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CAVITATION EROSION MONITORING OF MULLITE CERAMIC SAMPLE USING IMAGE ANALYSIS

SANJA MARTINOVIĆ
University of Belgrade, Institute of Chemistry, Technology and Metallurgy- National Institute of the Republic of Serbia, Belgrade, Serbia, s.martinovic@ihtm.bg.ac.rs

ANA ALIL
University of Belgrade, Institute of Chemistry, Technology and Metallurgy- National Institute of the Republic of Serbia, Belgrade, Serbia, ana.alil@ihtm.bg.ac.rs

TATJANA VOLKOV HUSOVIĆ
University of Belgrade, Faculty of Technology and Metallurgy, Belgrade, Serbia, tatjana@tmf.bg.ac.rs

Abstract: *Numerous industrial equipment are designed to withstand harsh operating conditions that among others include cavitation erosion. This study examined the cavitation erosion behavior of mullite, a common material used in furnace linings and casting processes such as Lost Foam which is a novel way to produce castings offering both high quality and reasonably priced. The ultrasonic vibratory method with a stationary sample was employed to achieve cavitation erosion, while image analysis was used to measure the degree of surface deterioration. This study aimed to assess the lifetime of mullite under cavitation exposure by quantifying the morphological parameters of the defects through image analysis and by monitoring material behavior. The obtained results were discussed and analyzed in order to understand degradation mechanisms and sample resistance to cavitation erosion. The results demonstrate that mullite is highly resistant to cavitation, as the volume loss is minimal and the surface degradation is below 6% after 180 minutes of exposure.*

Keywords: *Mullite, Cavitation erosion, Non-destructive evaluation, Image analysis.*

1. INTRODUCTION

Cavitation is a phenomenon in which vapor bubbles form in a rapidly flowing liquid when it suddenly enters a region of low pressure. While some bubbles already exist in the fluid, others are formed and expand under these conditions. The formation of low-pressure regions can be influenced by factors such as high fluid velocity, sharp edges or corners, and turbulent flow conditions, which can result in conditions where the pressure drops significantly and lead to the formation of cavitation bubbles. If fluid flow enters a region of high pressure afterward, bubbles may rapidly collapse or implode which often results in the generation of a micro-jet and shock wave. Various factors, including liquid temperature, chemical activity, flow rate, pressure drop, and the presence of dissolved or steam gas influence the implosion of bubbles. If the bubble collapse occurs close to a solid component, it can cause significant damage to the surface, resulting in erosion and a reduction in the material's overall lifespan and performance. Hardened stainless steels, titanium alloys, and high-performance ceramics are among the materials resistant to cavitation because they are designed to endure the erosive effects of cavitation and maintain their integrity even under high fluid velocities and turbulent flow conditions. The cavitation phenomenon affects various industries and equipment, such as automotive engines, marine propellers, pumps, hydraulic turbines, and fuel injectors. Therefore, it is crucial to select cavitation-resistant materials and explore all possibilities for extending the lifespan and improving the performances of these components [1-5].

Mullite, a ceramic material, was selected for this study due to its unique composition and structure offering a high melting point, low thermal expansion, and excellent mechanical properties. Specifically, its exceptional hardness gives it excellent wear resistance and allows it to endure repetitive impact and abrasion. In addition to its high hardness, mullite also possesses excellent fracture toughness and strength, making it highly resistant to cracking and deformation under the erosive forces of cavitation. Mullite's resistance to cavitation makes it a desirable material for various applications such as components for pump impellers, marine propellers, and hydraulic machinery. This property enables the material to endure high-velocity fluid flow and the erosive impact of cavitation, ensuring its durability and longevity. Furthermore, mullite is resistant to corrosion and extreme temperatures, making it an ideal choice for applications that require resistance to harsh environments, and also to a combination of all mentioned environment conditions. Additionally, mullite is lightweight, making it suitable for applications where weight is an important factor. Mullite is a well-known ceramic and refractory material often used for linings, coatings, or fillers of linings in furnace

Corresponding author: S. Martinović;
E-mail: s.martinovic@ihtm.bg.ac.rs
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walls. The extreme conditions in industrial furnaces, including high temperatures and erosion effects caused by solid particles from loading and the flow of molten slag and metal, are somewhat comparable to the harsh conditions experienced during cavitation. Specifically, parts of furnaces and devices are exposed to solid materials and high-speed fluid flow [6-10]. Therefore, it is very important to conduct various tests to examine the installed material, in this study the mullite, for cavitation resistance.

