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LOAD CAPACITY OF HARDENED GEAR WHEELS MACHINED WITH CUBIC BORON NITRIDE (CBN) WEDGES

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Preliminary Note – Prethodno priopćenje

The paper presents the results of exploitation examination of gear wheels with hardened bearing surface. The gears under investigation have been finish machined by the method elaborated by the author, with a tool possessing wedges made of CBN (cubic boron nitride). The symptoms of tooth surface wear having arisen during operation on the test rig with power loop. Assessment of the gear wheels' capacity of carrying loads under EHL (ElastoHydrodynamic Lubrication) conditions has been performed.

Key words: hardened gears, cubic boron nitride, load capacity, laboratory testing

INTRODUCTION

Manufacturing of gear wheels with not standardized reference profile in short series is an expensive process. Toothing manufacturing costs include, among others, the cost of special tools made upon order and the cost of operation of machine tools intended exclusively for machining teeth. The manufacturers of machining centers compete in modernizing products, but none of them has made solutions allowing for finish machining of gear wheels with hardened teeth. In order to reduce the cost of tooth machining, a complete technology has been elaborated, especially for finish machining of cylindrical gear wheels. The technology makes it possible to machine hardened bearing surfaces of teeth on machining centers. Machining requires universal, multiple tool head with wedges made of CBN. The head geometry, combined with the kinematics specially developed for the investigation, enables machining of gear wheels with geometrical parameters not directly related to the tool geometry to be effected [1, 2]. The gear wheels finish machined according to the elaborated technology can be categorized to the sixth class of accuracy [2], as regards smooth operation and kinematic accuracy. The machined side surfaces had adequate values of surface roughness parameters for carrying high loads. The surface roughness parameter did not exceed the value of 0,4 μm. Measurements of the toothing geometry and the surface structure allow only for the determination of the gear's potential capacity of load carrying. In order to find actual properties of the wheels in that respect, exploitation tests have been performed.

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INVESTIGATION CONDITIONS

Machining of the gear wheels has been performed on the DMU60 MonoBlock machining center without fluid cooling. Pairs of wheels, pinion of 16 teeth, gear wheel of 24 teeth, module pitch 4,5 mm were made of 16MnCr5 steel, gas carbonized and hardened. The carbonized layer, 1,1 mm thick, has reached the hardness of 60 to 61 HRC after hardening.

Finish machining has formed the tooth bearing surfaces in thirty orbital passes per each tooth side. During machining of the left sides of the teeth, the tool wedges machine the material backwardly; the opposite right sides are machined forwardly. In machining with the multiple head, the following parameters have been adopted, thickness of the allowance removed in one operation, q = 0,1 mm for rough passes and q = 0,04 mm for the finishing passes; feed per a wedge, fz =0,09 mm and cutting velocity, vc = 250 m/min.

In order to determine the exploitation features, experimental examination of gear wheel pairs mounted on the rig with power loop has been performed (Figure 1). The conditions of the examination corresponded to those of a speed reduction gear with a ratio of 0,6667. The gear was spray lubricated and cooled by means of a nozzle with the diameter of 0,3 mm directed towards the zone of mesh (Figure 1). Through the nozzle 0,1 litre of oil was supplied in 1 minute. The gear was examined when the oil reached the temperature of 90 ^{o}C. The examination period of one pair of gear wheels took 14 hours; the condition of the gears was inspected every 3,5 hours. During the examination, the rotational speed of the pinion has reached the value of 6 000 rpm. And the value of torque measured on the wheel 400 ± 8 Nm. Each bearing surface of the pinion has performed 0,5 x 10^7 load cycles. The face temperature of the pinion teeth reached the value of 143 ± 12 ^{o}C. The temperature was measured with a pyrometer just after the front shield of the gear has been removed, immediately after the gear wheel operation was stopped. During the operation of the gear, the acceleration resulting from the teeth getting in contact has not exceeded 160,9 m/s^2 in any of the three mutually perpendicular directions. The acceleration was measured on the transmission body; the mass directly energized by the transmission was about 340 kg. The accelerations resulting from the radial run-out reached the value of up to 29 m/s^2. For comparison, a pair of toothed wheels with geometrical parameters in conformance with those made for the investigation, executed upon an order in the 4^{th} class of accuracy, has generated accelerations lower only by 33,3 m/s. The vibration of the casing is transferred to the environment in the form of an acoustic wave. Considering the maximum transmission body acceleration difference between the gears made by the examined method and those made upon the order of below 20%, it can be stated that the exploitation test has proved high quality of the gear wheels under investigation as regards the level of emission of vibration generated by the examined transmission.

