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SLURRY EROSION – DESIGN OF TEST DEVICES

ABSTRACT

Degradation of material caused by impacts of a solid particle (erodent) suspended in a liquid is called slurry erosion and is a major problem in the hydropower and maritime industry. Slurry erosion depends on many factors, e.g. liquid and erodent velocity, size, shape, angle of impact, hardness and number of erodents, and strength of a target material. The various types of test devices have been designed to investigate an effect of mentioned parameters on material resistance. In the paper are described main types of the test apparatus showing their main advantages and disadvantages. Some results of slurry erosion resistance of few groups of materials are also presented.

Keywords: *erosion, slurry erosion, test apparatus*

INTRODUCTION

Degradation of material caused by impacts of a solid particle (erodent) suspended in a liquid is called slurry erosion [1,2]. This phenomenon is a major industrial problem and is especially dangerous in the region of India - Nepal, as well as China - Three Gorges Dam and the areas of the Huang He (Yellow River) [3,4]. Degradation caused by slurry occurs in fluid-flow machinery, mainly in the hydropower industry and in maritime industry, e.g. water turbines, valves, pipelines and marine propellers [2,5]. The main effects of the erosion are economic losses resulting from the need to replace or regenerate the device and stop the technological process. Erosion causes gradual mass loss of the surface layer, changes the geometry of the elements of the installations and machinery that leads to a reduction in their efficiency and service life [6,7]. The costs of failures associated with slurry erosion, i.e. part replacements or regeneration of eroded machine parts, loss of productivity, indirect losses of energy and the increased environmental burden, constantly increasing and are real business problems. Due to essential problem with damage of hydraulic machines, a special standard for testing hydro-abrasive erosion in Kaplan, Francis and Pelton turbines has been described in International Standard IEC 62364:2013 [8].

Since 1946, when the first technical papers on erosive wear were published [9], many investigation of material degradation due to slurry have been performed. In 1960 Finnie [10] published his pioneer work about slurry erosion, in which degradation mechanisms and

theoretical analyses for predicting erosion damage were presented. Although further work on improvement of theoretical considerations and extensive experimental investigations, slurry erosion remains the unsolved wear problem. The number of works devoted to solid particle or slurry erosion indicates the rank of these problems. Only in 2016 in Elsevier journals over 700 papers, which concerned the slurry erosion phenomenon, were published. In order to better learn slurry erosion phenomenon and correlations between material properties and material resistance, several types of test rigs have been designed. The aim of this paper is to present the key test rigs in investigating material resistance against slurry erosion. Additionally, the slurry erosion phenomenon has been also shortly presented in order to show the problem of material degradation. Furthermore, groups of materials used to slurry erosion test and some methods of surface treatment are presented.

SLURRY EROSION PHENOMENON

Slurry erosion is a process of surface degradation due to repeating impacts of solid particles flowing with a liquid (Fig. 1). Degradation of materials due to slurry erosion depends on many factors, which can be divided into three main groups: the first one connected with fluid flow conditions (flow velocity, angle of particle impingement, particles concentration, liquid density, liquid chemical activity, liquid temperature), the second one connected with solid particles (size, shape, hardness, strength) and the third one connected with target material (mechanical and endurance properties: toughness, fatigue, yield and ultimate strengths, work hardening, surface topography, microstructure, number and size of defects) [3,6,9-12]. Thus, the numbers of factors influencing slurry erosion is very big and the degradation of materials is a synergic effect of all mentioned factors.

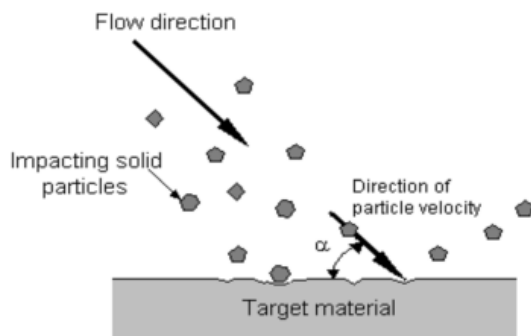


Fig. 1. Schematic of slurry erosion [13]

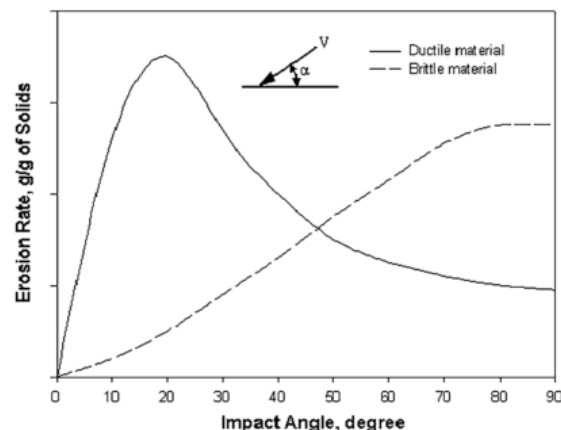


Fig. 2. The dependence of erosion rate on impact angle [13]

Impact velocity and the size of solid particle has an effect on the kinetic impact energy of a single particle. With increasing impact velocity and particle size increases erosion rate. Similar effect on erosion rate has an increase of particle concentration in a liquid that influences the total impact energy. Depending on impact velocity, slurry erosion is divided on

high- and low-velocity erosion. If velocity increases above 6-9 m/s, high-velocity erosion is formed, while below this velocity, slurry erosion is called low-velocity erosion [3]. In case of presence of sub-micron particles (30 – 150 μm in diameter) in a liquid flowing with velocity above 10 m/s, a sub-sonic erosion develops [13]. This type of erosion consists in inception of cavitation bubbles at particles surfaces [13].

