EARLY DETECTION OF CAVITATION EROSION USING THE MORPHOLOGY OF PARTICLES PRODUCED IN INCUBATION PERIOD

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Wear particles produced by cavitation erosion on Al-99.92, and carbon steels of ASSI 1045 and 5117 were analyzed using scanning electron microscope (SEM). The particle morphology features were clarified for the incubation stage (IS) and the subsequent stages (ES). It was observed that IS-particles have distinctive characteristics which differed from that of the ES. These characteristics include the lamella shape, folding and curving with one of the particle surfaces as the original surface of specimen. The ES-Particles have a larger thickness and a more irregular compared with that for the IS. Surface characteristics of IS-particles can be used as a successful tool to detect early cavitation erosion.

KEYWORDS: Cavitation erosion, Particle erosion, Particle morphology Incubation period, Fatigue.

INTRODUCTION

In high-speed hydraulic machinery and instruments, irreparable damage by cavitation erosion occurs very often. This severe erosion usually takes place at about twice the rate of ordinary erosion. Therefore, a growing interest has been focused on such problems in order to find practical methods for early detection of erosion, especially in closed systems without their complete disassembly. This would result in tremendous cost savings in maintenance, improved reliability, prevention of catastrophic failure and the development of maintenance schedules.

The accurate characterization of surface topography has become increasingly in machine condition monitoring (1), as a surface topography is a key factor affecting the function and reliability of a component.

Surface damage features and wear particles are the objects most often examined when considering the wear mode and mechanism. The recognition of wear condition in tribological system as well as wear mechanism in wear process mainly depends on the analysis of surface topographies of wear components. It is very difficult to access or analyze wear components which are in operation. However, wear particles can be easily gained (2). Careful examination of morphology of wear particles can yield specific information about the condition of the moving surfaces. For many years, in maintenance, wear debris analysis has been a subject of practical and economical interest, since wear condition in a machine can be monitored by the examination of debris without costly dismantlement of machinery (3). Very little effort has been made (4 – 10) however, to approach cavitation erosion studies from the particle analysis stand point. With the steadily increasing number of closed systems where cavitation erosion is a maintenance problem, study of the wear particles becomes highly desirable.
It is basically accepted that there are two stages at the cavitation-erosion damage: the incubation stage (IS), during which the surface is plastically deformed without a detectable weight loss and commonly characterized by a duration or incubation period (IP); and the erosion stage (ES), during which cracking and weight loss take place at different rate depending on time. Figure 1 illustrates the characteristic stages of cavitation erosion as reported by ASTM

![Characteristic stages of erosion rate-time pattern](image)

Fig. 1 Characteristic stages of erosion rate-time pattern

Due to the impossibility to measure by conventional gravimetrical techniques the threshold instant, in which the weight loss starts, several criteria (11-14) have been proposed to define the IP. These criteria to evaluate IP are limited to more or less precisely evaluate parameters related to weight or volume loss without considering other changes which occur in the material during the cavitation exposition as deformation mechanisms, material properties and dislodged particle.

Utilizing computer image analysis, (9, 10) the characteristics of Al-99.999 particles produced during cavitation erosion. In incubation period, the particles have distinctive characteristics which differed from that for the subsequent periods. These characteristics include the value of longitudinal ratio and roundness factor, limit size range and morphological features such as lamella shape, folding, curving and one of the particles surface was the virgin surface. In acceleration, steady-rate and attenuation period, the particles have a wide size range and larger thickness compared with that for the incubation period. The maximum particle size was in acceleration and steady-rate period, and it was about 360 \( \mu m \). For all cavitation erosion rate periods, the particles were out of sphericity and they have a roundness factor larger than 2. The particle generation mechanism is fatigue. Based upon these results, the authors concluded that the observation of particles characteristics during the incubation period can be used as a successful tool to detect early the cavitation erosion occurrence. Therefore, the aim of this work is to characterize the particles produced by cavitation erosion for typical tribomachinery materials. The study focuses on the particles produced in incubation stage, IS and the erosion stage, ES.
2. EXPERIMENTAL DETAILS

