio lead to thin lubricant film and mixed or boundary lubrication is often evident. These conditions lead to extended material wear and the performance of the machine element is strongly affected. In order to improve the wear resistance of the machine element, attempts could be made to the direction of material improvement. These attempts concern either the use of an old material with a surface coating or the use of a new material without a coating. Concerning that the surface coating procedure is expensive and time-consuming the use of wear-resistant materials is an attractive alternative. Such materials are powder metallurgical steels, used for cold work applications. They contain chromium (Cr), molybdenum (Mo), wolfram (W), vanadium (V) and other elements, such as nitrogen (N) and cobalt (Co).

The resistance against wear of such a material has to be tested in order to evaluate its suitability for a machine element use. Such wear tests were carried out on the two-disc test rig with parallel shafts of the Laboratory of Machine Elements and Machine Design (Fig. 1). Three different powder metallurgical steels were tested. An additional test series with 100Cr6 through hardened discs has been also carried out, in order to use its results as reference. For each material three experiments were carried out, two with higher sum velocity (1.75 m /s) and one with lower sum velocity (0.67 m/s), in order to include the low-speed wear in the study. The main parameters measured during the tests are:

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(a) The mass loss of the discs, used to obtain the wear rate.

(b) The friction and normal force, used to determine the friction coefficient.

(c) The surface roughness profiles at three pre-defined points of each test specimen along and across the direction of the sliding speed. They have been obtained at several time intervals during the experiment, in order to visualize the polishing effect, which is usually observed during running-in. From the digitized roughness profiles the most important roughness parameters have been calculated.

(d) The track of the contact ellipse along the circumference of the disks has been photographically documented in order to examine it for surface defects such as micropittings, cracks, etc.

(e) The surface temperature of both discs, near contact, in order to demonstrate the influence of the different thermal conductivity of the three materials.

The main criterion used to evaluate the resistance against wear is the mass loss per distance of sliding, i.e. the wear rate. The friction coefficient is also taken into account, concerning that besides the wear the power loss is an important factor of a machine's element efficiency as well. All other measured parameters are used to evaluate the results and to create a more complete overview of the experiments.

2. EXPERIMENTAL SETUP

The experiments have been carried out on the two-disc test rig with parallel shafts of the Laboratory of Machine Elements and Machine Design, shown in Fig. 1. A detailed description of the test rig can be found in ref. [1]; therefore, only the most important features will be mentioned here. The experimental discs are mounted at the free ends of the corresponding shafts. For that reason, one of the discs has to be crowned in order to account for the elastic deformation of the shafts due to normal force, see ref. [2]. Otherwise, edge loading of the discs would occur. The experimental discs are shown in Fig. 2. The shafts are driven independently by two inverter-controlled AC motors. Thus, rotating velocities and slide-to-roll ratio can be freely set.

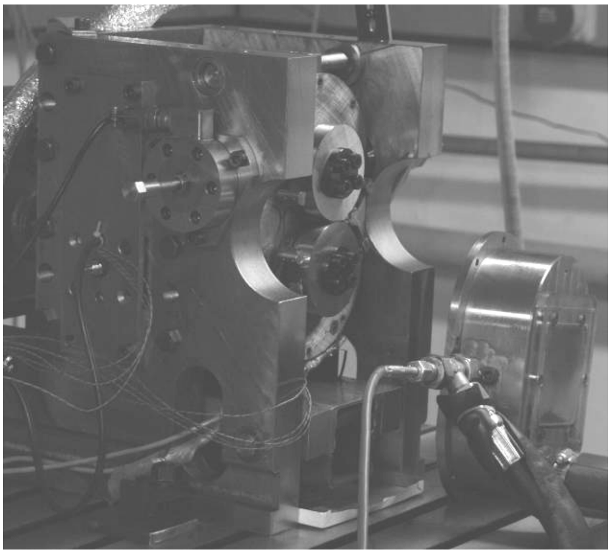

Fig. 1: The two-disk test rig with parallel shafts of the Laboratory of Machine Elements and Machine Design