Next key factor having huge impact on degradation is material stiffness, which is strictly connected with material hardness. With increasing stiffness / hardness of target material increases angle of critical impact, at which occurs maximum erosion rate (Fig. 2) [1,4,7,14]. In case of ductile materials, the maximum erosion rate occurs at approx. 20° . In case of brittle materials, the maximum erosion rate occurs at normal impacts. Despite the material hardness, the hardness of solid particles influences the material erosion rate [1,14].

Due to high importance of degradation caused by slurry erosion, a large number of materials have been tested. Tested materials can be divided into following groups: ferrous [5,15], cobalt-based [4,16] nickel-based [2,7,11], titanium-based [4] materials and bulk metallic glasses (BMG) e.g. zirconium-based bulk metallic glass ($\text{Zr}_{44}\text{Ti}_{11}\text{Cu}_{10}\text{Ni}_{10}\text{Be}_{25}$) [2]. In case of ductile ferrous materials, e.g. stainless steel SUS304, the erosion rate increases with increasing impact velocity, while decreases to a critical value in the test time [5]. On the eroded surface develops W-wear scars, which are characteristic of ductile materials. Coating of stainless steel AISI 316 with cobalt-based and titanium-based alloy using shielded metal arc welding (SMAW) method increases surface hardness and erosion resistance in comparison to bare stainless steel AISI 316 [4]. Investigations of zirconium-based bulk metallic glass ($\text{Zr}_{44}\text{Ti}_{11}\text{Cu}_{10}\text{Ni}_{10}\text{Be}_{25}$) and hydroturbine steel (CA6NM) shows that slurry erosion resistance of bulk metallic glass is higher 2.6 and 1.6 times at the impact angle of 30° and 60° , respectively, than the steel one [2]. On the other hand, for the impact angle 90° , the erosion rate for the bulk metallic glass is slightly lower compared to CA6NM. The main reason for good erosion resistance of bulk metallic glass at the impact angle below 90° is its high hardness, strength and elastic strain limit [2]. As it is shown in Fig. 2, stiff materials reaches the maximum erosion rate at impact angle of approx. 90° , while ductile materials - the minimum erosion rate. Also, deposition of hard $\text{Ni-Al}_2\text{O}_3$ coatings on hydroturbine steel CA6NM substrate by means of thermal spraying increases slurry erosion resistance from two to four times, depending on the impact angle, in comparison to that of the substrate steel [7]. Among $\text{Ni}+20\%\text{Al}_2\text{O}_3$, $\text{Ni}+40\%\text{Al}_2\text{O}_3$ and $\text{Ni}+60\%\text{Al}_2\text{O}_3$ coatings, the best slurry erosion resistance has $\text{Ni}+40\%\text{Al}_2\text{O}_3$ coating due to best fracture toughness [7]. Therefore, in order to mitigate the harmful effects of slurry erosion, various surface treatment methods to increase surface hardness have been introduced. The main method is to deposit coating. Several deposition methods are used: e.g. the detonation-gun spray process [17], oxy fuel powder (OFP) process [18,19], wire arc spraying (WAS) process [18], high velocity oxy fuel (HVOF) process [19], physical vapour deposition (PVD) [20], plasma and flame spray methods (thermal sprayed coatings) [21], laser surface alloying (LSA) [15]. There are also other methods, which enhancement of slurry wear resistance, e.g. work hardening [22], nitriding [23], predeposited by brush plating and next surface alloying [24], boronising [25], borided [25].

Deposition of Co-based coating on 16Cr-5Ni martensite stainless steel by using laser surface alloying (LSA) method and then hardening of coating using of high-power fiber coupled diode laser resulted in two times better resistance to slurry erosion as compared to bare 16Cr-5Ni stainless steel [15]. Applying HVOF methods for deposition of WC-12Co and $\text{Cr}_3\text{Cr}_2\text{NiCr}$ coating on 316L stainless steel decreased the wear rate almost 1000 times as compared to 316L stainless steel [57]. Moreover, slurry erosion resistance of WC-Co coatings



increased much more than other coatings: e.g. Al_2O_3 and $\text{Al}_2\text{O}_3\text{-TiO}_2$ coatings deposited using plasma-sprayed method, FeCrB based coatings deposited using pulsed laser clad method [57].

Addition of nanoparticles to coatings improves coating strength and erosion resistance. Deposition of polyurethane coating containing nanoparticles B_4C or SiC on 16Cr-5Ni martensitic steel resulted in an increase of erosion resistance due to high hardness of B_4C and SiC [29].

Due to uniform description of material degradation due to erosion caused by slurry, impingement by liquid jets or drops or by solid particles, as well as cavitation and cavitation erosion, the specialist terminology has been defined in the international ASTM Standards: G 40 [26] and G 73-10 [27].

SLURRY EROSION APPARATUS

As it was shown in the description of the slurry erosion phenomenon, the degradation of materials depend on impact angle, impact velocity and concentration of solid particles in liquid. Therefore, the design of slurry erosion devices allow to investigate an effect of mentioned parameters. However, not all parameters are fully controlled in each test rig. The slurry erosion devices are divided into two main types: jet type and rotating type rigs [6].