2.1 Apparatus.

The Schematic setup of the vibratory apparatus is shown in Fig. 2. A high intensity 550 W ultrasonic processor was used for running this test. It was programmed to resonate at 20 kHz+ 50 Hz. The ultrasonic power supply (generator) converts 50/60Hz frequency to a higher value of 20 KHz. The electrical energy is transmitted to the piezoelectric transducer within the converter is changed to mechanical vibrations. In vibration cavitation, the forces causing the cavities to form and collapse are due to a continuous series of high amplitude, high-frequency pressure pulsations in the liquid transmitted by the probe, creating pressure wave in liquid. This action forms microscopic bubbles (cavities), which expand during the negative pressure extrusion based on the vapor pressure of the liquid. Thus, a peak-to-peak amplitude (50 μm) was programmed for the effects of cavitation erosion to be visible.

Fig. 2 Schematic view of test apparatus

2.2. Materials and specimen preparation

The test materials were AISI 5117 Carbon steel, AISI 1045 carbon steel and Al-99.92. Since the surface roughness plays an important role in developing erosion and material removal (12), therefore the specimen’s working surfaces were highly polished with grade 3000 emery paper. The specimens made of AISL 5117 and AISL 1045 were flat-surfaced disks of 16 mm diameter which is larger than the horn tip of 12.7 mm in diameter. The aluminum specimen had an area of 22 x 22 mm² and thickness of 3 mm.
2.3 Particle collection

The wear particles were collected by two methods. A ferrography method has been used to separate the eroded particles of AISI 5117 and 1045. Figure 3 shows the schematic diagram of the ferrograph. A filtering method using a 0.45 μm pore diameter plastic filter made of porous cellulose nitrate membrane was used for collecting the eroded particles of Al-99.92. Then particles are placed on a brass stub covered with carbon tape.

Fig. 3 Working principle of ferrograph

2.4 Test condition

The specimen was placed co-axially with the horn and was hold stationary at the distance of 0.8 mm from the horn tip. The specimen and the end of the stepped horn were immersed in 1200 ml open beaker having 700 ml of tap water (test water). In order to stabilize the gas content and to release entrained gases, the test water was allowed to stand in an open atmosphere for at least 24h (13) before testing. Since the test water temperature markedly affects the degree of erosion (14, 15), the bulk water temperature was kept within $25 \pm 2^\circ C$ by circulating cooling water as shown in Fig. 2. Preliminary tests showed that the temperature of the liquid film on the specimen surface rose rapidly regardless of the constant temperature in the beaker. This temperature was measured for a maximum duration test time with a thermocouple inserted in the center of test piece It was found for a 10 minute (maximum duration test time), that the film temperature did not exceed the controlled temperature by more than $3^\circ C$. Before and after each test, the specimens were rinsed in acetone and dried in air and weighed with a 100g ± 0.1 mg sensitivity balance. The eroded surface and the collected particles were investigated by scanning electron microscope (SEM).
3. RESULTS AND DISCUSSION

3.1. Particle analysis

A typical dislodged particle for the tested materials Al-99.92, AISI 1045 and AISI 5217 are shown in Figs 4 and 5 for IS and in Fig. 6 for ES. The figures depict that the particles eroded during each stage have similar characteristics, irrespective of test material. However, these characteristics differed from stage to stage. It can be observed that IS-particles (Figs 4 and 5) are lamella in form, which has been folded and curved. In addition, one of the particle surfaces was of the virgin surface which is defined by its smoothness and traces of polishing lines.

Fig. 4  Scanning electron micrographs of particles removed at IS for (a) Al-99.92, (b) AISI 1045 and (c) AISI5117

Fig. 5 Similar particles to that shown in Fig. 4 removed at IS for (a) Al-99.92, (b) AISI 1045 and (c) AISI5117

The degree of foldness depends on the material properties and it is the less for AISI 5117. The foldness and the curving of IS-particles were interpreted as follow (10): at the beginning, due to the collapse of the formed cavities the superficial layer is subjected to compressive load, while the bulk material of the specimen is not or slightly affected by this compression load. This means that the superficial thin layer, which is subjected to normal compression load, tends to elongate (Spread) flatwise, but the bulk material resists this spreading. This will create residual compressive stresses in the superficial layer in the flatwise direction. This is consistent with the residual stress measurements (16, 17) which showed that cavitation leads to the development of compressive residual stress in the sample surface. As soon as an erosion particle in the form of lamella is dislodged due to fatigue it will curve or fold depending on the intensity of the residual stresses induced in it before its removal from the specimen surface. This feature is not observed for the particles removed in the ES. Therefore, it
can be concluded that the particles in the incubation stage have distinctive characteristics compared to particles in the ES. So these characteristics of IS-particles can provide direct and early information on the beginning of cavitation erosion.

