Author: David Stewart
Supervisor: Dr. Adrian Oila
CME 8060

Assignment Part A - 'Coinage Wear Report'

Lifetime Prediction and Design for Reliability

CME 8060

School of Engineering (Mechanical)

David Stewart – 180297339

Supervised by

Dr. Adrian Oila

25th March 2022

Words – 989

(Without Title Page, Contents and References)

Author: David Stewart
Supervisor: Dr. Adrian Oila
CME 8060

Table of Contents

Contents

Author: David Stewart
Supervisor: Dr. Adrian Oila
CME 8060

1. Discussion

1.1. Condition Coins are Exposed to During Circulation

1.1.1. Atmospheric conditions

Coins experience harsh conditions during their time in circulation and are designed to keep their surface reliefs identifiable for a minimum of 15 years (Cope, 1969). The coins wear rate can depend on the humidity, temperature and atmosphere of its present environment. A 70µm/year^{-1} surface thickness wear rate was observed for nickel-bonded-steel (NBS) alloyed coins in the hotter, humid, marine atmosphere of El Salvador compared to a 0.22µm/year^{-1} wear rate in the dryer, colder land-based climate of Canada (Ruscoe, 1987).

1.1.2. Contamination

Corrosion wear is an oxidation process common to metal coins caused by the presence of oxygen, chlorides or sulphur dioxides in the air. The rate of corrosion is accelerated with increasing quantities of moisture and dust suggesting coins present in humid and dirty environments will observe larger corrosive wear rates ("Conservation of coins", 2018). Sea water and human sweat (Gwozdz & Grass, 2004) are also common contaminants that accelerate coinage wear rates by increasing corrosion wear (Brandes et al., 2005).

Figure 1. Corroded Copper Coin

1.1.3. Storage Environment

Coins tend to be carried loosely with hard, contaminated objects in pockets or purses where they scrape, rub and collide against one another, dissipating kinetic energy in the form of frictional heat. These storage environments tend to be volumetrically small resulting in frequent collisions of coins with hard, wear inducing objects.

1.1.4. Coin Usages

The reliance on coins as a means of tender has seen a decrease due to cashless payment methods. Previously they would see frequent use in meters (Cope, 1969) and vending machines were abrasive wear would be predominant, encouraging larger surface wears.

1.1.5. Corrosion by Electrolytes

If two coins of different metals are in contact for a long time in a damp environment, an electrolyte induces an electric current which circulates causing the less noble metal to corrode ("Conservation of coins", 2018).

1.2. Wear Mechanisms of Coins During Circulation

1.2.1. Adhesive Wear

When surfaces of similar hardness are in relative motion, adhesive wear can occur when stress concentrations generate at asperities increasing the local temperature leading to instantaneous welding at junctions followed by subsequent ripping, creating a wear particle trapped in the contact area ("Wear mechanisms", 2001). Archerd's equation (1) can be used to describe the proportionality of frictional forces to the volume of wear debris removed (Hutchings, 1992).

$$Q = K\frac{WL}{H} \qquad (1)$$

Where:

Q = Total volume of wear debris produced [m^3]

W = Total Normal Load [N]

K = Constant [Dimensionless]

L = Sliding Distance [m]

H = Hardness of softest surface [N/mm^2]

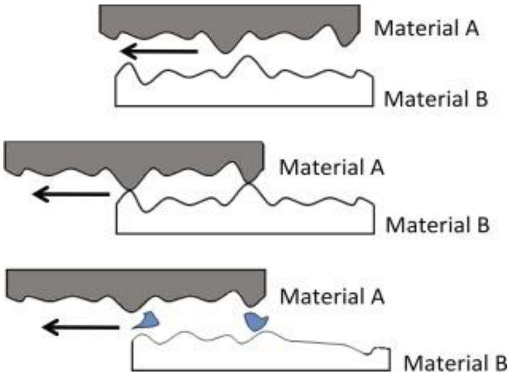

Figure 2. Adhesive Wear Process ("Wear mechanisms", 2001)

1.2.2. Abrasive Wear

Abrasive wear occurs when one of the sliding materials is harder than the other (usually 20% harder) and material is removed or displaced from a surface. The abrasive wear rate depends on the particles quantity, hardness, size and shape, and the brittleness of the surface material (Hutchings, 1992). The phenomenon comes in two categories: two-body wear and three-body wear. Hard protuberances or particles on the counter face produces two body abrasion. Hard particles free to roll and slide between two sliding surfaces produces three-body abrasion (Tanzi et al., 2019).