Some design of jet type rigs are presented in the ASTM G 73 and G 76 Standards [27,28]. However, these standards concern mainly on the test methodology in various types of erosion, not only on slurry erosion. The ASTM G 73 standard concerns liquid impingement erosion [27] and the ASTM G 76 standard concerns solid particle impingement using gas jets [28]. Most test apparatus are designed individually by researcher teams. The rotating type apparatus are not described in the ASTM standards.

Jet type apparatus

According to the name of this type apparatus, slurry (liquid with solid particles) as a jet impact the target material, which may be stationary or rotate [27,29]. In rigs with rotating specimens, a specimen crosses a slurry jet, causing cyclic collisions. In case of devices with a stationary specimen, a specimen is continuously exposed to a slurry jet.

The device, in which a test specimen is fixed to a rotating arm or disk, is described in the ASTM G-73 Standard. The whirling specimen crosses a jet with frequency depending on velocity of rotating disk (Fig. 3). The jet velocity is in range from 50 m/s to 1000 m/s and nozzle diameter have range from 0,1 to 5 mm [27]. Slurry is pumped through the impeller system and directed at a specimen via a nozzle. Thus, there is risk of pump damage, because the solid particles impact the rotor blades with different velocity and in this case lead to faster wear of pump. The test devices based on ASTM G 73 Standard has been used in Ref. [4,14, 29-34].



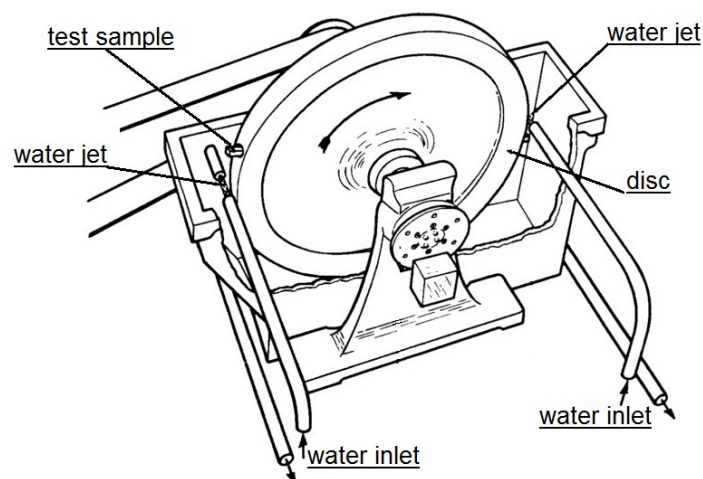


Fig. 3. Rotating disk-and jet repetitive impact apparatus, according to ASTM G 73 [27]

Next type of jet devices are the devices with stationary specimen. In this group of devices, the division can be performed according to the system of delivering and formation slurry. In the first one, erodent is added to a jet just before leaving a nozzle using either its gravitational drop or ejector (Fig. 4). The test devices with a gravitational drop of erodent are described in ASTM G 76 [28]. In the second group, erodent is mixed with liquid in a special tank, and then slurry is pumped to a nozzle (Fig. 5).

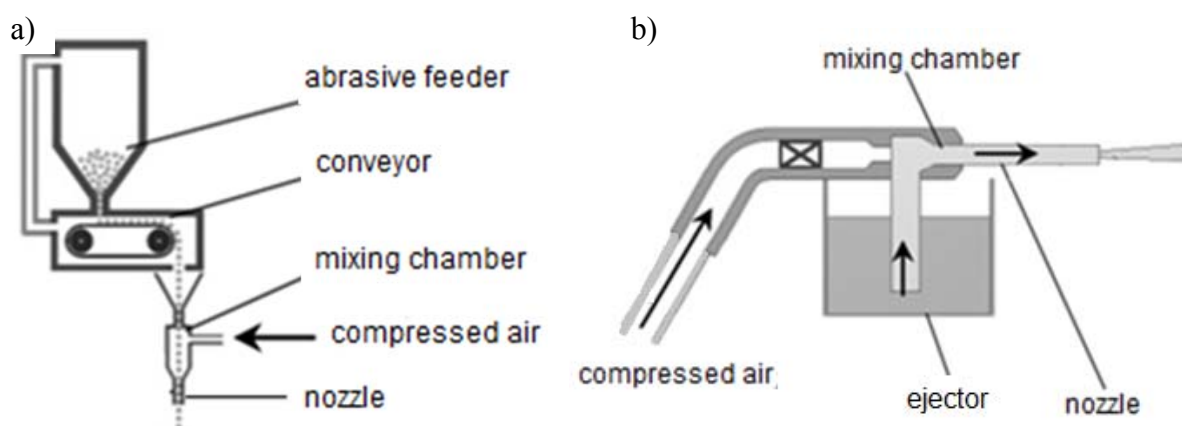


Fig. 4. Examples of the slurry jet devices with various dosing systems, (a) abrasive delivered by gravity [27], (b) with using an ejector [27]

According to ASTM G76 [28], the test device consists of a nozzle, mixing chamber, a source of compressed air and abrasive metering system (Fig. 4a). The compressed air and abrasives are supplied to the mixing chamber from which the mixture comes out through the nozzles with a diameter of 1,5 mm and a length of 50 mm. After leaving the nozzle, scattered in the air jet solid particles, impact the surface of a test specimen. The test specimen is located at a distance of 10 mm from the nozzle. During the test, the impact velocity of solid particles is 30 ± 2 m/s with a single particle size $20 \div 80$ μm . The flow is at approx. 8 l/min at a pressure of 140 kPa [6,28]. Thus, comparing to the test device built based on ASTM G 73, the impact velocity in this test device is much slower. However, in Ref. [35, 36], the design of the rig has been modified to reach impact velocity in the range up to 120 m/s.