Figure 6 illustrates the typical particles detached during the ES for the test materials. ES-particles have similar appearances and are more irregular and thicker than the IS-Particles.

![Image of particles](image-url)

**Fig. 6 illustrating the particles removed at ES for (a) Al-99.92, (b) AISI 1045 and (c) AISI5117**

The reason for the change in the shape of ES-particles from IS-particles may be attributed to the following (10): the surface of metals is known to consist of several layers having physicochemical characteristics peculiar to the bulk material itself (18), Fig. 7. Since specimens are polished and rinsed in acetone before experiments, the contaminated and/or oxidized layers are removed. The remaining specimen surface consists of the bulk material covered with thin layer of work-hardened metal of thickness of about 10µm. This layer is peeled in the IS in the form of lamella as described before. Now, the bulk material is subjected to cavitation erosion. Wear particles are removed by fatigue wear (8, 10) which is characterized by the formation of large wear fragments. Therefore, wear particles in ES are thicker than that in IS.

![Image of cross-section](image-url)

**Fig.7  Schematic illustration of the cross-section of the surface structure of metals (18).**

### 3.2 Morphologies of eroded surfaces

Figure 8 shows scanning electron micrographs of eroded surface of the three tested materials, during the IS. When the ductile materials such as the tested materials were exposed to cavitation, most of the test surface has local plastic deformation. This deformation was in the form of surface undulations as well as the appearance of the slip bands, the grain boundaries and the twin lines. In addition, pits were formed and particles began to be removed, which are in agreement with the reported results (19).
Fig. 8 micrograph of eroded surface at IS for (a) Al-99.92, (b) AISI 1045 and (c) AISI5117

Figure 8 (a) shows a developed macropit on the Al-Specimen. On the edge of this pit, it is easy to observe that some particles are still undetached (Labeled Pu) and some of them have been detached. The same observations can be seen also for the other two materials as shown in Fig 8 (Labeled Pu). The undetached particles manifest also the same above mentioned features. This strongly supports that the features of particles removed during the IS can be used as a reliable tool to detect early cavitations erosion.

4. CONCLUSIONS

The IS-Particles have distinctive features, which differ from that for ES, for the three tested materials, Al-99.92 and carbon steel, AIS 1045 and 5117. These features include the lamella shape, folding and curving. In addition, one of the particle surfaces appeared to be part of the original surface of the specimen. Therefore, these characteristic can be used as a monitor for early detection of cavitation erosion in closed systems.

REFERENCES


التنبؤ المبكر لتأكل التكهف باستخدام دراسة تشكل الحبيبات الناتجة في فترة الاحضان

الحبيبات الناتجة:

في هذا البحث تم تحليل الحبيبات الناتجة عند تأكل التكهف للمواد الآتية: الألومنيوم (99.92% AI ونوعين من الكربون ستيسل (AL1045.5117) باستخدام المجهر الإلكتروني. تم توضيح ودراسة بنية وشكل الحبيبات لكل من مرحلة الاحضان والمراحل المتاخمة. وقد لوحظ أن حبيبات مرحلة الاحضان لها خصائصها المميزة والتي تختلف عن تلك التي للمراحل المتاخمة. وهذه الخصائص تشمل الشكل الشعاعي وانحناءات وإطواءات مع أحد أسطح تلك الحبيبات هو السطح الأول للعينة قبل التآكل. وبالنسبة لحبيبات المراحل المتاخمة تكون أمراً وذات عدم انتظامية أكثر من حبيبات مرحلة الاحضان. وبناءً على علية فإن الخصائص السطحية المميزة لحبيبات مرحلة الاحضان يمكن استخدامها كوسيلة ناجحة للتنبؤ المبكر بتآكل التكهف.