Effect of High Hydrostatic Pressure on the Abrasive Wear of Hard Alloy Materials

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Abstract: The study of the influence of high hydrostatic pressure on abrasive wear of hard alloy materials has been done using a custom-made setup allowing testing of abrasive wear of materials under hydrostatic pressures of up to 250 atm. It has been confirmed that high hydrostatic pressure has a significant effect on the wear rate of studied materials. By increasing the hydrostatic pressure from atmospheric conditions to 200 atm, for materials with a high content of chromium the wear rate has been increased 7 times, while for materials based on tungsten carbide the wear rate has been increased twice. It has been established that the main damage to surfaces of materials is due to delamination and spalling of hard particles.

Keywords: Abrasive Wear, Hydrostatic Pressure, Hard Alloys, Deep Sea Mining

1. Introduction

The knowledge on actual wear rates of structural materials under the high hydrostatic pressure is critical for the design of wear life time of structural elements of the deep water offshore systems including the deep sea mining systems. The service life of wearing parts of subsea tools determines the profitability of expensive subsea structures and systems. Unexpected shutdowns to replace the broken parts with new ones lead to a significant reduction in productivity, reduce general product quality, rise non-production costs etc. Generally, such interruptions in the operations make it very difficult, and sometimes completely eliminate the possibility of production automation. All this enormously rises operational expenditures. An example of a system working offshore under the high hydrostatic pressure is the deep sea mining system, which are being nowadays developed in the different parts of the World. These systems are envisaged to mine deep sea deposits such as manganese nodules, seafloor massive sulfides etc., which can be found at the seabed at depths ranging from 1500 up to 6000 m. The most probable deep sea mining system would consist of the three main components: (1) subsea crawler, also referred to as seafloor mining tool, which moves along the seabed and performs mining by cutting or suction of the material and its further transportation as a diluted solid-water mixture, a slurry; (2) vertical hydraulic transport system comprising a system of (bundled) risers and a number of subsea slurry pumps; (3) mining support vessel (Figure 1). Obviously, the most subjected to wear parts of the deep sea mining system are the cutting tool, slurry pumps and risers. Read more details regarding the related deep sea mining applications in [1-10]. Another example of highly abrasive process that occurs under the high pressure is drilling in oil and gas industry.

Figure 1. An example of the deep sea mining system (courtesy of Royal IHC).
Pioneering studies related to the friction of materials under hyperbaric pressures have been performed by Bridgman [11]. Based on these studies, Kragelsky et al. [12] have proposed and developed hypothesis of binomial form of the specific friction force. There exist a number of studies aimed to simulate the conditions of high hydrostatic pressure using, for example the uniaxial compression method [13] and thin film method [14]. Most of the studies have been carried out for polymer materials and have confirmed the binominal dependence of the specific friction force. However, those methods have the following weak points: difficulties to account for the lubrication materials, no possibility to separately vary the value of compression pressure as well as the contact pressure, distribution of stresses in the material subjected to the friction does not always correspond to those that really take place under the high hydrostatic pressure [15]. Results of studies of friction in simulating the downhole conditions have been summarized in [15]. It has been concluded that most of existing studies are the applied studies for certain specific conditions and it is hardly possible to systematize them and to establish any laws revealing the effect of hyperbaric pressures on friction and wear. Normally, wear of metal alloys is characterized by two processes: delamination and spalling [17]. Domination of one of these processes depends on the loading conditions and structural condition of material. Also, a medium, in which wear occurs, can have significant effect, which can be exemplified by corrosion. The cyclic component of the load leads to wear-fatigue. The speed of accumulation of micro-damage such as micro pores and micro cracks in the areas of contact depends on cyclic component of stress, which magnitude is determined by the magnitude of the hydrostatic pressure in the liquid medium under consideration. Note that effect of hydrostatic pressure of the process of wear is studied poorly (at least only few results are publicly available). It is worth mentioning that relation of the wear rates to the magnitude of the hydrostatic pressure, under which the process of wear takes place has a nonlinear character. First of all, this is due to the effect of the hydrostatic pressure on strength and plastic proper-ties of metals. For some materials there exists a threshold pressure, for which hardness and plasticity of a metal change significantly [16]. For example, for steel with concentration of Co46%, depending on regimes of thermal treatment, such a threshold pressure is about 130–190 MPa. Until now, there is no universal model that would describe the mechanisms of wear and could forecast the wear rates at high hydrostatic pressures. An important role in the understanding of processes of wear of high-strength alloys belongs to the accumulation of experimental data using the physical methods of investigation such as scanning-electron microscopy (SEM). Summarizing the aforesaid, one can see that analysis of the existing literature clearly shows that studies of friction and wear under the high hydrostatic pressures are limited and obtained results are yet insufficient for a general description of the friction process.
The main objective of this experimental study was to answer the question: how does high hydrostatic pressure affect abrasive wear of structural materials contacting with a substantially hard material (whose hardness is much higher than hardness of the samples)? The study focuses entirely on “pure” abrasion wear within the friction pair placed in a highly pressurized tap water so that any other sources of wear (such as different water chemical compositions, high temperature, different angles of attack (erosion) etc.) or any other type of material deterioration (such as corrosion) do not occur.