In the slurry device with an ejector (Fig. 4b), carrier fluid is pumped from a holding tank to an ejector. In the ejector is formed a region of low pressure due to the difference in diameter between the input and output nozzles. This low pressure region draws erodent into the ejector. The erodent and the carrier fluid are mixed to form a slurry jet which is accelerated through the ejector and impinges on the specimen surface. This device design prevent a pump against erosion, but the amount of erodent impacting a specimen is related to the fluid velocity and the pressure fall in the ejector. This type of test device has been used in Ref. [3,29,37-41].

An example of a slurry device with stationary specimen and mixing tank is shown in Fig. 5a. This type of test device allows controlling well impact velocity, mass flux rate, distance between a nozzle and a specimen, an impact angle and solid particle distribution, but a pump is exposed to erosion. The eroded surface has characteristic shape of ring with undamaged protruded island at the middle (Fig. 5b). Among others jet type slurry device, this type of test rig is quite popular, it has been used by in Ref. [2,3,5,7,11,40-45].

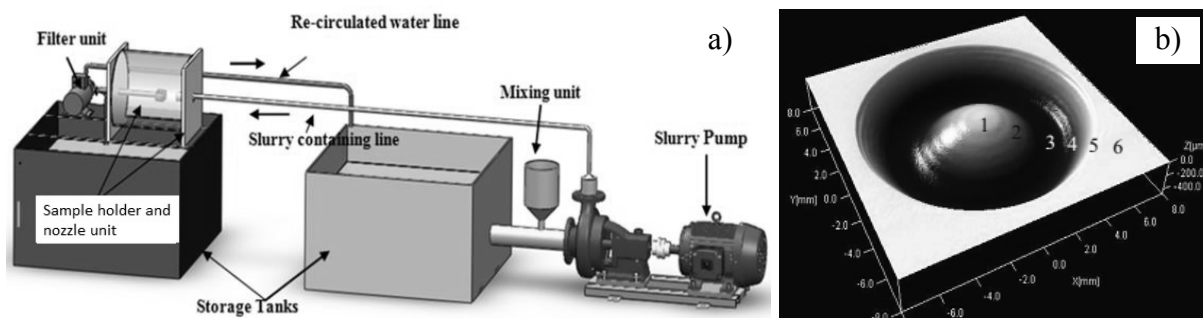


Fig. 5. Examples of the slurry jet devices with stationary specimen (a) [16] and an eroded surface (b) [5]

The jet impingement testers can be also divided depending on circulation system into two groups: recirculation (RC) [46-49] and nonrecirculation (NRC) [7,11,31,50]. The advantage of the RC type is the ease of construction and operation, while the advantage of the NRC type is the ability to eliminate influence connected with changing the particle size after collision with the test surface. Moreover, using the RC type, there is a problem with controlling the concentration of the solid particles in the liquid.

The major drawback of the jet type of test device is the wear of the nozzle, leading to the need for periodic measurements and calibration of the impact velocity. Furthermore, the impact angle of all solid particles (abrasive) is not the same. In addition, the jet with solid particles is locally concentrated on the test surface, this situation lead to create simulations of slurry erosion with slightly different from that occurring in the natural environment.

Rotating type of test apparatus

The rotating type devices can be divided onto slurry pot, Coriolis erosion devices and whirling arm devices. In this type of test device, motion is caused by rotation test specimens and slurry [4].



Slurry pot

This type of a slurry device has very simple design. A slurry pot was introduced by Tsai et al. [51] and similar one was designed and fabricated in 1995 by Gupta et al. [52]. The pot tester of approximately 3,8 l capacity consists of aluminum cylindrical container, rotating arms, specimen holders, shaft, motor, stirrer and bearings (Fig. 6) [52]. The aluminum container of 135 mm height and diameter of 205 mm is covered 12-mm perspex lid. The propeller attached at the bottom of the shaft (10 mm in diameter) protects against falling solid particles and has uniformly distribute solids in a liquid medium. The test specimens (28x6.5x2 mm) are placed in four specimen holders, which are parallel to the central shaft at equal distances. The impact angle has large range (0°-90°), but in steps of 15°. The shaft is connected to the motor. The test specimens are placed on both sides parallel to the central shaft. The flow of the liquid is directed perpendicular to the axis of the specimen. The appropriate (predetermined) mass abrasive is added to the stainless steel pot, then it is closed tightly fitting lid. The next step is the addition of an appropriate amount of water through the opening in the upper shell to completely fill the pot. The propeller is mounted at the bottom of the pot. The purpose of the propeller is to maintain the slurry at a distance of 24 mm from the bottom and this part is rotated by a motor. After all testing, drain the slurry mixture [52,53].

