Influence of diameter–thickness ratio on alloy Zr-4 tube under low-energy impact fretting wear

Ying-wu Lin¹, Zhen-bing Cai^{1*}, Zhi-qiang Chen¹, Hao Qian², Li-chen Tang²,
Yong-cheng Xie², Min-hao Zhu^{1**}.

(1.Tribology Research Institute, Southwest Jiaotong University, Chengdu, 610031, China

2. Shanghai Nuclear Engineering Research and Design Institute, Shanghai, 200233, China)

Abstract: Impact fretting wear test of alloy Zr-4 tubes with varied diameter–thickness ratios (D/t ratio) against a GCr15 steel cylinder was performed with a new impact wear testing device at dry room temperature. The deformation behavior, impact energy absorption, and damage of the tested tubes resulting from the influence of diameter, thickness, and impact cycles were investigated. Results showed that under the same tube outer diameter, an increase in the D/t ratio leads to an increase in contact time and a reduction in peak force, energy absorption ratio, and damage degree. Under the same wall thickness, an increase in the D/t ratio leads to reduced contact time, peak force, energy absorption ratio, and depth. The bending section coefficient significantly affects contact stiffness, and wear damage is positively correlated to the bending moment value of the tube. The wear mechanisms of impact fretting wear of alloy Zr-4 tubes are contact fatigue spalling and oxidation.

Keywords: impact fretting wear, impact kinetic energy, diameter–thickness ratio, Zirconium alloy

Generally, in popular friction and wear tests, such as reciprocating sliding wear, pin-on-disk, and four-ball wear tests, the interface of the tribopairs has no separation. However, fluid lubrication acts as a smooth buffer or isolation layer in several immersion test conditions. Impact and erosion wear belong to the surface damage caused by repeated dynamic crashes and collisions between two separated interfaces [1]. The kinetic energy from anti-pairs is transformed to other types of energy for hardening, cracking, and heating surfaces or energy for material damage [2, 3]. Another view is that the lost impact energy may be consumed in four different means, namely, frictional loss, residual energy stored in the target after the impact, conversion to kinetic energy of the moved material, and crack formation and propagation [4]. Many research methods have been used to explore the damage or mechanism induced by impact. One example is the erosion wear test, which is usually utilized to evaluate

*Correspondence to: Zhen-bing Cai, Tribology Research Institute, Southwest Jiaotong University, Chengdu 610031, China, E-mail addresses: caizb@swjtu.cn

**Correspondence to: Min-hao Zhu, Tribology Research Institute, Southwest Jiaotong University, Chengdu 610031, China, E-mail addresses: zhuminhao@swjtu.cn

the wear property of materials. A common method is to observe the effect of particles on the tested material surface under pressure. Shortage indicates that a single “impactor” (particle) has different impact energy and contact conditions [5–7]. Another method is the drop hammer impact test, which is used to measure the impact toughness of a material. Its limitation is that the test can only be performed once. Meanwhile, the cycling impact test involves loading from a cam, spring, or electromagnetic vibration exciter. All these methods usually produce minimal test data. Most studies investigated wear performance through follow-on physical measurement or chemical characterization. Related data on the kinetic processing between two impact objects are rarely found.

In many industrial processes, such as power, petrochemical, mining, marine aerospace, and other areas, machine components are subjected to a large number of mechanical collisions during their useful lifetime [8]. Numerous fretting wear problems induced by flow-induced vibration exist in nuclear power equipment, such as in the interface between the steam generator tube and anti-vibration bar, fuel rods, and support.

Various studies [9, 10] have been conducted to reveal the tangential fretting wear behavior via failure analysis for tubes or fuel rods (zirconium alloy), but only a few studies have explored impact behavior. Research on the cladding tube has mainly focused on the following aspects.

(1) *Damage prediction and detection modeling.* Cheng [11] developed an online detection system for fuel rod damage in a nuclear power station in China. Peter [12] proposed a multi-stage wear model for grid-to-rod fretting of nuclear fuel rods based on the data of the corrosion and wear of the reactor.