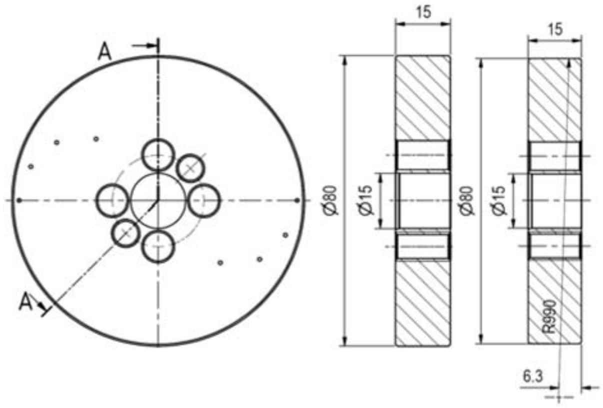

Fig. 2: The experimental discs used

As mentioned above, the materials tested are three commercially available powder steels used for cold work applications and 100Cr6, which is a typical rolling bearing steel, used as reference. Their chemical composition and their main mechanical properties are shown in Tab. 1. Steel A i s used for heavy-duty machining tools, such as hobs, milling cutters and shaper cutters and tools used under extreme compressive stresses, such as shaping punches. Steel B i s used for blanking and as plastics mould tooling element. Finally, typical applications of steel C are blanking and forming, cold extrusion, deep drawing and powder pressing.

The experimental conditions are shown i n Tab. 2. These test conditions have been chosen really tough, so that the differences in the wear resistance of the tested materials are as evident as possible. Similar conditions also are met in modern highly loaded gears and rolling bearings. The crowned disc was made of the tested materials, while the cylindrical one was always a 100Cr6 disc. As mentioned above, for each material two series of experiments can be discriminated, a series of two experiments with higher sum velocity and another of a single experiment and lower sum velocity. These two series will be named from now on as "series 1" and "series 2" respectively.

Tab. 1: Chemical composition of the tested powder steels.

	100Cr6	Steel A	Steel B	Steel C
% C	0.95	1.64	1.28	1.1
% N	-	-	-	1.8
% Si	0.35	0.6	-	0.5
% Mn	0.4	0.3	-	0.4
% Cr	1.55	4.8	4.2	4.5
% Mo	-	2.0	5.0	3.2
% W	-	10.4	6.4	3.7
% V	-	4.8	3.1	8.2
% Co	-	8.0	-	-
Density [kg/m3]	7810	8100	7980	7700
Modulus of elasticity [MPa]	$210 \cdot 10^3$	$231 \cdot 10^3$	$230 \cdot 10^3$	$209 \cdot 10^3$
Hardness [HRC]*	62 - 66	59 - 68	56 - 66	57 - 64
Thermal conductivity [W/mK]	50	24	24	21

* Depending on the heat treatment conditions.

Tab. 2: Experimental conditions.

Contact Geometry	Cyli ndri cal – Crowned test discs
Resultant ellipticity	a/b=e = 12
Oil	FVA 2 without additives
Oil supply rate & temperature	0.5 lt/mi n @ 90^{o}C
Maximum Pressure	1.25 GPa
Vsum	series 1: 1.75 m/s series 2: 0.67 m/s
V1 & V2	seri es 1: 1 & 0.75 m/s seri es 2: 0.42 & 0.25 m/s
Slide-to-roll ratio	seri es 1: 28.6% seri es 2: 50.75%

Each experiment lasted 24h with stops for weighing of the discs, photographing and surface roughness measurements: 19h of running and 5h of measurements. The measurement stops were made just before each experiment and then after – 0.5h – 1h – 5h – 10h – 19h of running time. This means that the running periods had a duration of 0.5h – 0.5h – 4h – 5h – 9h respectively. The stops are frequent at first, in order to observe the effects of running in wear. In order to take accurate measurements of the experimental discs mass, one has to consider things: First, that the lubricant which is chemically attached on discs surface has to be removed and second that the mounting and dismounting of the discs on the shafts of the test rig has to be done without wear. The discs were cleaned in an ultrasonic bath with a suitable cleaner. The efficiency of both cleaning and mount/dismount procedure was ensured by the following test: an experimental disc was cleaned and weighed. Then, it was mounted onto the test rig and was let to operate alone in the lubricant for sufficient time. Afterwards the disc was dismounted, cleaned and weighed once again. This procedure was followed three times. The results are given in Tab. 3 and show that the disc cleaning and disc mounting/dismounting procedures are reliable. For the weighing of the discs an ultra precision balance of 1 mg accuracy and 5 kg maximum capacity has been used.