This test device has advantages and disadvantages. The disadvantages may include the difficulty in controlling the flow conditions and the parameters of the particles such as the real density of impacting particles and temperature of slurry. In contrast to jet type, this test device is easier to use, manufacture and very cheap. A big advantage of this type of test device is the ability to quickly conduct simultaneously tests of four specimens of different materials in compare to other test rigs with this same erosion intensity [12,54].

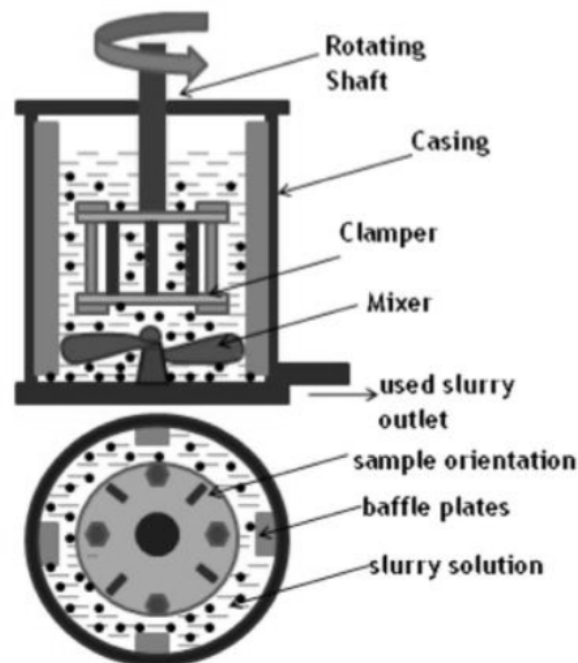


Fig. 6. Slurry pot test device [55]

Coriolis erosion tester

Coriolis tester was originally introduced in 1984 by Tuzson [56], to investigate the movement of slurries and their interaction with surfaces such as pumps and pipelines. Slurry erosion tester was modified by Clark et al. in 1999 [57]. The purpose of the modification was to adapt the device for using flat test specimens with dimensions of 29 x 15 x 6 mm [57]. The scheme of a tester is shown in Fig. 7. Coriolis slurry tester uses centrifugal and Coriolis forces. Freshly prepared slurry from container fed into the center of the rotor (diameter 150 mm), where is a slurry inlet port (diameter 12,7 mm). The specimen holders are located at equal distances from the center of rotation of the rotor. In the specimen holders are the channels through which flows the slurry, while the base of the channel forms the test specimen. The channels are 1 mm wide and 6,35 mm high with rectangular cross-section [58,59]. The test specimen rotates at a speed up to 7000 rpm [57]. The tester uses an electric motor of 1.5 kW and speed controller under low impact angle. Slurry is accelerated outwards by centrifugal force, while under the influence of Coriolis force erodent particles settle on the surface of the test specimen, thereby increasing the interaction of the slurry with the surface of the specimen. Due to high rotation speed, this method shortens the testing time [60]. The design of the tester allows testing simultaneously two specimens.

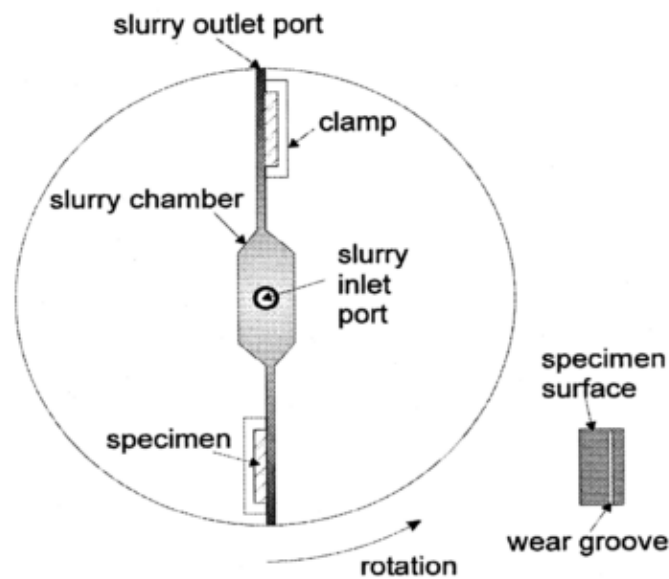


Fig. 7. Coriolis erosion tester [56]

Whirling arm test device

The whirling arm test device was developed by Lin and Shao [61]. The slurry tank (25 l in capacity) contains a mixture of solid particles and water, which are mixed using a stirrer. Then the thus prepared mixture flows to the next tank in the shape of a funnel with a stirrer. It is important that the mixture is mixed properly. The test device has four horizontal arms, on which placed test specimens. The arms are attached to a shaft. During the test, on test specimens falling jet from the slurry tank (funnel-shaped) with a velocity of 1,62 m/s. An important feature is the ability to fine adjustment of impact angle (0° - 90°) and impact velocity. Tests are carried out in a vacuum (up to 37.3 kPa) because the authors wanted to eliminate the effect of air flow (aerodynamic effect) on the slurry stream [62,63].

