Metallurgical and Materials Data 2, no. 2 (2024): 51-54

Publisher: Association of Metallurgical Engineers of Serbia

Metallurgical and Materials Data

www.metall-mater-data.com

Non-destructive evaluation of cavitation erosion behavior of alumina-based ceramic materials

Ana Alil[1]*, Sanja Martinović[1], Tatjana Volkov Husović[2]

[1] University of Belgrade, Institute of Chemistry, Technology and Metallurgy - National Institute of the Republic of Serbia, 12 Njegoševa St., Belgrade, Serbia
[2] University of Belgrade, Faculty of Technology and Metallurgy, 4 Karnegijeva St., Belgrade, Serbia.

ARTICLE INFORMATION:

https://doi.org/10.56801/MMD31

Received: 13 June 2024
Accepted: 09 July 2024

Type of paper: Research paper

ABSTRACT

Numerous industrial parts, devices, and processes are designed to withstand the conditions that lead to cavitation erosion. Metallic, ceramic, and composite materials used for these conditions must achieve specific mechanical characteristics required to resist cavitation erosion. When molten metal or alloy flows and comes into contact with refractory material or coated furnace linings, cavitation erosion can occur. This phenomenon is particularly expected in metallurgy, especially in casting operations. Alumina-based refractories, specifically low cement castable (ALCC), are often used in furnace lining applications due to their superior properties, such as high refractoriness, thermal stability, and mechanical characteristics. Mullite is another refractory material frequently used in foundry lining applications. It can be utilized as a coating in casting processes, such as the Lost Foam process, which is a novel method for producing high-quality, cost-effective castings. These two refractory materials were chosen to study their behavior under cavitation conditions. An ultrasonic vibratory test with a stationary specimen (ASTM G-32) was used for experimental cavitation determination. The results of mass loss and surface morphological parameters of degradation revealed that ALCC samples eroded predominantly at the surface, while the mullite samples exhibited more significant degradation by depth.

Keywords: Alumina low cement castable (ALCC), Mullite, Cavitation erosion, Defects, Non-destructive evaluation.

1. Introduction

Cavitation resistance of material for engineering applications is one of the demands which is very common. This results from conditions with fluid flow which can cause erosion of material induced by cavitation. Conditions including fluid flow are often part of the processes in chemical and metallurgical engineering. Parts of the equipment used in these processes (valves, turbines, hydropower plant reactors, pipelines, and parts of the furnaces in metallurgy) are often exposed to cavitation erosion. In metallurgical engineering conditions when the refractory lining is exposed to liquid metal or flue gases can be estimated by cavitation erosion testing.

Gas or vapor pockets can frequently result from high-velocity liquid pressure variations in hydraulic parts. These pockets suddenly collapse on the surface of the material due to a change in pressure near the surface. These burst gas bubbles, also known as micro-jets, eventually cause material damage (Hammitt 1980; Franc and Jean-Marie 2006; Brennen 2011; Karimi 1986).

Bubble cavitation and sheet cavitation are two of the several varieties of cavitation erosion. The following are some cavitation erosion influences (Okada et al. 1995; Huballi and Sondur 2013; Brennen 1995; Krella and Zakrzewska 2018):

- The claimed material's microstructure, hardness, and other material-specific characteristics,
- Other operational characteristics include the kind of pressure fluid, operating pressure, and operating viscosity,
- The length between the vulnerable solid surface and the flow resistance, the flow resistance's geometry, and additional constructive factors.

Several factors can lead to cavitation erosion:

- Element creation via basic water or acid and electrolytic erosion,
- Chemical reactions under high pressure or temperature were impacted by oxygen,
- Pressure rise brought on by pushing a fluid/liquid over its boiling point and experiencing an abrupt collapse of the vapor bubble,
- Pressure-induced local speed increase reduces bubble formation.

* Corresponding author.
E-mail address: alil@tmf.bg.ac.rs (Ana Alil).

Two very often used refractory materials based on alumina were used in this investigation: alumina-based low cement castable (ALCC) and mullite-based samples. In this study, results related to the monitoring of the level of degradation of these samples caused by cavitation erosion will be the goal of the paper. Cavitation erosion testing was performed using standard ultrasonic vibratory testing with stationary specimen (ASTM G-32, 2021).