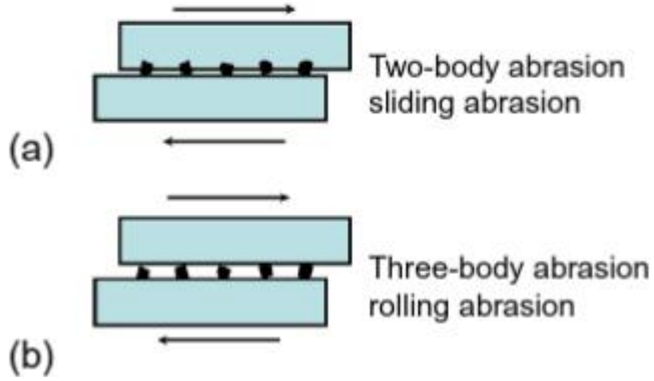

Figure 3. Abrasive Wear Processes (Hutchings, 1992)

1.2.3. Oxidative Wear

Oxidative wear is a wear mechanism that occurs in unlubricated ferrous systems such as coinage in air. Oxygen is absorbed into the surface of the metal and these layers can be released as wear particles once a critical thickness is reached, accelerating the surface wear rate (Hutchings, 1992). Tribo-oxide layers are formed on the areas of contact during high temperature frictional wear processes (Feng & Shao, 2021).

1.2.4. Contact Fatigue Wear

Contact fatigue is a less common wear mechanism for coinage. It's due to the cyclical loading of surfaces (coin collision) which can release abrasive wear particles.

1.2.5. Corrosive Wear

Please refer to section 1.1.2.

1.3. Laboratory Tests to Simulate Usage Conditions

1.3.1. Early Wear Testing Machines

In 1803 Charles Hatchett (Hatchett, 1803) conducted three accelerated wear tests at the request of the Privy Council to investigate the degradation of gold coins in circulation.

1.3.1.1. First Test

C. Hatchett's (Hatchett, 1803) first test investigated the wear associated with the rubbing of gold coins on similar gold, copper and silver coins. The apparatus was a hand-driven reciprocating accelerated wear testing machine capable of investigating twenty-eight specimens simultaneously, each statically loaded with a 13.6N force. Limitations include manual input required to perform.

1.3.1.2. Second Test

Hatchett's (Hatchett, 1803) second test evaluated the coins resistance to rubbing and impacts. 200 coins were tumbled in an oak box of sides 200cm for at least 72000 revolutions (Dowson, 1985). The limitation was the wooden box wore faster than the coins.

1.3.1.2. Third Test

His third test was a hand-driven turntable with coins loaded against the rim pf 740cm diameter with abrasive powders introduced to the system through a shallow grove to investigate abrasive wear rates (Hatchett, 1803). A limitation was the mechanism jammed due to abrasive particles