Tab. 3: Results of the cleaning and mounting/ dismounting procedure reliability test. As shown, for each weighing three partial measurements were made and the mean value was calculated.

1st weighing	1st	534.510
	2nd	534.511
	3rd	534.509
	mean value	534.510
2nd weighing	1st	534.509
	2nd	534.510
	3rd	534.510
	mean value	534.5097
3rd weighing	1st	534.510
	2nd	534.511
	3rd	534.511
	mean value	534.5107

The circumferential surface of the test discs was photographed during the above mentioned stops. 360^o photos were made by using a custom-made device, shown on Fig. 3. The test disc rests on a base. This base can be rotated stepwise in 15^o (24 sectors). On each step a picture was taken. The 24 pictures were transferred to a pc and combined to a large picture of the circumference of the disc. Such a photo is given with the other results.

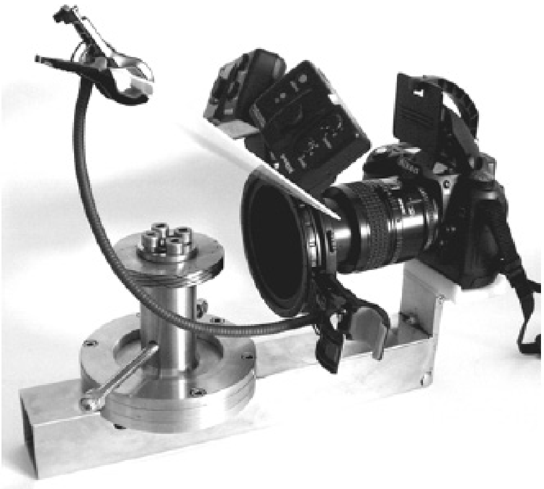

Fig. 3: The custom-made device for circumferential photographing of the discs

In order to visualize the polishing effect, which is usually observed during running-in, the surface roughness profiles have been obtained on every stop of the experiment. The measurements took place at three predefined points of each test specimen along and across the direction of the sliding speed, as shown in Fig. 4.

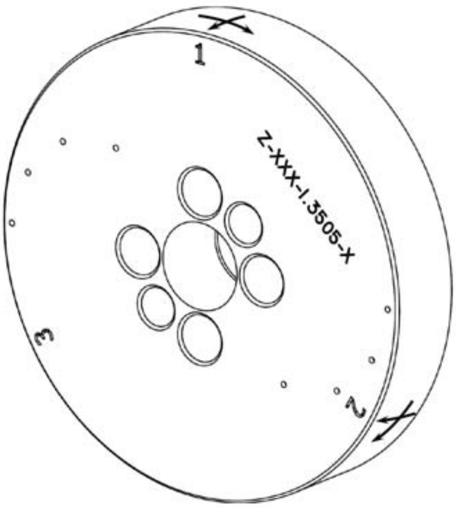

Fig. 4: Illustration of a test discs with the three predefined points of roughness measurements marked. The two different directions (along and across sliding speed) are marked with arrows

A custom-made device was developed, in order to take measurements of the surface profile in both directions and make sure that they will be made every time on the same point of the disc. This custom-made device is shown in Fig. 5. A reference disc with the same outer diameter with the experimental discs is used in order to transform the linear movement of the roughness measuring device to rotational via a friction lever. So, the resting measuring stylus has the capability to measure along the circumference of the disc. The measurements across the direction of the sliding speed were made by rotating the probe holder by 90^o. From the digitized roughness profiles the most important roughness parameters have been calculated, such as Ra, Rq, Rmax, Rz, Rsk and Rku.

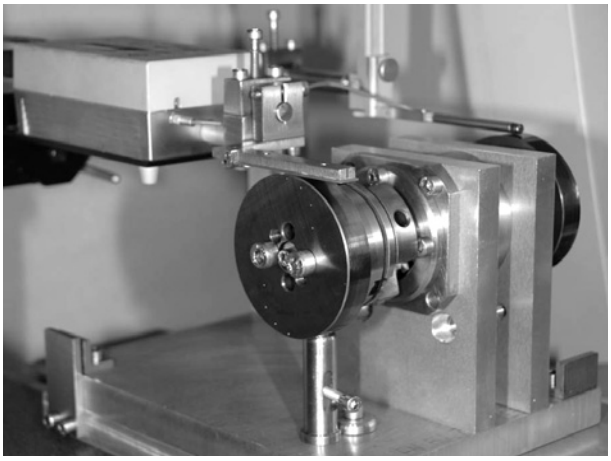

Fig. 5: The roughness measurements custom-made device. In front is shown the reference disc, while in the background is shown the measured disc and the measuring stylus