2. Materials and methods

Two ceramic materials used as refractories for various applications in metallurgy were selected. The low-cement castable was prepared using tabular alumina (T-60, Almatis, Ludwigshafen, Germany) as an aggregate, with a matrix comprising fine fractions of tabular alumina, 5 wt.% calcium–aluminate cement (CA-270, Almatis, Botlek, The Netherlands), reactive alumina (CL-370, Almatis, Ludwigshafen, Germany), and dispersing aluminas (ADS-3 and ADW-1, Almatis, Ludwigshafen, Germany). Alumina low cement castable (ALCC) samples, sintered at 1600 °C for 3 hours, were synthesized and analyzed by the procedure earlier explained in detail (Martinovic et al., 2010; Martinovic et al., 2013). Mullite ceramic samples were prepared using pure mullite powders initially ground to a size of 15-25 μm from 40 μm granules through micronizing grinding in a vibrating mill with agate balls. The goal was to achieve specific grain sizes and shapes that improve properties, grain packing, and densification during pressing, aiming for a homogeneous sintered structure resistant to cavitation. These powders were pressed into cylindrical samples (20 mm diameter, 3 mm thickness) at 1 MPa pressure. The mullite samples were sintered at 1200 °C with a dwell time of 3 hours.

Cavitation erosion testing was performed using the standard ultrasonic method with a stationary specimen (ASTM G32, 2021). The procedure is described in detail (Martinovic et al. 2021; Martinovic et al. 2023). For both samples, the time of cavitation exposure was 120 minutes. After certain periods, samples were dried, weighted by analytical balance, and scanned with a resolution of 1200 dpi.

3. Results

3.1. Mass loss

One of the most used simple methods to follow the behavior of the samples subjected to the degradation caused by cavitation erosion is mass loss monitoring. According to the ASTM G32 standard mass loss is used. Obtained results for ALCC and mullite samples are presented in the Figure 1.

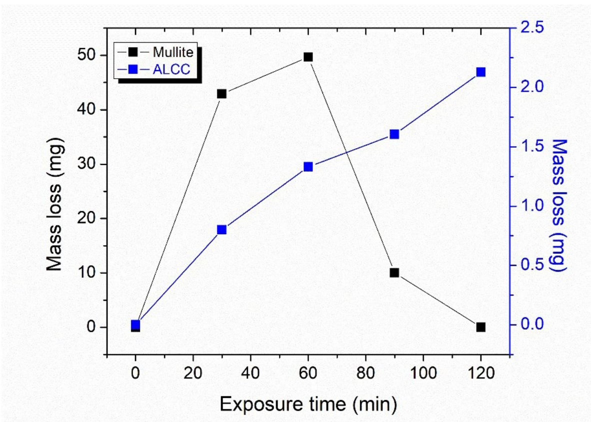

Fig. 1. Mass loss of ALCC and mullite samples during the cavitation

3.2. Image analysis

Image analysis of the sample surface was used for degradation monitoring, and this approach is more reliable compared to mass loss measurements. An image analysis approach for different morphological parameters can be measured, describing the formation and growth of formed pits, as a result of the cavitation erosion process. One of the most used parameters are pits area, pits diameters, and number of pits. Discussion of these parameters can be used for the determination of the degradation mechanism.

Images of the sample's surface during cavitation testing are given in Figure 2. Images of the samples were obtained by scanning with high resolution (1200 dpi), to monitor the total surface of the samples.

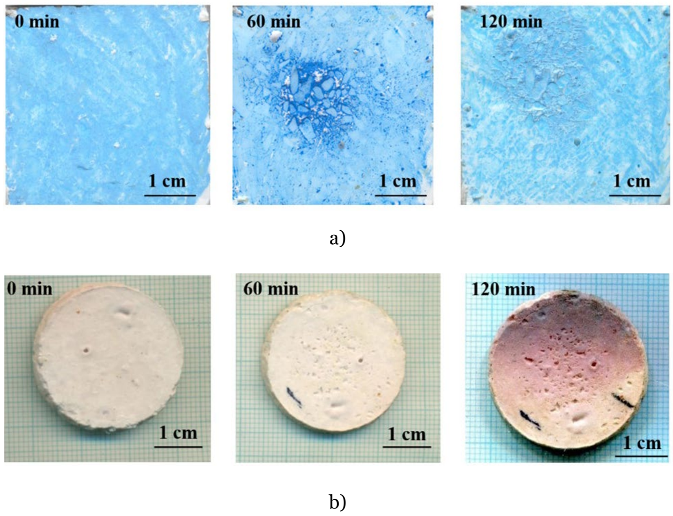

Fig. 2. Scanned macro images of the sample surface during the cavitation: a) ALCC and b) mullite sample