(2) *Fretting wear induced by the service environment.* Kim [13] compared the fretting wear properties under flow and static water lubrication. Tang [14] investigated fretting wear and fretting fatigue properties under room and high temperatures.

(3) *Corrosion and oxidation behavior of zirconium alloys.* Hamed [15] revealed that surface roughness affects the oxidation rate and weight gain of cladding tubes. Huang [16] reported the effect of Bi on the corrosion resistance of a Zr-1Nb alloy at 400 °C of superheated steam. Corvalán-Moya [17] investigated a model that can accurately predict the “critical” oxidation time corresponding to the overall ductile-to-brittle transition of a high-temperature (HT) oxidized clad. Sridharan [18] examined the oxidation behavior of a plasma surface modified zirconium alloy in pressurized high-temperature water.

(4) *Hydride effect on failure.* Kumar revealed the texture and hydride orientation relationship of a Zircaloy-4 fuel clad tube during its fabrication for pressurized heavy water reactors [19]. Fumihisa applied the tube burst test and studied the effect of the hydride rim on the failure of Zircaloy-4 cladding [20].

(5) *Mechanical properties of zircaloy based on a series of uniaxial tensile, strain cycling, and uniaxial ratcheting tests.* Wen [21] studied the ratcheting behavior of Zr-4 under different loading conditions. Fuloria [22] investigated the tensile properties and microstructural evolution of Zircaloy-4 processed through rolling at different temperatures. However, research on fretting wear of cladding tubes, especially impact

fretting wear, is relatively scarce.

In this study, the dynamic response and damage behavior of a Zr-4 alloy tube were investigated in a novel test machine by changing its diameter and thickness (D/t) ratio. The damage mechanism was also explored.

1 Experiment process

1.1 Experimental equipment parameters

The test in this research was conducted in a novel impact wear testing machine composed of three parts, namely, the mechanism section, the control system, and the measurement section. The mechanical structure of the test machine is shown in Figures 1(a) and 1(b). The voice coil motor is (1) was the core power component; it can reach a certain speed by 0–10 G acceleration in a very short time. When impact occurs, the kinetic energy of the motor is transferred to the impact block (4) by a fixed-position collision between the damping punch (2) and the impact block (4). Given that the impact block (4) is guided by a linear bearing element (3) with a very low friction coefficient, the block (4) approximately goes forward with uniform velocity. Impact velocity v_1 is measured by a magnetic scale (5), and the impact block (4) is connected to the fixture (6) of the upper specimen by a piezoelectric force sensor (7). The tube sample (8) is fastened by the fixture (9), and rebound velocity v_2 is also measured by the magnetic scale (5) after the collision between the upper and lower specimens. The impact block (4) is pulled back to the fixed starting position of the voice coil motor through a pull rod. Furthermore, no interaction occurs during the collision between the upper and lower specimens. According to the above process, the test machine reciprocates cycles of impact.

The controlling section consists of the following parts (Fig. 1(c)): constant power supply (UPS), computer control system (PC), motion controller, servo driver, power acquisition card, force sensor, and magnetic scale. A diagram of the experimental operation is shown in Figure 1(c). The PC issues a control order to the motion controller after the setting of the velocity and frequency. By decoding the control instruction of the motion controller, the voltage signal is issued to the servo driver. Then, the servo driver enables the voice coil according to the signal of the controller. The position encoder takes the tube sample interface as the reference point of 0. Test data on impact velocity, impact contact force, interfacial deformation, and rebound speed are collected by the magnetic scale, and the data are displayed and stored by the upper computer.

Fig. 1. Diagram of the wear test equipment and control system.

The test machine can provide varied initial impact energy E_1 by changing the impact speed of the motor and the mass m of the impact block. The absorbed energy resulting from wear or deformation of the material is ΔE . With the increase in the number of impact cycles (N), cumulative impact energy E_n exhibited a sustained increase. The main performance parameters of the test machine are as follows: impact speed v is 50–300 mm/s, the mass of the impact block is 0–10³ g, the frequency is 1–15 Hz, the sampling frequency of the impact force is 10³–10⁵ Hz, and the sampling frequency of velocity is 1000–8000 Hz.