The measuring of the temperature near contact was achieved as shown in Fig. 6. Trailing thermocouples were glued onto 0.1mm thick steel straps. The difference between the temperature measured by a trailing thermocouple and the temperature measured by an embedded thermocouple 2mm beneath the disc surface is shown in Fig. 7. It is obvious that this difference is negligible. So, the surface temperature can be considered as body temperature up to 2mm depth.

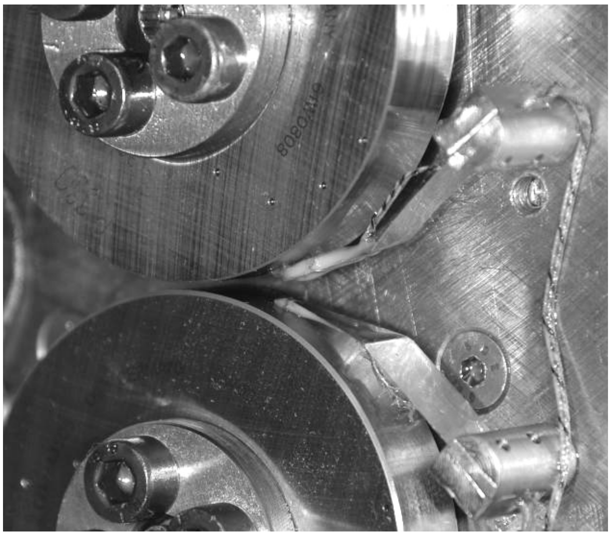

Fig. 6: Trailing thermocouples on the test discs surface. It should be noticed that the thermocouples are located as close as possible to the contact area

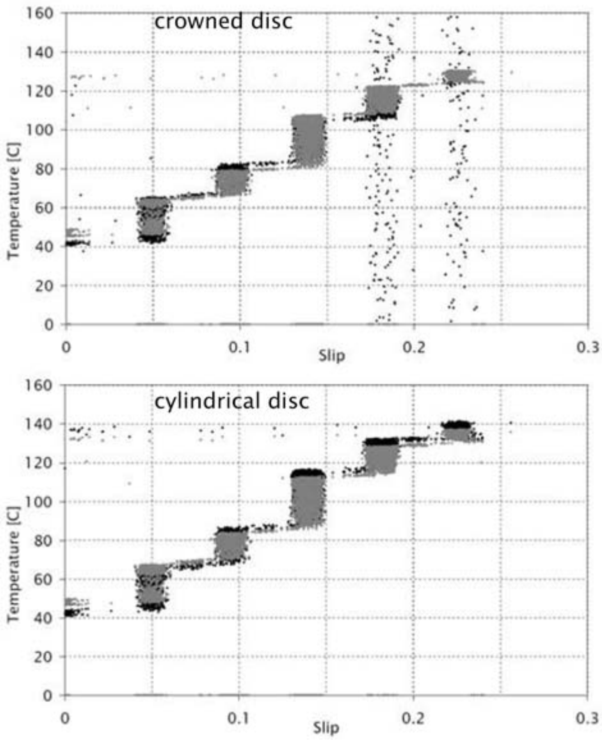

Fig. 7: Temperature measured from a trailing thermocouple (grey) and an embedded thermocouple located 2mm beneath the surface (black). The differences are less than the measurement accuracy

3. RESULTS

(a) The main criterion in order to evaluate if the tested steels are suitable for using as machine elements materials is their resistance against wear. In order to compare the mass loss of the experiments of the two different series, the wear rate defined as the mass loss over the sliding distance has been calculated. So, the wear rate of the tested materials is obtained independently from the operating conditions. The wear rate during running-in and its total value are presented in different charts, in Fig. 8. These charts show the mean values of the three experiments of each material combination. The scattering of the partial results was, as expected, wide. The mean values of the maximum deviation for the running-in wear rate are 4.42 and 8.8 mg/km for the crowned and the cylindrical discs respectively. For the total wear they are 0.23 and 0.86 mg/km for the crowned and the cylindrical disc accordingly. As running-in time has been considered 1 hour of running. This is justified by the typical mass loss vs time chart given in Fig. 9, which shows the mass loss of a disc made from steel A running against a 100Cr6 reference disc. As easily can be shown, until the first hour of running the mass loss is very rapid, while after the first hour the mass loss becomes smooth.