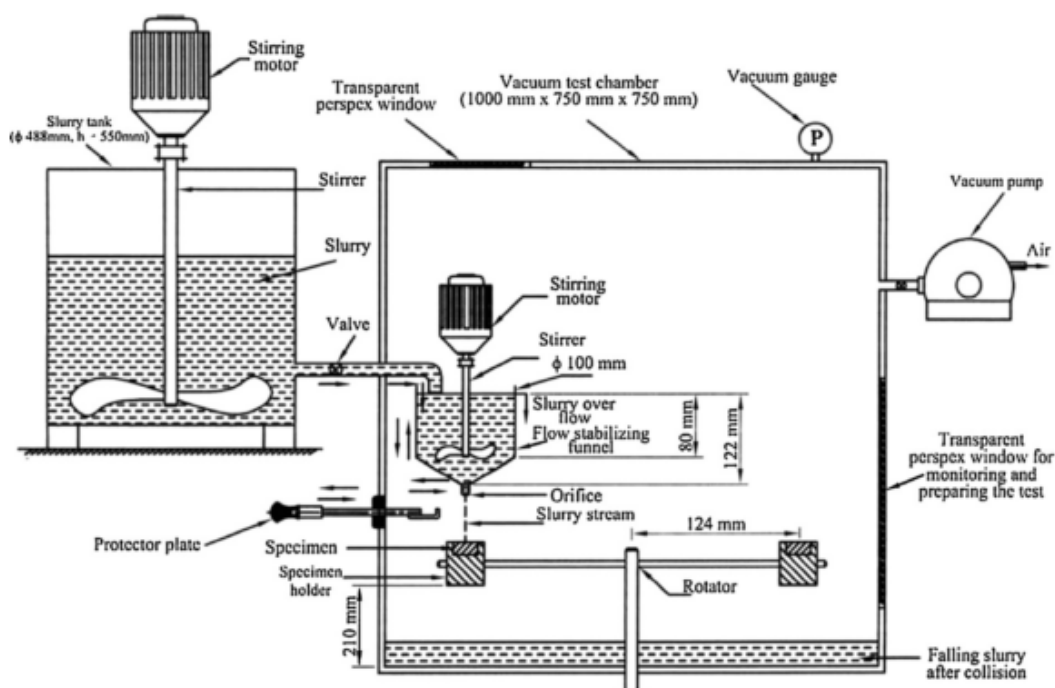


Fig. 8. Schematic diagram of whirling arm test device [63]

SUMMARY

In the paper are presented the slurry erosion phenomenon and test devices. Until now investigation showed that degradation of materials depends on fluid flow conditions (flow velocity, angle of particle impingement, particles concentration, liquid density, liquid chemical activity, liquid temperature), solid particles (size, shape, hardness, strength) and properties of target material (hardness, fatigue, strength, ability to work hardening). With an increase of material hardness increases erosion resistance. The most popular method of an increase of surface strength is deposition of coating. There are several methods of coating deposition, e.g. plasma methods, HVOF, arc-spraying. For example, deposition of WC-Co coatings on 316 steel by means of HVOF method increased erosion resistance almost 1000 times [57].

Besides material properties, fluid flow conditions influences material erosion resistance. For that reason, two main types of test devices are designed: jet impingement and rotating type rigs. Devices to investigate an effect of liquid jet impingement and solid particle impingement using gas jets have been standardized. There are many modification of test devices in order to faithfully reproduce the conditions, in which occurs erosion, and test slurry resistance of materials at various conditions, e.g. various velocity of impacting liquid with erodents, and various types of slurry erosion. Among many parameters influencing slurry erosion rate, impact velocity of solid particles is a key parameter for material deformation and degradation. Therefore, relative erosion resistance obtained in different devices, e.g. a Coriolis erosion test and a jet erosion tester, varies essentially. This may be due to different velocities of erodent impact in both devices and also to the fact, that the critical normal impact velocity to produce plastic deformation is very low for soft materials and high for hard materials.