The following are the formulas used in this research.

$$\Delta E_i = E_{i1} - E_{i2} = \frac{1}{2} (mv_{i1}^2 - mv_{i2}^2), \quad (N=10^i, i \geq 2) \quad (1)$$

$$E_n = \sum_{i=2}^n (\Delta E_i * 10^i - E_{i-1}), \quad (N=10^n, n=1) \quad (2)$$

$$I = \int F dt \quad (3)$$

$$I_x = \frac{\pi(D^4 - d^4)}{64} \quad (4)$$

$$W_z = \frac{\pi D^3}{32} (1 - a^4) \quad (5)$$

In the equations above, ΔE_i is the absorbed energy, E_n is the cumulative impact energy, m is the impact mass, N is the impact number, I is the impulse, F is the contact force, t is the contact time, I_x is the moment of inertia of the cross section, W_z is the bending section coefficient, D is the outer diameter of the tube, d is the inner diameter of the tube, and $a=d/D$.

1.2 Experimental materials

A tube/cylindrical impact fretting wear model was used in this research (Fig. 2). A simply supported beam structure was utilized to fix the pipe, and the supporting structure of the fuel rod was partially simulated. The column sample is bearing steel (GCr15) with a size of $\varnothing 10 \text{ mm} \times 20 \text{ mm}$. Zr-4 alloy is one type of commonly used alloy in nuclear power devices, and it was selected as the tube specimen. Its chemical composition is shown in Table 1. A three-group test was designed.

(1) **Group I.** The tubes had the same outside diameter but different wall thickness values. Their D/t ratios were 44, 22, 11, and 5.5 corresponding to the increasing moment of inertia of the cross section, namely, 0.20, 0.36, 0.63, and 0.96.

(2) **Group II.** The tubes had a different outside diameter and the same wall thickness. Their D/t ratios were 22, 15, 10, and 7 corresponding to the increasing moment of inertia of the cross section, namely, 0.01, 0.03, 0.11, and 0.36.

(3) **Group III.** This group was used to investigate the effect of impact number on the material (10^2 , 10^3 , 10^4 , 10^5 , and 10^6). The parameters of the test plan are shown in Table 2. Impact velocity in the experiments was set to 181.5 mm/s, and the frequency of impact was 6 Hz. The initial distance between the column and tube was 6.5 mm, and the support span of the pipe was 40 mm. The mass of the impact block was 450 g, which is equal to 7.41 mJ if it is converted into the impact energy of one cycle.

Table 1. Chemical composition of Zr-4 alloy and GCr15 steel

Material	Zr	Sn	Fe	Cr	C	W
Zr-4	98.1	1.5	0.2	0.1	0.027	0.01
Material	Fe	C	Mn	Si	Cr	Ni
GCr15	96	1.0	0.32	0.19	1.52	0.2

Table 2. Parameters of the impact wear test

Group	I				II			III			
Specimen	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#	11#
Diameter (mm)	22	22	22	22	7	10	15	22	22	22	22
Thickness (mm)	0.5	1	2	4	1	1	1	1	1	1	1
D/t	44	22	11	5.5	7	10	15	22	22	22	22
Section moment of inertia (I_x, cm^4)	0.20	0.36	0.63	0.96	0.01	0.03	0.11	0.2	0.2	0.2	0.2
Bending section coefficient (W_z, cm^3)	0.18	0.33	0.58	0.87	0.02	0.06	0.14	0.18	0.18	0.18	0.18
Impact cycle	10^5	10^5	10^5	10^5	10^5	10^5	10^5	10^2	10^3	10^4	10^6

Fig. 2. Schematic of nuclear plant and impact wear the test design.

1.3 Analysis and Testing

After the test, the surface morphology of the sample was observed under an optical microscope (OM, OLYMPUS-BX60M) and a scanning electron microscope (SEM, JSM6610LV). An EDX energy spectrometer (model 7760/68E) was used to analyze the characteristics of tribo-chemistry during the impact fretting effect. A series of data is automatically stored in the test machine, which can calculate the evolution and response of load, displacement, and energy during the testing process.