2. EXPERIMENTAL

Mullite ceramic samples were prepared using pure mullite powders with granulation of 40 µm, which were initially processed by micronizing grinding in a vibrating mill with agate balls to achieve a grain size of 15-25 µm. The goal was to obtain powders with specific grain sizes and shapes that would exhibit improved properties, better grain packing, and greater densification during pressing. This process aimed to provide a homogeneous sintered structure that would have good resistance to cavitation. Such finely ground powders were then pressed in a mold under a pressure of 1 MPa to form cylindrical samples with a diameter of 30 mm and thickness of 3 mm. The sintering process was carried out at a temperature of 1200 ºC according to the following regime: raising the temperature to 1000 ºC at a rate of 5 ºC/min for 200 min; 1000-1200ºC with a heating rate of 2ºC/min for 100 min; at 1200ºC, the samples were dwelled for 1 hour.

The resistance of mullite samples to cavitation erosion was assessed using the ultrasonic vibration method with a stationary sample, following the ASTM G-32 standard. The purpose of this method is to simulate cavitation erosion conditions to predict the material's behavior within a short period, typically 2-10 hours. The advantages of this approach include its small testing device, sample size, and low energy input. The method involves creating and imploding cavitation bubbles on the sample's surface and then measuring the sample's mass loss during exposure to cavitation, thus providing a quantitative measure of material resistance. The ASTM G-32 standard defines testing conditions, sample preparation, and procedures for result interpretation. The stationary sample method is an indirect cavitation testing technique, which involves placing the sample in a water bath under a mechanical vibrations concentrator at a specified distance. This method is particularly useful for testing hard and brittle materials like mullite. Cavitation erosion tests were conducted in distilled water at a temperature of 22 ± 2 °C, using a vibration frequency of 20 ± 0.2 kHz, and an amplitude of mechanical vibrations at the top of the ultrasonic probe of 50 ± 2 µm. The distance between the test sample and the ultrasonic probe was 0.5 mm. During the cavitation test, the samples were dried to constant mass, weighed with an analytical balance with an accuracy of ± 0.1 mg to calculate the mass loss, and photographed in digital form for further image analysis after each certain testing period. The monitoring of cavitation erosion was 180 minutes.

The Image Pro Plus 6.0 software program (IPP) was used to quantify surface defects caused by cavitation erosion (Media Cybernetics, 2006, Rockville, MD). This process involves the recognition of differently colored damaged and undamaged areas on the sample surface thus extracting defects and providing valuable information about the objects. The IPP analyzes photographs in various formats and automatically counts, measures, and classifies data about the extracted objects. The IPP allows the direct export of all measured data into Microsoft Excel thus enabling the enormous datasets of measured values to be processed.

3. RESULTS

According to the standard that establishes criteria for the interpretation of the results, after measuring the sample weight, mass loss of material was calculated. Subsequently, knowing the value of tested material density, the volume loss of material was calculated and the results are shown in Figure 1.

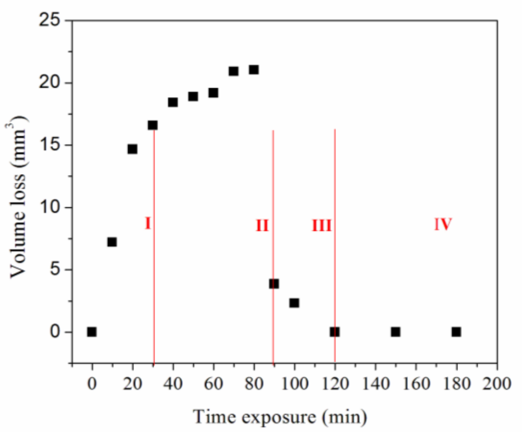

Figure 1. Volume loss of eroded material during cavitation.

Besides the proposed way of analyzing results, a non-destructive method of image analysis was applied to monitor the surface changes that occurred during the testing.

After each period of cavitation exposure, surface samples were scanned with a resolution of 1200 dpi, Figure 2. The obtained images were then processed using the Image Pro Plus software program. Using IPP tools, the total area of the surface defects was measured so the level of degradation could be calculated according to Equation 1. The level of surface degradation is defined as the ratio of the damaged surface area and the original surface area.

Level of degradation (%) = $P/P_0 \cdot 100$

where P is the total degraded area (mm^2) and P_0 is the area of the sample surface (mm^2). The diagram in Figure 3 shows the calculated values of degradation level during the testing. This method provides a reliable and objective assessment of the extent of degradation caused by cavitation exposure.