REFERENCES

1. Oka Y. I., Yoshida T.: Practical estimation of erosion damage caused by solid particle impact: Part 2: Mechanical properties of materials directly associated with erosion damage. *Wear* 259 (2005) 102–109.
2. Arora H. S., Grewal H. S., Singh H., Mukherjee S.: Zirconium based bulk metallic glass-Better resistance to slurry erosion compared to hydroturbine steel. *Wear* 307 (2013) 28–34.
3. Grewal H. S., Agrawal A., Singh H.: Design and development of high-velocity slurry erosion test rig using CFD. *Journal of Materials Engineering and Performance* 22 (2013) 152–161.
4. Singh G., Viridi R. L., Goyal K.: Experimental investigation of slurry erosion behaviour of hard faced AISI 316L Stainless Steel. *Universal Journal of Mechanical Engineering* 3 (2015) 52-56.
5. Nguyen Q. B., Lim C.Y.H., Nguyen V.B., Wan Y.M., Nai B., Zhang Y.W., Gupta M.: Slurry erosion characteristics and erosion mechanisms of stainless steel. *Tribology International* 79 (2014) 1–7.
6. Zbrowski A., Mizak W.: Analiza systemów wykorzystywanych w badaniach uderzeniowego zużycia erozyjnego. *Problemy eksploatacji* 3 (2011) 235–250.
7. Grewal H. S., Agrawal A., Singh H., Shollock B. A.: Slurry erosion performance of Ni-Al₂O₃ based thermal-sprayed coatings: Effect of angle of impingement. *Journal of Thermal Spray Technology* 23 (2014) 389–401.
8. International Standard IEC 62364:2013 Hydraulic machines - Guide for dealing with hydro-abrasive erosion in Kaplan, Francis and Pelton turbines
9. Finnie I.: Some reflections on the past and future of erosion. *Wear* 186-187 (1995) 1-10.
10. Finnie I.: Erosion of surfaces by solid particles. *Wear* 3 (1960) 87–103.
11. Grewal H. S., Agrawal A., Singh H.: Slurry erosion mechanism of hydroturbine steel: Effect of operating parameters. *Tribology Letters* 52 (2013) 287–303.
12. Lathabai S., Pender D. C.: Microstructural influence in slurry erosion of ceramics. *Wear* 189 (1995) 122–135.
13. Arora M., Ohl C.D., Morch K.A.: Cavitation inception on microparticles: A self-propelled particle accelerator. *Physical Review Letters* 92 (2004) 174501–1 - 174501-4
14. Shitole P. P., Gawande S. H., Desale G. R., Nandre B. D.: Effect of Impacting Particle Kinetic Energy on Slurry Erosion Wear. *Journal of Bio- and Tribo-Corrosion* 1(29) (2015) 1–9.
15. Basha S. S., Periasamy V. M., Kamaraj M.: Slurry Erosion Resistance of Laser-modified 16Cr – 5Ni Stainless Steel. *International Journal of ChemTech Research* 6 (2014) 691–704.
16. Pugsley V. A., Allen C.: Microstructure / property relationships in the cavitation erosion of tungsten carbide – cobalt. *Wear* 225–229 (1999) 1017–1024.
17. Grewal H.S., Bhandari S., Singh H.: Parametric study of slurry-erosion of hydroturbine steels with and without detonation gun spray coatings using taguchi technique. *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.* 43 (2012) 3387–3401.
18. Santa J.F., Baena J.C. Toro A.: Slurry erosion of thermal spray coatings and stainless steels for hydraulic machinery. *Wear* 263 (2007) 258–264.
19. Santa J.F., Espitia L.A., Blanco J.A., Romo S.A., Toro A.: Slurry and cavitation erosion resistance of thermal spray coatings. *Wear* 267 (2009) 160–167.

20. Mann B.S., Arya V., Maiti A.K., Rao M.U.B., Joshi P.: Corrosion and erosion performance of HVOF/TiAlN PVD coatings and candidate materials for high pressure gate valve application. *Wear* 260 (2006) 75–82.
21. Kumar A, Sapra P.K., Bhandari S.: A review paper on slurry erosion of plasma and flame thermal sprayed coatings. National Conference on Advancements and Futuristic Trends in Mechanical and Materials Engineering 2011.
22. Mohammadi F., Luo J.: Effect of cold work on erosion-corrosion of 304 stainless steel. *Corros. Sci.* 53 (2011) 549–556.
23. Recco A.A.C., López D., Bevilacqua A.F., da Silva F., Tschiptschin A.P.: Improvement of the slurry erosion resistance of an austenitic stainless steel with combinations of surface treatments: Nitriding and TiN coating. *Surf. Coatings Technol.* 202 (2007) 993–997.
24. Xu J., Zhuo C., Han D., Tao J., Liu L., Jiang S.: Erosion-corrosion behavior of nano-particle-reinforced Ni matrix composite alloying layer by duplex surface treatment in aqueous slurry environment. *Corros. Sci.* 51 (2009) 1055–1068.
25. Mann B.S.: High-energy particle impact wear resistance of hard coatings and their application in hydroturbines. *Wear* 237 (2000) 140–146
26. ASTM G 40-15: Standard Terminology Relating to Wear and Erosion
27. ASTM G73-10: Standard Test Method for Liquid Impingement Erosion Using Rotating Apparatus.
28. ASTM G76-13: Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets.
29. Syamsundar C., Chatterjee D., Kamaraj M., Maiti A. K.: Erosion Characteristics of Nanoparticle-Reinforced Polyurethane Coatings on Stainless Steel Substrate. *J. Mater. Eng. Perform.* 24 (2015) 1391–1405.
30. Lina H.C.Wub., S.K., Yeha C.H.: A comparison of slurry erosion characteristics of TiNi shape memory alloys and SUS304 stainless steel. *Wear* 246 (2001) 557–565.
31. Lin M. C., Chang L. S., Lin H. C., Yang C. H., Lin K. M.: A study of high-speed slurry erosion of NiCrBSi thermal-sprayed coating. *Surf. Coatings Technol.* 201 (2006) 3193–3198.
32. Zhang J., Richardson M. O. W., Wilcox G. D., Min J., Wang X.: Assessment of resistance of non-metallic coatings to silt abrasion and cavitation erosion in a rotating disk test rig. *Wear* 194 (1996) 149–155.
33. Padhy M. K., Saini R. P.: Effect of size and concentration of silt particles on erosion of Pelton turbine buckets. *Energy* 34 (2009) 1477–1483.
34. Rai A. K., Kumar A., Staubli T.: Developing a Test Rig To Measure Hydro-Abrasive Erosion in Pelton Turbine. *Int. Conf. Hydropower Sustain. Dev.* 05-07 (2015) 535–547.
35. Oka Y. I., Mihara S., Yoshida T.: Impact-angle dependence and estimation of erosion damage to ceramic materials caused by solid particle impact. *Wear* 267 (2009) 129–135.
36. Momber A.W.: Effects of erodent flow energy and local exposure time on the erosion of cement-based composites at high-speed hydro-abrasive flow. *Wear* 378-379 (2017) 145–154
37. Zu J. B., Hutchings I. M., Burstein G. T.: Design of a slurry erosion test rig. *Wear* 140 (1990) 331–344.
38. Wentzel E. J., Allen C.: The erosion-corrosion resistance of tungsten-carbide hard metals. *Int. J. Refract. Met. Hard Mater.* 15 (1997) 81–87.
39. Li Y., Burstein G. T., Hutchings I. M.: The influence of corrosion on the erosion of aluminium by aqueous silica slurries. *Wear* 186–187 (1995) 515–522.