2 Results and discussion

2.1 Influence of wall thickness

The curves of contact force and deformation of the tube with time are shown in Fig. 3. With the increase in the D/t ratio of the tube, the contact peak force decreased, the contact time of the interface gradually increased (Fig. 3(a)), and the value of maximum deformation of the tube increased (Fig. 3(b)). When the D/t ratio was 11, the peak contact force F_p was 204 N, and the amount of deformation was 44 μm . When $D/t = 22$, $F_p = 114$ N and $D(\text{deformation}) = 71$ μm . When $D/t = 44$, $F_p = 56$ N and $D(\text{deformation}) = 156$ μm . Thus, when the outer diameter of the tube was the same, the thicker tube experienced greater contact force and shorter impact contact time.

(a) Contact force vs. time

(b) Deformation vs. time

Fig. 3. Curve of impact contact force and deformation vs. time ($\Phi = 22$ mm).

Fig. 4 presents the curve of velocity versus time after the block impacted. When $D/t = 44$, the steady-state velocity decreased by 5.89 mm/s after impact compared with the initial velocity. When the D/t ratio decreased to 22, 11, and 5.5, the velocity decreased by 44.80, 56.58, and 65.79 mm/s, respectively. Obviously, although the initial impact velocity was the same, the rebound velocity of the cylinder sample increased, and its fluctuation gradually decreased with the increasing D/t ratio. The kinetic energy of the impact block changed with the D/t ratio of the tube, as shown in Fig. 5. Impact energy was partly dissipated by the deformation and material loss of the tube, which are the main reasons for the occurrence of damage on the impact interface. Fig. 5(a) shows that when the cylinder had the same impact energy, as the D/t ratio of the Zr-4 alloy tube decreased, the energy absorption capacity increased. When the D/t

ratio was 44, 22, 11, and 5.5, the energy absorption was 0.87 mJ, 2.75 mJ, 3.94 mJ, and 4.39 mJ, respectively. Fig. 5(b) shows that the impact peak force and impact energy absorption rate increased as the D/t ratio decreased. When the D/t ratio was 44, 22, 11, and 5.5, the energy absorption rate was 11.74%, 37.11%, 53.17%, and 59.24%, respectively. Thus, when the outer diameter was the same, an increase in the tube wall thickness (high stiffness) meant an increase in the absorbed energy. As the D/t ratio increased, the dissipation amount of kinetic energy decreased.

(a) Rebound velocity vs. time

(b) Kinetic energy vs. time

Fig. 4. Kinetic energy of the impact block vs. time (outer diameter = 22 mm).

(a) Rebound and absorbed energy

(b) Peak force and absorbed energy

Fig. 5. Energy response at different D/t ratios ($\Phi = 22$ mm).

Fig. 6(a) presents the evolution of energy absorption with an increasing number of impact cycles. Within the trial period of 10^5 times, the kinetic energy absorption of the alloy tube always increased with decreasing D/t ratio. When the D/t ratio was 44, 22, 11, and 5.5, the absorption energy corresponded respectively to the following: 0.99, 2.84, 3.77, and 4.54 mJ when cycle = 10^2 th and 0.94, 3.34, 4.02, and 4.55 mJ when cycle = 10^5 th. Meanwhile, when $N = 10^5$, the cumulative amount of kinetic energy dissipation decreased as the D/t ratio increased. The value of the total absorbed energy is shown in Fig. 6(b). More absorbed energy at the interface can lead to severe damage, which can be seen from the size of the wear scar in Fig. 6(a). Thus, we conclude that although the impact energy applied on the Zr-4 alloy tube is the same, the cumulative kinetic energy dissipation is greatly increased by decrements in the D/t ratio. Decrements in the D/t ratio also increase wear scarring, which reduces the

service life of Zr-4 alloy tubes.

(a) Absorbed energy

(b) Total energy, cycle = 10^5

Fig. 6. Energy absorbed as affected by impact cycles at different wall thickness values ($\Phi = 22$ mm).