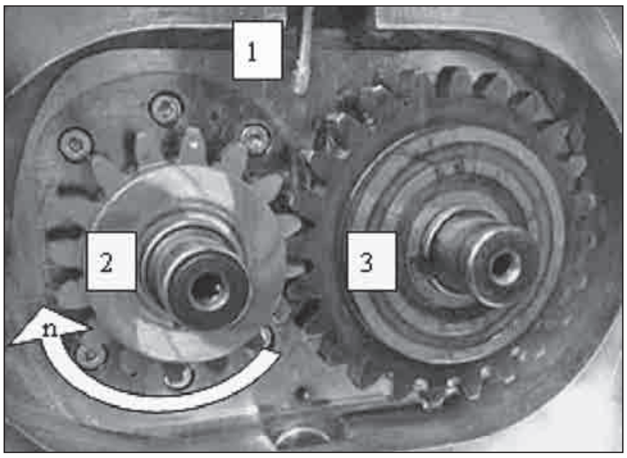

Figure 1 The transmission under investigation on the rig with power loop: 1 – oil nozzle, 2 – pinion, 3 – gear wheel

Due to the geometry of the transmission, where the values of sliding between the teeth are moderate even when the pinion was running at 6 000 rpm, no seizure has been found No large symptoms of fatigue wear have been found, either. The area of the occurrence of shallow fatigue pinholes has not exceeded 6% of tooth area for the pinion. The area was located in the region of the base diameter where the radius of the involute curvature is smallest. In the case of gears, uniform area with fatigue pinholes did not appear, only single pinholes could be observed. In addition to the moderate, admissible fatigue wear, activity of the process of abrasion has been observed, particularly in the region of tooth vertex. The investigation has proved the ability of the examined gears to bear high loads. The maximum calculated pressure load for the pinion, under the imposed working conditions was nominally up to 1 300 MPa. As a result of not uniform working of the transmission due to execution deviations of the gear wheels, the true load reached momentary values in excess of the calculated one. When designing transmissions with carbonized and hardened gear wheels pressure values up to 1 250 MPa are assumed for unlimited fatigue strength of tooth sides, in exceptional cases up to 1 500 MPa [3, 4]. Tests with the transmission loaded by a torque of 500 Nm and other parameters unchanged have also been performed. Increase of the torque up to 500 ± 10 Nm has resulted directly in the growth of the pressure on the pinion teeth up to above 1 550 MPa. Symptoms of fatigue wear and seizing have been found during inspection after 7 hours of operation. The temperature of the tooth face has reached 161±8 ^{o}C (for five trials).

SYMPTOMS OF WEAR OF TOOTH BEAING SURFCES

In the conditions of transmission load resulting in nominal pressure of 1 300 MPa, only small symptoms of abrasive wear have been found. Scratches of direction in conformance with the sliding direction of the pinion and wheel side surfaces has been observed in contact when the pressure was increased up to 1 550 MPa (Figure 2). The wear symptoms shown in Figure 2 prove activation of the processes of adhesion wear [5]. Occurrence of scratches and accretions has been found on the teeth of pinions and wheels. They have significantly spoiled the primary structure of the tooth surfaces in the region of their vertices. In the regions of the vertices, the relative speed of the surfaces moving in relation to each other has reached the highest values.

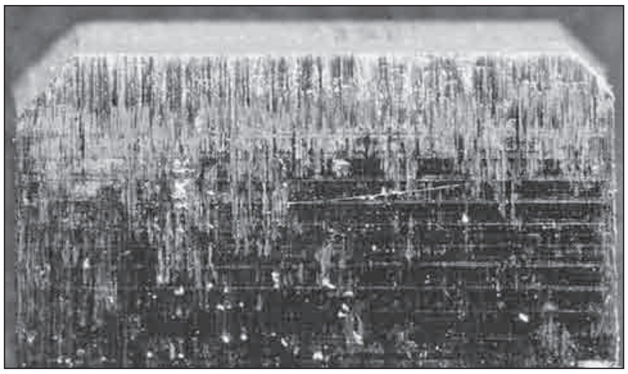

Figure 2 Adhesion wear of the pinion tooth vertex

The significant quantities of heat generated as result of friction in those areas have activated the process of adhesion wear. Due to the high hardness of the gear wheel surfaces, the depth of scratches did not exceed 2 μm (Figure 3).