2. Methodology

This study is emphasized on four structural materials: sample 1: tungsten carbide alloy (~90% WC ± 10% Co) and three alloys with a high Cr content:
- sample 2: (0-3% Mo, 2.5% Ni, 25% Cr, 20-36.3% C, the rest is Fe),
- sample 3: (16-18% Cr, 0-3% Mo, 2.8-3.2% C, the rest is Fe),
- sample 4: (5% C, 1.25% Si, 20% Cr, 6% Mo, 6% Nb, 0.8% V, the rest is Fe).

An experimental setup that allows studying abrasive wear at high hydrostatic pressures was designed and built by the authors, see Figure 2. It consists of a high-pressure hand pump 1, pressure vessel 2 and electric drive 3. Hydrostatic pressures of up to 250 atm can be generated, which corresponds to the water depth of approximately 2.5 km.

A room temperature was maintained throughout all the tests. Samples had a cylindrical shape with the diameter of 3 mm and height of 12 mm (see Figure 3). Inside the pressure vessel, samples were fixed vertically at the rotating disk (see Figure 4).

A constant frequency of rotation of 0.8 Hz has been maintained. The top side of the samples was in contact with immovable cylindrical polycrystalline diamond head (PCD), fixed in the center of a weight 3 (see Figure 5) and placed on top of the samples (see Figure 6). The reason of choosing this type of material as a friction counterpart can be explained as follows. Before choosing the PCD, a number of rocks with the different harnesses has been tested. It has been discovered that even after longer times of testing weight losses for the tungsten carbide were too low to be properly measured. Using the material, whose tribological properties are, first, higher than those of the samples and, second, which
almost does not wear out itself make the experiment more “clean” since only the samples in this case would be subject to wear.

The following type of the diamond head has been used: AW20*20*80*8 AC4 80/63 M2-01 (100% 14.1), which stands for: 20*20*80*8 dimensions (diameter of the head, height and bore diameter), AC4 is a mark of the diamond powder (synthetic diamonds with increased fragility, whose grains represent aggregates with developed surface), 80/63 is the grain sizes range, (63/80mm are the smallest/largest sizes of grains of the main fraction), M2-01 is the type of the binder (0.1% copper, 20% tin). The total mass of the weight placed above the PCD head including its own weight was 432 g. A scheme of the frictional contact between samples and the diamond head is shown in Figure 7. Each test was carried out during 3 h. Four different values of the hydrostatic pressure were used: 1, 100, 150, and 200 atm. To estimate the repeatability of results, each experiment was repeated three times.

Figure 6. Rotating disk 1 holding samples, subjected under weights 3 (with diamond head 2) and 4.

Figure 7. A scheme of the frictional contact between the diamond head and the samples.

3. Results of Experiments

Weight losses of studied samples as functions of the hydrostatic pressure are shown in Figure 8. Analysis of surfaces of samples has been carried out using scanning electron microscopy. It shows that the main mechanism of wear of the first sample is spalling of tungsten particles, see Figure 9. In contrast to all other samples, in the area of friction of this one there is no there is no “smearing” of micro cracks, which indicates insufficient amount of binder, which in this particular case is Co.

Figure 8. Weight losses of studied samples as functions of the hydrostatic pressure: a–for sample 1, b–for sample 2, c–for sample 3, d–for sample 4.