Figs. 7 and 8 show micrographs of the worn scar of Zr-4 tubes with different D/t ratios after 10^5 cycles under the same impact energy. Figs. 7(a) to 7(c) show that when the D/t ratio was 44, the damage of the Zr-4 tube was relatively slight; however, the damage increased sharply with a D/t ratio of 5.5. As the D/t ratio decreased, the area of worn scars (A) increased, $A_{D/t=44} < A_{D/t=22} < A_{D/t=5.5}$. The same information can be obtained from Fig. 8. As shown in Figs. 7(d) to 7(f), debris was found on the wear surface of the tubes, indicating that the surface of the tubes underwent spalling wear. The wear of the Zr-4 tube with a ratio of 44 was less than that of the others. Noticeably, the debris changed into blocks, and the area and thickness of blocks

increased. When the ratio was 5.5, the contact force load had the largest value (see Fig. 3(a)). No large pieces of debris accumulated because the debris bed was crushed under the high compression force.

Fig. 7. SEM micrographs of the worn scars under different D/t ratios ($\Phi = 22$ mm, $N = 10^5$).

Fig. 8. 3D morphology of the wear scars under different wall tube thickness values ($\Phi = 22$ mm, $N = 10^5$).

The profile of the worn scars is shown in Fig. 9a. When the D/t ratio was 5.5, the depth increased to the maximum value of about $10\ \mu\text{m}$. However, the depth was small (about $2\ \mu\text{m}$) when the D/t ratio was 44. In short, the depth of the worn scars increased with the decrease in the D/t ratio, that is, $D_{D/t=44} < D_{D/t=22} < D_{D/t=11} < D_{D/t=5.5}$ ($D_{D/t=44}$, depth of the worn scar of the tube (D/t ratio is 44). Fig. 9(b) indicates the

area of depth values with the change in thickness (D/t ratio). The worn scar of the D/t ratio = 5.5 had 2.4 times the area of D/t ratio = 44.

At the same outer diameter and after obtaining the same impact effect, the above results can be summarized as follows. First, if the tube has a large D/t ratio, then the contact time is long and the level of contact force is low. Second, if a large D/t value has a high section moment of inertia, then the rigidity of the material increases. Thus, the material does not deform easily, and the kinetic energy of the block is absorbed by the tube. Third, serious wear occurs at small D/t ratios.

(a) Cross-section profiles of the worn scars

(b) Wear area and depth

Fig. 9. Wear area and depth of worn scars under different D/t ratios ($\Phi = 22$ mm, $N = 10^5$).

2.2 Influence of the outer diameter

Aside from thickness, the outer diameter can also affect the D/t ratio. Thus, in the second group test, we used tubes with identical thickness (1 mm) and different outer diameters. Fig. 10(a) shows that the evolution of the kinetic energy of the block during the impact progress was demonstrated in the 10^3 th cycle. After an impact, the kinetic energy value decreased from 7.4 mJ to 4.28 mJ, 4.16 mJ, 3.96 mJ, and 3.88 mJ, which correspond to D/t ratios of 22, 15, 10, and 7, respectively. Minor changes in the deformation of the tube also occurred when the D/t ratio decreased from 22 to 7 (Fig. 10(b)). Under this condition, the impact energy absorption was slightly affected by the outside diameter.

(a) Kinetic energy of the block vs. time

(b) Deformation of the tube vs. time

Fig. 10. Kinetic energy of the impact block and deformation of tube vs. time curves (thickness = 1 mm).

With regard to the wear morphologies (Fig. 11), a decrease in outer diameter led to a decrease in wear scarring. Furthermore, the shape of the wear scar evolved into a circle (Fig. 11(c)) from an ellipse (Figs. 11(a) to 11(b)) and presented the final shape

of an ellipse (Fig. 11(d)). The Hertz contact mechanism provides a simple explanation for this phenomenon. When $D/t = 10$, the block cylinder and tube had the same diameter of 10 mm; thus, the wear scar was circular (Fig. 11(c)).

Notably, although the geometric dimensions of contact wear are not the same because the diameters of the tubes are not uniform, the wear depth value provides important data to resolve the wear rate. The results here are similar to those in the preceding section: a large D/t ratio increased contact time and contact level force, and serious wear (deep scar) was found in tubes with a small D/t ratio.