40. Fang Q., Sidky P., Hocking M.: Erosive wear behaviour of aluminium based composites. *Mater. Des.* 18 (1997) 389–393.
41. Gopi K. R., Nagarajan R., Rao S. S., Mandal S.: Erosion model on alumina ceramics: A retrospection, validation and refinement. *Wear* 264 (2008) 211–218.
42. Manisekaran T., Kamaraj M., M. Sharrif S., Joshi S. V.: Slurry erosion studies on surface modified 13Cr-4Ni steels: Effect of angle of impingement and particle size. *J. Mater. Eng. Perform.* 16 (2007) 567–572.
43. Shivamurthy R. C., Kamaraj M., Nagarajan R., Shariff S. M., Padmanabham G.: Influence of microstructure on slurry erosive wear characteristics of laser surface alloyed 13Cr-4Ni steel. *Wear* 267 (2009) 204–212.
44. Shivamurthy R. C., Kamaraj M., Nagarajan R., Shariff S. M., Padmanabham G.: Slurry erosion characteristics and erosive wear mechanisms of Co-based and Ni-based coatings formed by laser surface alloying. *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.* 41 (2010) 470–486.
45. Grewal H. S., Arora H. S., Agrawal A., Singh H., Mukherjee S.: Slurry erosion of thermal spray coatings: Effect of sand concentration. *Procedia Eng.* 68 (2013) 484–490.
46. Wood R. J. K., Mellor B. G., Binfield M. L.: Sand erosion performance of detonation gun applied tungsten carbide/cobalt-chromium coatings. *Wear* (1997) 70–83.
47. Turenne S., Fiset M., Masounave J.: The effect of sand concentration on the erosion of materials by a slurry jet. *Wear* 133 (1989) 95–106.
48. Yngve N.: Material removal mechanism of Ni(200) when eroded by a slurry at 30° incidence. *Wear* 105 (1985) 123–130.
49. Neville A., McDougall B.A.B.: Erosion- and Cavitation-Corrosion of Titanium and Its Alloys. *Wear* 250 (2001), 726–735.
50. Santa J. F., Espitia L. A., Blanco J. A., Romo S. A., Toro A.: Slurry and cavitation erosion resistance of thermal spray coatings. *Wear* 267 (2009) 160–167.
51. Tsai W., Humphrey J. A. C., Cornet I., Levy A. V.: Experimental measurement of accelerated erosion in a slurry pot tester. *Wear* 68 (1981) 289–303.
52. Gupta R., Singh S. N., Sehadi V.: Prediction of uneven wear in a slurry pipeline on the basis of measurements in a pot tester. *Wear* 184 (1995) 169–178.
53. Gandhi B. K., Singh S. N., Seshadi V.: A study on the effect of surface orientation on erosion wear of flat specimens moving in a solid-liquid suspension. *Wear* 254 (2003) 1233–1238.
54. Gadhikar A. A., Sharma A., Goel D. B., Sharma C. P.: Fabrication and testing of slurry pot erosion tester. *Trans. Indian Inst. Met.* 64 (2011) 493–500.
55. Thakur L., Arora N.: A comparative study on slurry and dry erosion behaviour of HVOF sprayed WC-CoCr coatings. *Wear* 303 (2013).
56. Tuzson J. J.: Laboratory Slurry Erosion Tests and Pump Wear Rate Calculations. *J. Fluids Eng.* 106 (1984) 35.
57. Clark H. M., Hawthorne H. M., Xie Y.: Wear rates and specific energies of some ceramic, cermet and metallic coatings determined in the Coriolis erosion tester. *Wear* 233–235 (1999) 319–327.
58. Xie Y., Clark H. M., Hawthorne H. M.: Modelling slurry particle dynamics in the Coriolis erosion tester. *Wear* 225–229 (1999) 405–416.
59. Xie Y., Jiang J.J., Tufa K. Y., Yick S.: Wear resistance of materials used for slurry transport. *Wear* 332–333 (2015).

60. Bhushan B.: *Fundamentals of Tribology and Bridging the Gap between Macro- and Micro/Nanoscale*. B. Bhushan [ed.], Kluwer Academic Publishers, Netherlands, 2014.
61. Lin F. Y., Shao H. S.: Effect of impact velocity on slurry erosion and a new design of a slurry erosion tester. *Wear* 143 (1991) 231–240.
62. Abouel-Kasem A., Abd-elrhman Y. M., Emara K. M., Ahmed S. M.: Design and performance of slurry erosion tester. *J. Tribol.* 132 (2010) 1–10.
63. Al-Bukhaiti M. A., Ahmed S. M., Badran F. M. F., Emara K. M.: Effect of impingement angle on slurry erosion behaviour and mechanisms of 1017 steel and high-chromium white cast iron. *Wear* 262 (2007) 1187–1198.