3.3. Line profile

One of the simplest analyses implemented using IPP can be a line profile related to the diameter of the probe (16 mm) where most degradation during cavitation testing happens. This approach can be useful for comparison level and frequency of the formed pits. Results for the samples are presented in Figure 3.

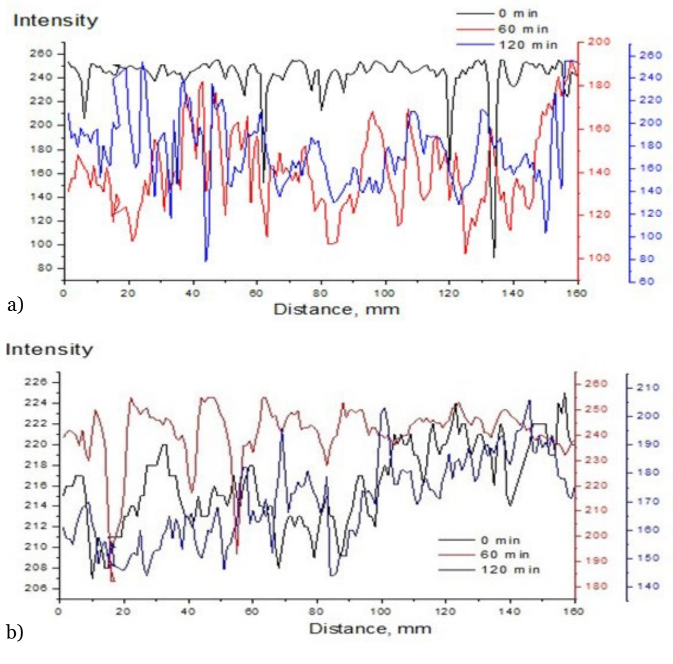

Fig. 3. Line profiles during cavitation testing: a) ALCC and b) mullite sample

Different intensity degradation levels can be observed in Figure 3. ALCC samples show a much lower level of degradation than mullite samples. Also, the level of degradation of both samples with longer times to cavitation exposure, increased. For ALCC samples depth of the pits is lower, and the formed pits are similar dimensions. Different behavior is observed for mulite samples, as formed pits are with higher depth, and the size of the formed pits on the line is different, formed pits are different, there are formed new pits with smaller dimensions, and larger ones result in pit growth during cavitation.

3.4. Morphological analysis

Morphological analysis is related to different parameters chosen to describe the formed pits, which are represented as the degradation of the samples caused by cavitation erosion. A large number of morphological parameters can be used, as a list of the possible parameters is described in detail (Martinovic et al. 2013; Martinovic et al. 2023). In this paper several parameters are chosen: average pit diameter, total area of the formed pits, and number of pits. These three chosen parameters are most representative of describing and quantifying the level of damage during cavitation erosion testing. This method is also helpful for comparing the degradation behavior of different samples and monitoring degradation during testing.

As it could be seen before testing, both samples have some defects, due to the preparation. During the different times of exposure, the level of degradation rises, as well as some parameters, such as the number of pits, and the average diameter and area of the pits which are given in Figures 4-6.