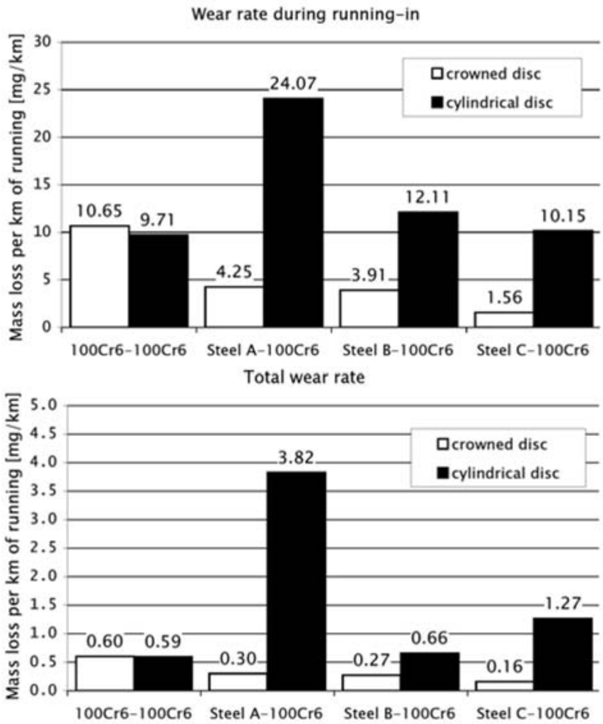

Fig. 8: Wear rate during running in and total wear rate. The wear rate was obtained by reducing the mass loss to the length of sliding

(b) The initial and the final friction coefficients are presented in the charts of Fig. 10. The value given for the series 1 is the mean value of the two experiments. The mean value of the maximum deviation is for the initial friction coefficient 0.008 and for the final 0.01.The typical behaviour of a friction coefficient is shown in Fig. 11. It can be clearly seen that the friction coefficient decreases rapidly during running-in and afterwards it remains practically unchanged.

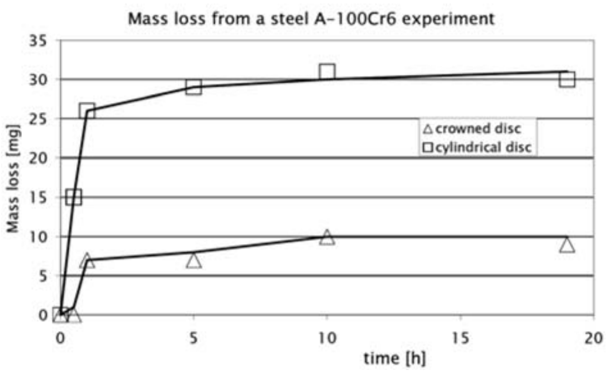

Fig. 9: Typical mass loss over time chart. The running in period (first hour) is clearly seen