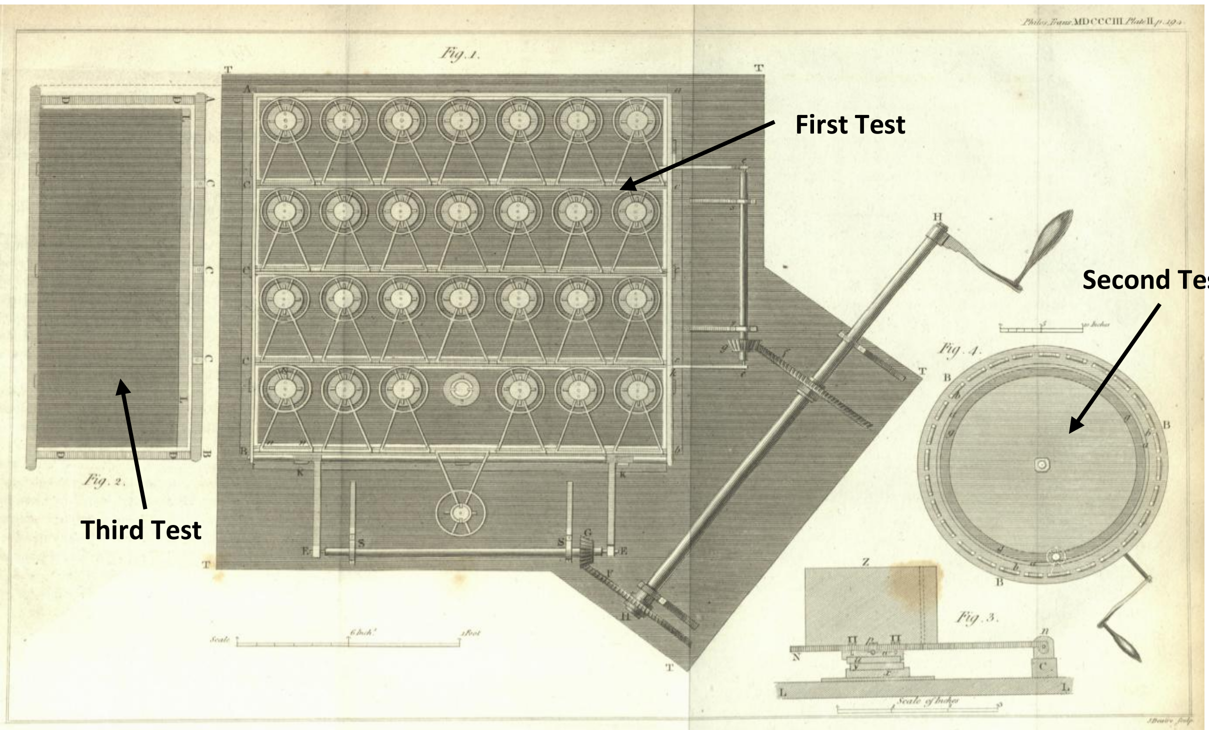

Figure 3. Charles Hatchett's Accelerated Wear Tests (Hatchett, 1803)

1.3.2. Tumbling Wear Tests

Hammer (Hammer, 1973) and M. J. H. Ruscoe (Ruscoe, 1987) conducted tumbling accelerated wear tests on coins using a rotating cylinder to measure their weight loss as a function of time. The latter analysed NBS, nickel and cupronickel ally coins under three different conditions; dipped in an artificial sweat solution, initially dipped in sea water and dipped in sea water daily. A limitation of this test was the initial set-up proved expensive.

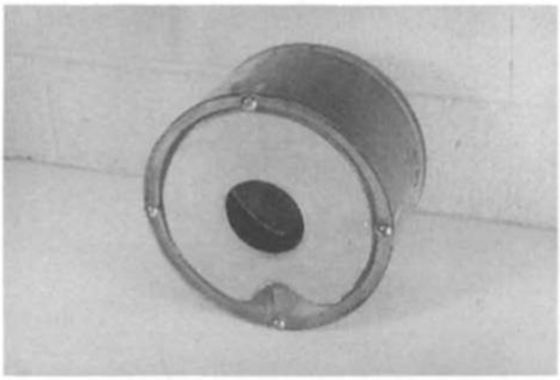

Figure 4. Wear Test Cylinder (Ruscoe, 1987)

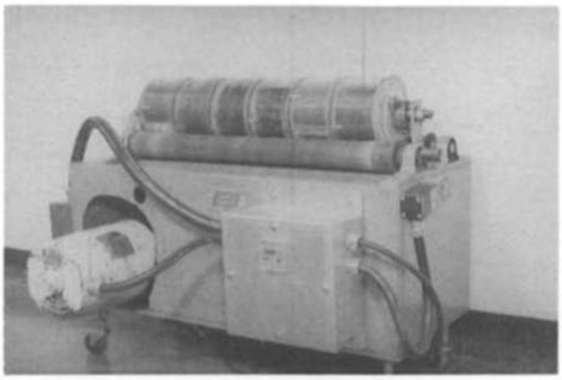

Figure 5. Wear Test Apparatus (Ruscoe, 1987)

1.3.3. Pocket Wear Tests

Roscoe (Ruscoe, 1987) also carried around the three of the aforementioned alloyed coins in his pocket for 891 days with frequent handling to simulate circulation conditions and measured the weight loss and surface thickness loss. The limitation of this test is the conditions aren't accelerated so results took extended times.