Fig. 11. Micrographs of the worn scars with different D/t ratios (wall thickness = 1 mm, $N = 10^5$).

(a) Cross-section profiles of the worn scars

(b) Wear area and depth

Fig. 12. Profile and area of worn scars under different D/t ratios (wall thickness = 1 mm, $N = 10^5$).

2.3 Influence of impact cycle–damage evolution

The damage evolution of the tube can be indicated by the increasing impact cycles. The worn scars are shown in Fig. 13. The wear area and depth of the worn scars increased as the impact cycle increased. In the initial cycles, the area of the worn scars was small, and their depth was shallow; even the original machining traces on the surface of the pipe could be seen. When cycle = 10^4 , the scar looked dark, and the machining marks were still visible in the worn scars. When the cycle exceeded 10^4 , wear became severe, and the area of the wear track gradually increased at the same time. Debris was evenly compacted on the worn surface, especially at cycle = 10^6 , where the wear area was twice that at the 10^5 cycle. Obviously, the wear of the material increased after the high-cycle effect (Fig. 13(e)).

Fig. 13. OM micrographs of worn scars with increasing cycles ($\Phi = 22$ mm, wall thickness = 1 mm, $D/t = 22$).

The 3D morphology (Fig. 14) shows that the wear of the tubes was slight in the low-impact cycles, such as cycles of 10^2 (Fig. 14(a)) and 10^3 (Fig. 14(b)). In general, the depth and area of the worn scars gradually deepened and enlarged as the number of cycles increased (Fig. 14(c) to 14(e)). More intuitive results can be obtained from Fig. 14. When the number of cycles increased from 10^4 to 10^5 and from 10^5 to 10^6 , the depth value of the wear scar doubled.

Fig. 14. 3D morphology of worn scars with various cycles ($\Phi = 22$ mm, wall thickness = 1 mm, $D/t = 22$).

(a)

(b)

Fig. 15. Profilometry of worn scars with varied impact cycles ($\Phi = 22$ mm, wall thickness = 1 mm, $D/t = 22$).

Fig. 16 illustrates the EDX of the worn scars. Compared with the debris of tubes with different D/t ratios at the same impact energy and cycle, we found that O and Fe peaks appeared (Fig. 16(a)). This phenomenon demonstrates the occurrence of oxidation during the process and that the Fe element of the columnar sample transferred to the tube sample. Fig. 15(b) shows the EDX of worn scars with the same D/t ratio under different cycles. Compared with those in the base material, the Fe peaks are visible in the graph. The O peaks increased with the increase in the number of cycles. Therefore, the oxidation of surfaces was aggressive with increments in the number of cycles.

(a) Different D/t ratios, $N = 10^6$

(b) Different cycles, $D/t = 22$

Fig. 16. EDX of the worn scars (outer diameter = 22 mm).

3. Conclusion

In this research, the impact wear of a Zr-4 alloy tube as affected by the D/t ratio was investigated. The behavior of the tube, as influenced by outer diameter and wall thickness, was explored. Several conclusions were obtained from the results.

(a) Under the same outer diameter of the tube, an increase in the D/t value induces long contact time and low peak force, energy absorption ratio, and degree of damage during impact wear.

(b) Under the same wall thickness of the tube, an increase in the D/t value results in short contact time and low peak force, energy absorption ratio, and depth of the wear scar during impact wear.

(c) The bending section coefficient significantly affects contact stiffness, and

wear damage is positively correlated to the bending moment value of the tube.

(d) Oxidation and contact fatigue spalling are the primary wear mechanisms of Zr-4 tubes under the impact wear effect.

Acknowledgements

This study was supported by National Science Foundation of China (51375407 and U1530136).