This proves moderate intensity of the process of seizing. The Figure 4 shows the topography of a surface with a visible scratch being a trace of an adhesion sticking moving in the direction of the tooth sliding. The scratch is surrounded by a plastically deformed area. For comparison, figure four shows photographs of a

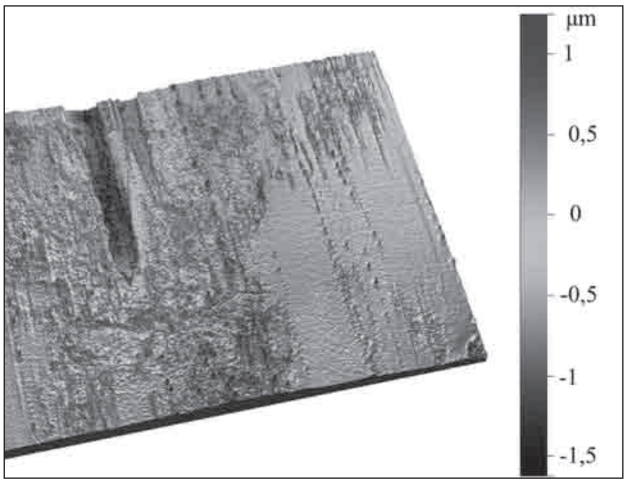

Figure 3 Topography of a tooth surface damaged as result of adhesion processes

pinion tooth vertex without symptoms of wear. In the photograph, one can see a periodical structure consisting of bands parallel to the tooth line. The bands are reflections of the kinematics of machining and they correspond to the subsequent orbital passes of the tool. The source of the transmission seizure can also be traced back to the high temperature of the wheels and oil. Further testing, exceeding 7 hours would result in seizure of the gear wheels. The tooth surfaces near the roots have been completely deformed by the adhesion processes.

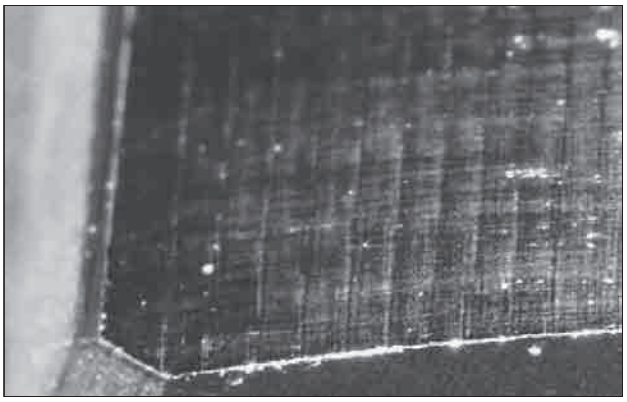

Figure 4 The surface of a pinion tooth vertex without traces of wear

An image of an adhesion pinhole surrounded by plastically deformed area can be seen in Figure 5. In the vicinity of the base diameter, an area with the surface destroyed by the processes of fatigue wear. Single fatigue pinholes have been found.

Uniform wear on the whole width of the tooth proves good contact. None of the tested wheels has worked with an edge contact. Fatigue pinholes in the vicinity of the base diameter have created hollows resulting from unbinding of flat flakes, number one in figure six. The depth of the fatigue pinholes has reached the value of up to 8 μm from the level of the average roughness height. It is visible in the roughness profile through a fatigue pinhole (Figure 6). Around a pinhole, the surface irreg-