Comparative pocket wear test

Coin[a]	*Starting weight* (g)	*Cumulative weight loss* (mg)				*Cumulative surface thickness loss* (µm)			
		Days in pocket[b]				*Days in pocket*[b]			
		65	*259*	*447*	*891*	*65*	*259*	*447*	*891*
N–B–S (token)	4.0430	2.0	3.3	5.4	8.7	0.27	0.45	0.74	1.19
Ni (1981 Canadian 5¢ piece)	4.4981	3.7	4.4	7.4	10.2	0.51	0.60	1.01	1.39
Cupronickel (1982 Canadian 5¢ piece)	4.5885	3.9	8.5	13.3	23.1	0.53	1.16	1.82	3.15

[a]It should be noted that the nickel and cupronickel coins were identical in design apart from the date.
[b]The three coins were carried around together in the same pocket with frequent handling.

Table 1. Comparative Pocket Wear test (Ruscoe, 1987)

1.3.4. Tribometers

Traditional methods of tribological investigations can be adapted to perform accelerated wear tests to measure the friction and wear rates of coins by using tribometers (Stachowiak et al., 2004).

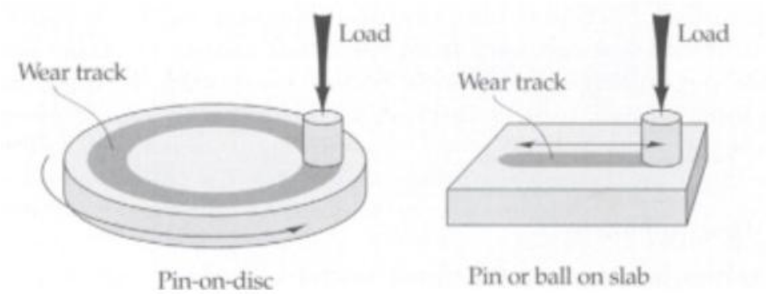

Figure 6. Pin-on-disc Tribometer Figure 7. Pin-on-Slab Tribometer

1.4. Al (Stachowiak et al., 2004) w Coins

1.4.1. Coinage Material Selection Criteria

A lot of research effort has been invested into attaining new coinage materials that meet a strict selection criteria ("The United States Mint and Coinage", 1864) (*Alternative metals study*, 2012) (Rice, 1965). The bullet points below represent a colaborated specification outlined by the Royal Mint ("The Royal Society and the Royal Mint", 1964)) and US Department of Tresurey ("Department of the Treasury", 1973):

- Raw Material Availability
- Wear Resistance
- Corrosion Resistance
- Cost
- Strip and Production Costs
- Ease of fabrication
- Compatibility with Present Coinage
- Density
- Counterfeiting Potential
- Energy Consumption
- Vending Machine Use
- Strain Hardening
- Toxicity
- Recyclability
- Acceptability
- Longevity

1.4.2. Materials Advantages and Disadvantages

The table below created incorporates a weighted system to compare feesible coinage materials against one another with the key of; 1 = Very Good (**Advantage**), 6 = very Bad (**Disadvantage**), X = not feessible (X=10 for summations).

The material with the lowest number is recommendedly used as the prodominant alloy, coupled with another metal.

Feasible Metal	**Selection Criteria**								
	Ease of Coin Fabrication	Raw Materials and Strip			Long Range Seigniorage Production	Public Acceptability			Total
		Present Cost	Present availability	Production Feasibility		General	Coin Machines	Durability	Σ
Penny Bronze	4	X	4	2	X	2	2	4	**38**
Copper - 30% Zinc	5	6	4	4	X	3	2	4	**38**
Bronze Clad Steel	X	5	4	4	3	3	4	4	**37**
Chromised Steel	X	3	X	X	2	4	4	2	**45**
Aluminium	2	1	4	4	1	5	5	4	**26**

Table 2. Weight Advantages and Disadvantages of Feasible Coinage

("Aluminium and other coin metals", 2018), (Rice, 1965) ("U.S. Mint alternative metals testing finds options with potential", 2022)

2. References

[1] Dowson, D., 1985. Wear oh where? *Wear*, 103(3), pp.189-203.