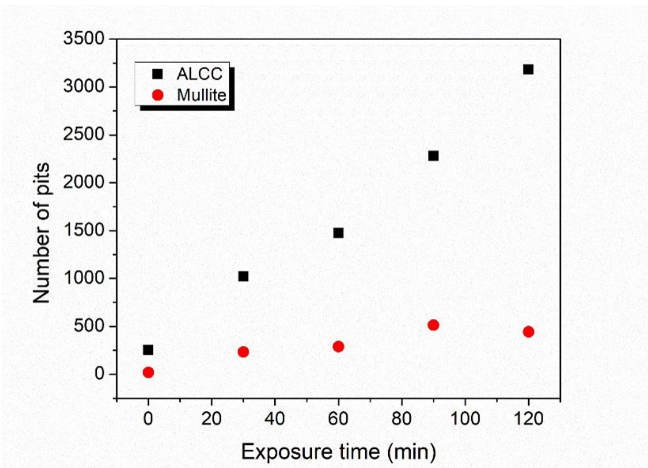

Fig. 4. Number of pits during different exposure times to cavitation

The number of formed pits and changes during the exposure time of testing is related to the mechanism of its behavior. Since the number of formed pits for ALCC is rising during testing, the dominant mechanism is its formation, as, only results for the number of pits are discussed. Similar results were obtained for mullite samples. Pit formation dominates the mechanism for up to 60 minutes, as the number of produced pits increases during testing. A period of 60 to 90 minutes is also connected to the process of pit growth. Since the number of pits rises only slightly between 90 and 120 minutes, pit growth is also included in the degradation mechanism (Figure 4).

After 60 minutes, the average area of the pit for the ALCC sample decreased from 60 minutes is related to the pits' growth and merging of the formed pits. As expected, the total area of the formed pits increased, from 7.92 mm^2 at the beginning, before the exposure, to 101.57 mm^2 after 120 minutes, as can be observed in Figure 5. As expected, the total area of the formed pits increased, from 4.5 mm^2 before the exposure, to 45 mm^2 after 120 minutes for mullite samples, while the total area of the formed pits increased, from 8 mm^2 before the exposure to 100 mm^2 for the ALCC sample, which can be considered similar degradation rate (Figure 5). The average area of the single pit for ALCC is related to the number of pits, as pit formation is dominant, and the average area of the pit is between 0.03 and 0.04 mm^2, while for mullite samples is below 0.1 mm^2 for the whole testing period (Figure 6).

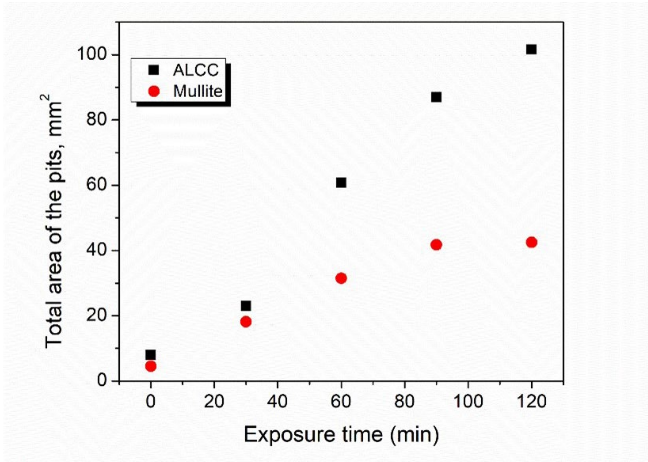

Fig. 5. Total area of the pits during different exposure times to cavitation

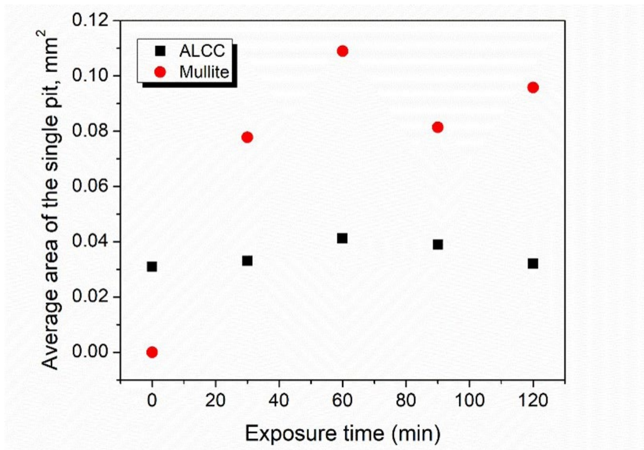

Fig. 6. The average area of the single pit during different exposure times to cavitation

4. Discussion

Results for morphological parameters analysis are similar for both samples. It is evident that there was some degree of degradation before testing; for mullite samples, it was lower than 5 mm^2 and for ALCC samples it was around 8 mm^2. Degradation was approximately 40 mm^2 for mullite samples and up to 100 mm^2 for ALCC samples after 120 minutes, which may indicate that mullite samples are more resistant to cavitation erosion.