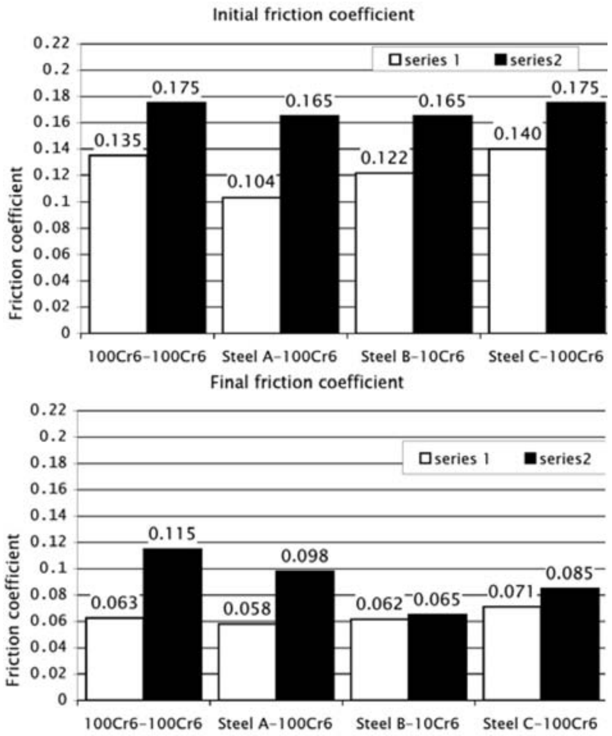

Fig. 10: Initial and final friction coefficient

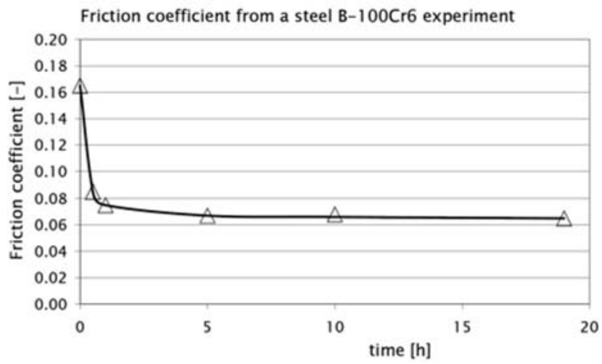

Fig. 11: Typical friction coefficient over time chart. The friction coefficient is rapidly decreased during running-in and then is practically stabilized

(c) Fig. 12 shows a typical surface roughness measurement. The polishing effect during the running-in period and the regeneration of the surface roughness can be clearly observed. In Tab. 4 the most important roughness parameters before the start of the experiment, right after running-in and after the end of the experiment are given.

Tab. 4: The most important roughness parameters of the Fig. 14 roughness measurements before the start of the experiment (0 h), after running-in (1h) and after the end of the experiment (19 h)

	0 h	1 h	19 h
Ra	0.236	0.089	0.105
Rq	0.310	0.125	0.143
Rmax	1.400	0.690	0.820
Rz	1.394	0.684	0.812
Rsk	-1.169	-0.367	0.087
Rku	1.548	0.589	0.488

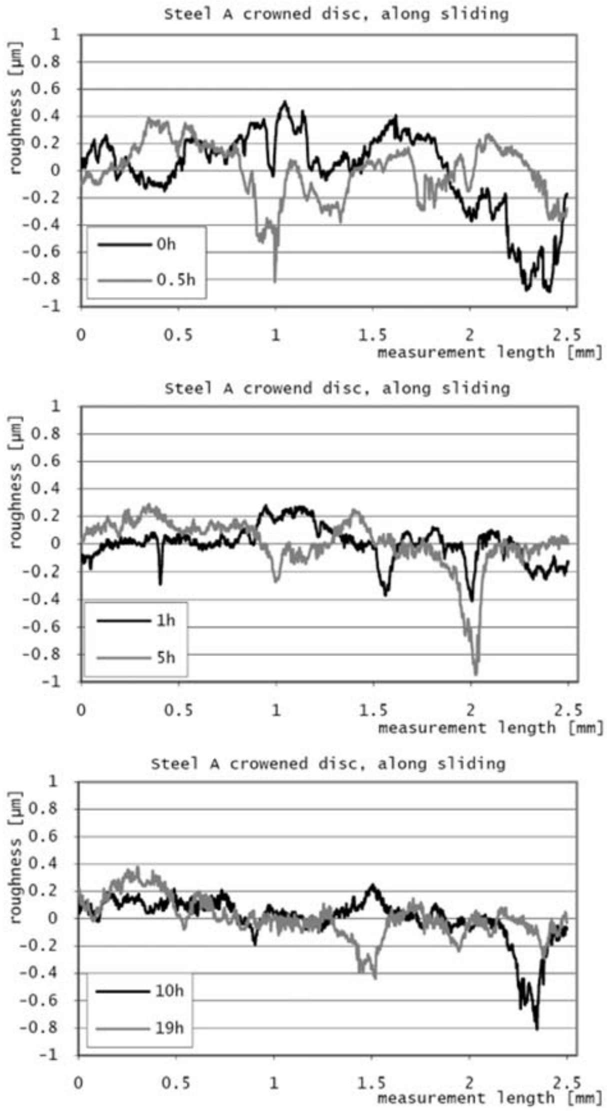

Fig. 12: Surface roughness of a steel A disc, along the sliding speed

(d) The charts of Fig. 13 show the final surface temperature of the discs, as indicative of the relative temperature rise for each material. The same temperature is evident almost throughout the duration of the experiment.