References

- [1] Rabinowicz, E., and K. Hozaki. "Impact wear of ductile metals." Proceedings of the JSLE International Tribology Conference.. Vol. 2. 1985.
- [2] Engel, Peter A., and Qian Yang. "Impact wear of multiplated electrical contacts." *Wear* 181 (1995): 730-742.
- [3] Engel, Peter A. *Impact wear of materials*. Vol. 2. Elsevier, 1978.
- [4] Qi, Huan, et al. "Impact erosion by high velocity micro-particles on a quartz crystal." *Tribology International* 82 (2015): 200-210.
- [5] Rice, Stephen L., Hans Nowotny, and Steven F. Wayne. "Characteristics of metallic subsurface zones in sliding and impact wear." *Wear* 74.1 (1981): 131-142.
- [6] Tian, Harry H., Graeme R. Addie, and Edward P. Barsh. "A new impact erosion testing setup through Coriolis approach." *Wear* 263.1 (2007): 289-294.
- [7] Liu, Rong, et al. "Effects of molybdenum content on the wear/erosion and corrosion performance of low-carbon Stellite alloys." *Materials & Design* 78 (2015): 95-106.
- [8] Bayer, R. G., P. A. Engel, and J. L. Sirico. "Impact wear testing machine." *Wear* 19.3 (1972): 343-354.
- [9] Xu, Linmin, et al. "Fretting wear behaviors of hoisting rope wires in acid medium." *Materials & Design* 55 (2014): 50-57.
- [10] Qu, Jun, et al. "Assessment of wear coefficients of nuclear zirconium claddings without and with pre-oxidation." *Wear* 356 (2016): 17-22.
- [11] Cheng P. The development of fuel rod damage character analysis code for light water reactor of nuclear power plant[D]. Doctoral dissertation of China Institute of Atomic Energy, 2006.
- [12] Blau, Peter J. "A multi-stage wear model for grid-to-rod fretting of nuclear fuel rods." *Wear* 313.1 (2014): 89-96.
- [13] Kim, Jin-Seon, Se-Min Park, and Young-Ze Lee. "The effects of wear debris under fluid flow environment on fretting wear mechanism of nuclear fuel cladding tube supported by supporting grid." *Tribology Transactions* 53.3 (2010): 452-462.

[14]Tang LC,Ding SR,Qian H, Xie YC, Huo YZ. Fretting fatigue tests and crack initiationanalysis on zircaloy tube specimens. *Int J Fatigue* 63(2014): 154–61.

[15] Akhiani, Hamed, and Jerzy A. Szpunar. "Effect of surface roughness on the texture and oxidation behavior of Zircaloy-4 cladding tube." *Applied Surface Science* 285 (2013): 832-839.

[16] Jiao, Huang, et al. "Corrosion Resistance of Zr-1Nb-XBi Alloys in Super-heated Steam at 400 degrees C/10.3 MPa." *Rare Metal Materials and Engineering* 44.1 (2015): 214-218.

[17] Corvalán-Moya, C., et al. "Numerical modeling of oxygen diffusion in the wall thickness of Low-Tin Zircaloy-4 fuel cladding tube during high temperature (1100–1250 C) steam oxidation." *Journal of Nuclear Materials* 400.3 (2010): 196-204.

[18] Sridharan, K., et al. "Oxidation of plasma surface modified zirconium alloy in pressurized high temperature water." *Materials & design* 28.4 (2007): 1177-1185.

[19] Vaibhaw, Kumar, et al. "Texture and hydride orientation relationship of Zircaloy-4 fuel clad tube during its fabrication for pressurized heavy water reactors." *Journal of Nuclear Materials* 383.1 (2008): 71-77.

[20] Nagase, Fumihisa, and Toyoshi Fuketa. "Investigation of hydride rim effect on failure of Zircaloy-4 cladding with tube burst test." *Journal of Nuclear Science and Technology* 42.1 (2005): 58-65.

[21] Wen, Mingjian, et al. "Uniaxial ratcheting behavior of Zircaloy-4 tubes at room temperature." *Materials & Design* 46 (2013): 426-434.

[22] Fuloria, Devasri, et al. "Tensile properties and microstructural evolution of Zircaloy-4 processed through rolling at different temperatures." *Materials & Design* 103 (2016): 40-51.

Influence of diameter–thickness ratio on an alloy Zr-4 tube under low-velocity impact fretting wear

Figure. Diagram of the low velocity impact wear test equipment and the results.