Formation of pits was the dominant mechanism for ALCC to 30 minutes, then pit growth and merging of formed pits was to 60 minutes. For mullite samples till 90 minutes pits formation was dominant, and after 90 minutes pits growth and merging of formed pits was observed. The average area of a created single pit and the number of formed pits indicate the behavior of the degradation in means of its mechanism. For both samples, the average area of pits increases, to 60 minutes, and decreases after that which can be related to pits growth and merging the formed pits simultaneously with pits formation. Considering the results of mass loss and surface morphological parameters of degradation it can be concluded that ALCC samples eroded dominantly at the surface, while the mullite samples degraded much more by depth.

5. Conclusions

In this paper two ceramic materials often used for refractory application were subjected to cavitation erosion tests. Monitoring the behavior of the samples was using mass loss changes, as well as, image analysis by using selected morphological parameters. The morphological parameters that best describe the behavior of the samples and the degradation mechanism were the number of pits, the average pit size, and the total area of the pits. If these two samples are compared, results for mass loss, as well as, results of image analysis point out similar behavior in cavitation erosion conditions. The results demonstrate the dependability of ALCC and mullite ceramic use under cavitation erosion conditions.

Acknowledgments

This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-66/2024-03/200026 and 451-03-65/2024-03/200135).

References

ASTM G32; Standard Test Method for Cavitation Erosion Using Vibratory Apparatus. ASTM International: West Conshohocken, PA, USA, 2021

Brennen, Christopher. 2011. Review of An Introduction to Cavitation Fundamentals. In Cavitation: Turbo-Machinery & Medical Applications. WIMRC FORUM 2011 University of Warwick, UK.

Brennen, Christopher. 'Cavitation and Bubble Dynamics'. Cavitation and Bubble Dynamics 44 (1995).

Franc, Jean-Pierre, and Jean-Marie Michel. Fundamentals of Cavitation. Springer Science & Business Media, 2006.

Hammitt, Frederick Gnichtel. Cavitation and Multiphase Flow Phenomena, 1980.

Hubballi, B., and V. Sondur. 'A Review on the Prediction of Cavitation Erosion Inception in Hydraulic Control Valves'. International Journal of Emerging Technology and Advanced Engineering 3 (2013): 110–19.

Karimi, A., and J. L. Martin. "Cavitation erosion of materials." International Metals Reviews 31, no. 1 (1986): 1–26.

Krella A. K. and Zakrzewska D. E.. "Cavitation Erosion – Phenomenon and Test Rigs" Advances in Materials Science 18, no.2 (2018): 15-26.

Martinovic, Sanja, Milica Vlahovic, Marina Dojcinovic, Tatjana Volkov-Husovic, and Jelena Majstorovic. "Thermomechanical Properties and Cavitation Resistance of a High-Alumina Low-Cement Castable." International Journal of Applied Ceramic Technology 8, no. 5 (2010): 1115–24.

Martinovic, Sanja, Milica Vlahovic, Tamara Boljanac, Marina Dojcinovic, and Tatjana Volkov-Husovic. "Cavitation resistance of refractory concrete: Influence of sintering temperature." Journal of the European Ceramic Society 33, no. 1 (2013): 7–14.

Martinović, Sanja, Milica Vlahović, Maja Gajić-Kvaščev, Marija Vuksanović, Dragomir Glišić, and Tatjana Volkov-Husović. "Principal component analysis of morphological descriptors for monitoring surface defects induced by thermal shock." Journal of the European Ceramic Society 41, no. 16 (2021): 423–29.

Martinović, Sanja, Ana Alil, Sonja Milićević, Dragana Živojinović, and Tatjana Volkov Husović. "Morphological assessment of cavitation caused damage of cordierite and zircon based materials using principal component analysis." Engineering Failure Analysis 148 (2023): 107224.

Okada, Tsunenori, Yoshiro Iwai, Shuji Hattori, and Norio Tanimura. "Relation between impact load and the damage produced by cavitation bubble collapse." Wear 184, no. 2 (1995): 231–39.

Prstić, A., Z. Aćimović-Pavlović, A. Terzić, and L. Pavlović. "Synthesis and Characterization of New Refractory Coatings Based on Talc, Cordierite, Zircon and Mullite Fillers for Lost Foam Casting Process." Archives of Metallurgy and Materials 59, no. 1 (2014): 89–95.