(e) Two 360o photos are shown in Fig. 14. In the first, a new disc is presented, while in the second the same disc after the end of the experiment, i.e. after 19 hours of running

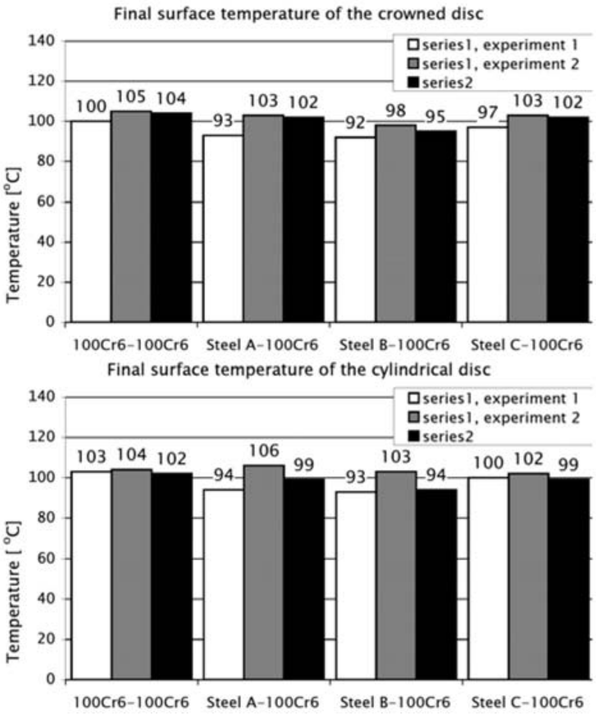

Fig. 13: Final surface temperature near the contact area

4. CONCLUSION

The wear resistance of three powder metallurgical steels and of 100Cr6 used as reference was experimentally investigated. From the results reported here can be conclude that:

(a) All tested powder steels show better resistance against wear than the common 100Cr6 steel. However, attention should be paid, because, in spite of the good wear resistance of the tested steels themselves, the cooperating 100Cr6 discs show high, even extreme wear. Steel A, for example, has about the half wear rate of the 100Cr6, but the wear rate of the cylindrical disc is unacceptable high. Steel B shows good wear resistance and the wear resistance of the co-operating cylindrical disc is satisfactory. Steel C has very good wear resistance, but the wear of the cylindrical disc is not satisfactory.

(b) The friction coefficient of the series 2 experiments is generally higher than the one of the series 1 experiments. This can be explained by the tougher experimental conditions. Since the initial friction coefficient is temporary and the friction coefficient after running-in is stabilized, the final friction coefficient is much more significant. 100Cr6 and steel A seem to give higher final friction coefficient than the other two steels. Steel B has the lowest final friction coefficient, in both series of experiments.

(c) Practically, no effect on the bulk temperature of the discs could be observed, despite the differences in the thermal conductivity of the tested materials.

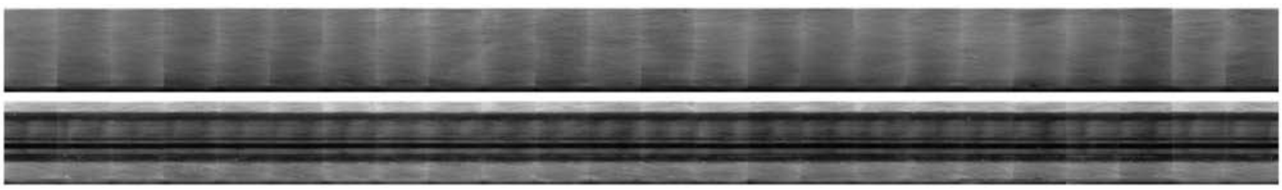

Fig. 14: 360^o photo of the circumference of a test disc before and after the end of the experiment

REFERENCES

[1] Mihailidis A., Salpistis C., Drivakos N., Panagiotidis K., *"Friction behaviour of FVA reference mineral oil obtained by a newly designed two-disk test rig"*, Proc of the Int. Conf. "Power transmission 03", Varna, Bulgaria, 2003, 32-37.

[2] Salpistis Ch., Mihailidis A. Drivakos N. and Gatsios S., *"Experimentally obtained solid contact time curves as criterion of the EHL performance of rough surfaces"*, Proc of the Int. Conf. "Power transmission 06", Novi Sad, Serbia 2006, 347-350.