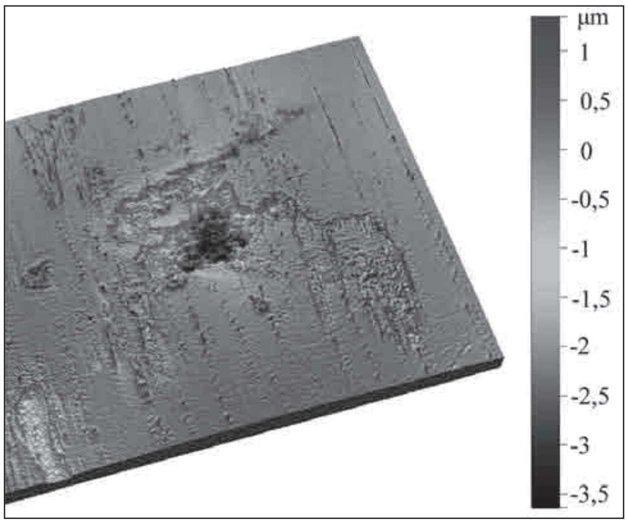

Figure 5 Topography of a tooth surface with an adhesion crater

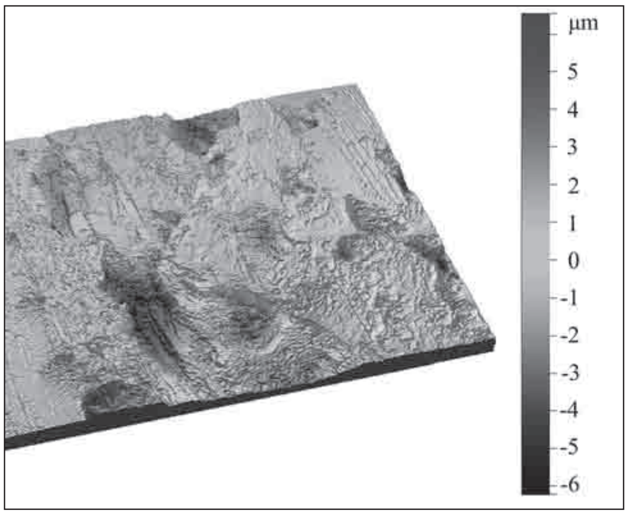

Figure 6 Topography of a tooth surface with fatigue pinholes

ularities exceed the height of 3 μm; this proves strong deformation of the whole area in the vicinity of the base diameter.

Prior to the exploitation test, the value of the roughness parameter, *Ra*, of the surface did not exceed 0,4 μm After the exploitation test, the roughness parameter for the profile shown in Figure 7 was as high as 1,95 μm.

Due to the vanishing of the oil film, an area of metallic contact of the side surfaces of the wheel and the pinion has been reflected on the pitch diameter. Although there was a metallic contact, no scratches has been made as in the vicinity of the tooth vertex because, at this point the wheels roll upon each other without sliding. The transmission load increase by 20 % has activated intensive wearing of the gear wheels. Further operation of the transmission has led to severe modification of the tooth outline. Removal of the tooth material as result of surface fatigue in the region of its smallest curvature has resulted to the profile flattening and, consequently, to reduction of the pressure values and lower fatigue wearing process intensity [6]. Moderate fatigue wearing

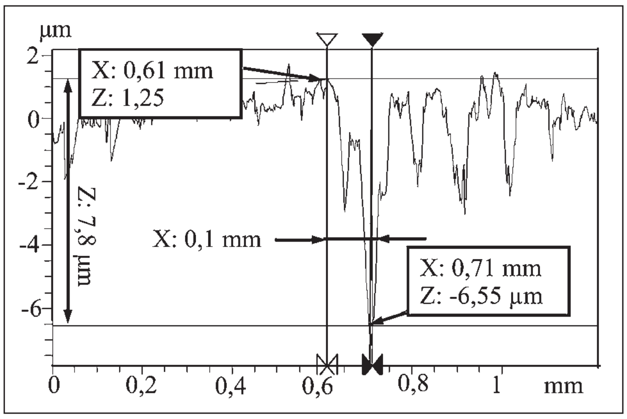

Figure 7 Surface roughness profile through the fatigue pinholes

intensity has been found in the central tooth part. The tooth surface, free of fatigue pinholes has been run-in, *Ra* parameter has reached values not exceeding 0,09 μm. After incorporating the surface with fatigue pinholes and shallow scratches made as result to the matching of the gear wheels, the *Ra* parameter has increased up to 0,82 μm. Corrugation of the surface, being a remainder of the machining process, has also been observed. The depth of affection of the wear processes was not large. In the vicinity of the tooth vertex, the wear processes have completely removed the traces of machining; the *Ra* parameter has even grown up to 0,18 μm as related to the condition prior to the fatigue test. The exploitation properties of the tested gear wheels finish machined with the defined wedge geometry and those ground with a CBN coated grinding wheel do not differ to a statistically significant extent for the confidence level of 95%.

SUMMARY

The experimental tests performed have proved the ability of gear wheels finish machined on machining centres to bear high loads. The processes of adhesion wear and surface fatigue get activated after the pressure values assumed as limit ones in the process of designing transmissions of internal combustion vehicles and general destination transmissions are exceeded [4]. Finish machining of hardened gear wheels with CBN wedges has qualified the wheels to the sixth class of accuracy as regards kinematical precision and smooth operation [1, 2]. This has resulted in limitation of the generated acoustic power in the tooth contact and reduction of the difference between the nominal and actual values of stresses occurring when the teeth are in contact. Matching of gear wheels bearing large nominal pressures of values reaching 1 300 MPa has not resulted in destruction of the bearing surfaces of the teeth. Destructive wear processes have got activated only after the pressure values were increased up to 1 550 MPa. Hardened gear wheels, finish machined by the elaborated method can be successfully applied in silent running transmissions of machines and automotive vehicles working under the conditions of elastohydrodynamic lubrication (EHL).

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Note: Responsible translator: N. Trawinska, The Poznan College of Modern Languages, Poznan, Poland