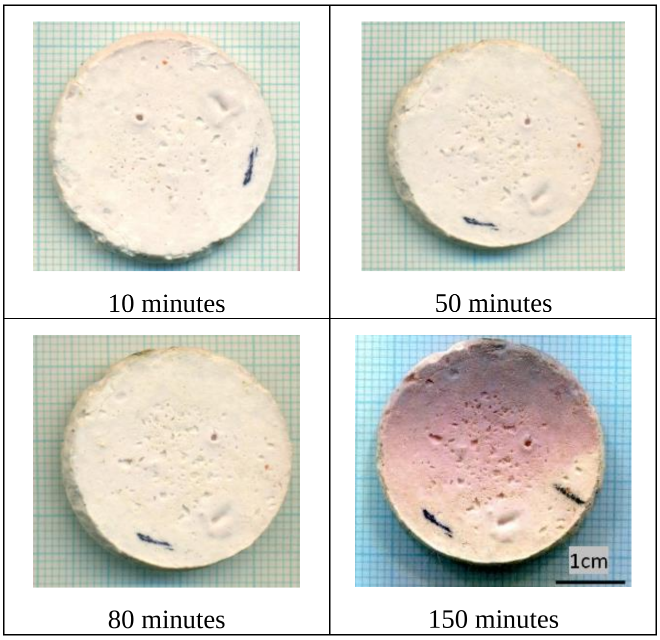

Figure 2. Scanned images of the specimens' surface during the cavitation testing.

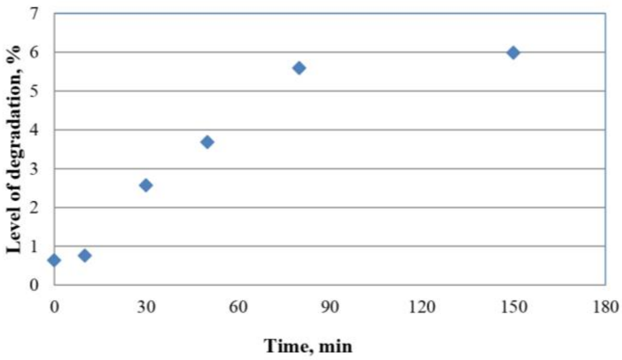

Figure 3. Level of degraded area during the cavitation testing.

4. DISCUSSION

Material volume loss is a consequence of material erosion during the cavitation experiment, as shown in Figure 1. It is evident that there is a continuous increase in volume loss during the first 80 minutes of treatment, firstly very rapid up to 30 minutes and then getting quite slower reaching a maximum. It can be assumed that the number of defects and pits, along with their dimensions (area and depth) increased throughout the experiment. The results also indicate that initial surface imperfections were present at the beginning of the experiment.

A visual inspection of the mullite samples, shown in Figure 2, indicates that the surface of the reference sample was not ideal and that there were already some damages present even before the sample was tested. Additionally, it is evident that with the exposure to cavitation, the number, shape, and size of surface defects will increase and will change over time as they are exposed to cavitation.

The graph in Figure 1 shows the results of volume loss over time exposure to the cavitation. The diagram distinctly identifies the four typical stages of the cavitation process, as marked in Figure 1. The first is known as the incubation period, which lasts for the initial 30 minutes of cavitation exposure. As shown in Figure 3, during this period, a slight degradation occurs amounting to less than 3% of the sample's surface area. This period is characterized by the appearance of small and shallow surface flaws and pits. In the second stage, known as the acceleration period, there is significant mass and volume loss as well as surface degradation. This stage lasts until 80 minutes of cavitation exposure, as shown in Figs 1 and 3. The results indicate that this period is characterized by the appearance and growth of defects and pits equally on the surface and in the depth. During the third stage, which occurs after 80 minutes and lasts until 120 minutes of cavitation testing, new defects rarely form on the sample surface. Instead, the prevailing degradation mechanism involves the growth of defects that have already formed. The last period is known as the steady state during which there is no substantial material loss and the surface degradation level is nearly negligible as well.

Obtained results show that mullite is a very resistant material under exposure to cavitation since values of volume loss are quite small and the surface degradation level is below 6 % after 180 minutes of cavitation exposure.

5. CONCLUSION

The cavitation erosion of the mullite sample was studied by measuring and calculating the material volume loss and assessing the level of surface degradation using image analysis.
In summary, the applied approach is useful for determining the extent of degradation caused by cavitation exposure reliably and objectively.

The volume loss results showed the existence of four distinct periods of cavitation erosion and the duration of each period. The obtained results demonstrate that mullite exhibits high resistance to cavitation. The volume loss is minimal, and the surface degradation is below 6% after 180 minutes of exposure.

The level of surface degradation was quantitatively determined by measuring the total area of the formed pits using image analysis software tools. Image analysis showed a slight degradation of less than 3% occurs initially, with minor surface flaws appearing. In the acceleration period, which lasts until 80 minutes of cavitation, significant mass loss, volume reduction, and surface damage occur. Defects and pits grow during this stage. In the final stage, from 80 to 120 minutes, new surface defects rarely form.

Changes observed in material volume loss and the level of degradation during testing can be related to the degradation mechanism, which is essential for optimizing material selection and designing the material production process.

Acknowledgments

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