[2] P. Hammer, Schmierungstechnik, 4 (1973) 6, 165.

[3] IV. Experiments and observations on the various alloys wear of gold. (1803), *93*, 43-194. https://doi.org/10.1098/rstl.1803.0005

[4] Ruscoe, M. (1987). A predictive test for coin wear in circulation. *Wear*, *119*(3), 329-342. https://doi.org/10.1016/0043-1648(87)90039-1

[5] Cope, R. (1969). The wear of U.K. coins in circulation. *Wear*, *13*(3), 217-224. https://doi.org/10.1016/0043-1648(69)90152-5

[6] *Conservation of coins*. Bcb.gov.br. (2022). Retrieved 29 December 2018, from https://www.bcb.gov.br/ingles/museu-espacos/conserv-i.asp?frame=1.

[7] Wear mechanisms. (2001), 1-3. https://doi.org/10.1016/b978-075065154-7/50113-3

[8] Goldman, A., & Smith, W. (1980). *Alternative materials for one-cent coinage*. Dept. of the Treasury.

[9] Brandes, E., Brook, G., & Smithells, C. (2005). *Smithells metals reference book*. Butterworth-Heinemann.

[10] Hutchings, I. (1992). Tribology: friction and wear of engineering materials. *Materials & Design*, *13*(3), 187. https://doi.org/10.1016/0261-3069(92)90241-9

[11] Hutchings, I. (1992). *Tribology*. CRC.

[12] Tanzi, M., Farè, S., & Candiani, G. (2019). Mechanical Properties of Materials. *Foundations Of Biomaterials Engineering*, 105-136. https://doi.org/10.1016/b978-0-08-101034-1.00002-5

[13] Stachowiak, G., Batchelor, A., & Stachowiak, G. (2004). Tribometers. *Experimental Methods In Tribology*, 25-78. https://doi.org/10.1016/s0167-8922(04)80019-1

[14] Julander, A., Midander, K., Herting, G., Thyssen, J., White, I., Odnevall Wallinder, I., & Lidén, C. (2013). New UK nickel-plated steel coins constitute an increased allergy and eczema risk. *Contact Dermatitis*, *68*(6), 323-330. https://doi.org/10.1111/cod.12092

[15] Feng, K., & Shao, T. (2021). The evolution mechanism of tribo-oxide layer during high temperature dry sliding wear for nickel-based superalloy. *Wear*, *476*, 203747. https://doi.org/10.1016/j.wear.2021.203747

[16] Gwozdz, R., & Grass, F. (2004). Contamination by human fingers: The Midas touch. *Journal Of Radioanalytical And Nuclear Chemistry*, *259*(1), 173-176. https://doi.org/10.1023/b:jrnc.0000015824.18586.42

[17] Rice, L. (1965). *Final report on a study of alloys suitable for use as United States coinage to U.S. Department of the Treasury*. Battelle Memorial Institute.

[18] The United States Mint and Coinage. (1864), *10*(7), 99-99. https://doi.org/10.1038/scientificamerican02131864-99

[19] Alternative Materials for One Cent Coinage. (1973). United States: Department of the Treasury.

[20] *Aluminum and other coin metals – aluminium-guide.com*. Aluminium-guide.com. (2018), from https://aluminium-guide.com/en/alyuminij-i-drugie-monetnye-metally/.

[21] *U.S. Mint alternative metals testing finds options with potential*. CoinWorld. (2019), from https://www.coinworld.com/news/us-coins/us-mint-continues-alternative-metals-experiments.html.

[22] Concurrent Technologies Corporation. (2012). *Alternative metals study*.

[23] The Royal Society and the Royal Mint. (1964), *19*(2), 156-167. https://doi.org/10.1098/rsnr.1964.0014