Initial surface of the second sample has numerous pores and micro cracks (see Figure 10a). The friction zone is characterized by “lamellar punching” and partial peeling of the film layer that has been “rolled over”, which one can easily see on the obtained micrographs (see Figure 10b). One can say that the surface is intensively smeared.
Initial state of a surface of the third sample is characterized by extended micro cracks and numerous pores (see Figure 11a). In the area of friction, there are almost no cracks (see Figure 11b), which means that the cracks are getting smeared over. It can be concluded that the balance of the elements comprising the alloy is such that in the area of friction the viscous properties of the alloy are triggered and eventually the initial micro cracks are getting “smeared”. A group of dark spots is also observed in the area of friction. X-ray microanalysis in the mapping mode along the line showed that these areas are rich in Cr and C, thus the composition of the alloy is characterized by a certain heterogeneity, which is manifested by the presence of regions with embedded phase of chromium carbides.
The material of the fourth sample has a high percentage of binder, which is in this case iron. Long strips are observed (see Figure 12b) that have been obtained by sliding diamond particles over the surface of the sample. A part of the material is extruded along the edges of the strips. A chipping of solid particles is observed. The material is characterized by absence of Ni in the alloy element, which usually imparts viscosity, and high content of C 5%, Cr 20%, Mo 6%, Nb 6%, providing a hardness and embrittling the alloy. Spalling for this sample is less intense than one that occurs for the first sample, material of which is based on tungsten carbide.

To describe the wear process in the absence of hydrostatic pressure the most widely used theory is the theory of fatigue wear. The basis of this theory is the concept of fatigue failure in sliding near-surface material layers. According to this mechanism of failure, embedded and flattened protrusions of rough contacting surfaces are exposed to constantly repeated stresses and strains. The intensity of wear (wear rate) depends on the type of contact (elastic, plastic), frictional strength and elastic properties of the material, surface micro-geometry, temperature, etc. [16]. To calculate wear rates based on these factors, fatigue models consider specific protrusions in the form of a hemisphere, cylinder, etc. However, the real protrusions have an arbitrary shape and are distributed randomly. The process of fatigue wear depends on many random factors affecting the separation of wear particles. Therefore, the theory of the fatigue wear provides mostly only qualitative description of the process of frictional destruction.

4. Conclusions

Experiments that have been carried out have proven that high hydrostatic pressure leads to the increase of wear of all four materials under consideration. Analysis of surfaces of hard alloy samples has shown that the main mechanism of wear is delamination and spalling of hard particles. Clearly, hydrostatic pressures of up to 200 bars have a considerable effect of the wear rates. For the third sample (16-18% Cr, 0-3% Mo, 2.8-3.2% C, the rest is Fe), weight loss increases 7 times, for the first sample based on tungsten carbide, it increases twice. The least effect of the hydrostatic pressure occurs for the fourth sample (5% C, 1.25% Si, 20% Cr, 6% Mo, 6% Nb, 0.8% V, the rest is Fe). Generally, higher wear (larger weight losses) at high hydrostatic pressures mainly occur to the brittle-to-ductile transition. When material becomes more ductile, then the interaction forces in the contact area change compared to those at atmospheric conditions and/or small hydrostatic pressures due to the “smearing” and “punching”. Due to the increased vertical force as well as due to the increased ductility of samples the total contact area between two (generally irregular) surfaces increases. Thus, more material is subjected to the actual friction, so the weight loss also increases. Apart from that, talking on a micro level, more ductile behavior of binder allows hard particles to chip out easier from the matrix. Obtained
results clearly indicate that effect of high hydrostatic pressure on wear of must be always taken into account during the design phase of subsea structures and tools working at large depths.

Also, it is necessary to consider that increase of the hydrostatic pressure leads to the change of the ratio of spherical part of stress tensor to the deviatoric one, which also affects the speed of accumulation of micro damage. According to [18], the rate of damage accumulation (micro pores and micro cracks) depends on the strain energy release rate of the damaged body. The deformation energy is calculated as a sum of the shear strain energy and energy of the volumetric expansion. The ratio of the spherical to the deviatoric parts of the stress tensor is very important for the development of damages. Change of the hydrostatic pressure up to 200 atm leads to a noticeable change of the spherical part of the stress tensor, which should be revealed in the rate of wear. In a general case, the speed of accumulation of fatigue damage depends nonlinearly on the amplitude of applied stresses [19].

Apart from that, there exists a threshold hydrostatic pressure, for which hardness and plasticity of materials change significantly.

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