Performance Testing and Comparison of Thoriated Tungsten and E3 Tungsten Electrodes

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Executive Summary

Tungsten electrodes are critical to gas tungsten arc welding process performance. Refractory oxides are added to tungsten electrodes to lower the work function for thermionic electron emission, electrode tip temperature, and fall voltage. For years ThO_2 (thoria) was preferred for direct current electrode negative conditions. Thorium is weakly radioactive and contains trace levels of naturally occurring isotopes that emit alpha particles at a very long half-life. Due to the increased awareness and trends to eliminate all radioactive sources (even at safe levels) from the work environment, some welding communities recommend using nonradioactive alternatives. Tungsten electrode suppliers have developed a range of alternative alloys that are not radioactive with potentially better process properties. Mixed oxide tungsten electrodes that combine yttrium, lanthanum, and zirconium oxides have been reported to offer superior electrode properties. Independent studies have concluded that alloys that contain all three oxides; yttrium, lanthanum and zirconium oxide electrodes, commercially known as E3, outperformed commercial thoriated tungsten electrodes in arc starting, electrode life, and arc stability. This project developed independent, reproducible, and consistent testing procedures that compare arc starting and electrode life on two tungsten electrodes: ThO_2(2.0%)-W and Astaras E3. This comparison will be accomplished by means of two duty test methods, the heavy current loading and the stop-start tests. The heavy current loading test found that the E3 electrode experienced significantly less erosion and tip degradation than the ThO_2(2.0%)-W electrode. Increasing current and time caused more severe erosion for both electrodes, as well as rim formation. This rim formation and erosion is related to the rare earth metal oxides in these electrodes, their electron work functions, and their reactions with tungsten during arcing. After a 100-arc start test, the E3 electrode showed less tip degradation than the ThO_2(2.0%)-W electrode, as well as a lower arc-start failure rate.

Introduction/Background

Tungsten electrodes are critical to gas tungsten arc welding (GTAW) process performance. Refractory oxides are added to tungsten electrodes to lower the work function for thermionic electron emission, electrode tip temperature, and fall voltage. For years, thorium oxide was preferred for direct current electrode negative (DCEN) conditions. Thorium is weakly radioactive and contains trace levels of naturally occurring isotopes that emit alpha particles at very long half-life. Due to the increased awareness and trends to eliminate all radioactive sources (even at safe levels) from the work environment, some welding communities recommend using nonradioactive alternatives. The International Institute of Welding (IIW) (ref.1) and American Welding Society (AWS) (ref.2) have provided careful guidance to reduce radioisotopes from the welding environment. AWS's Safety & Health Fact Sheet No.27 principal recommendation is to choose thorium-free tungsten electrodes such as those containing cerium, lanthanum, yttrium, or zirconium.

AWS's Fact Sheet notes the hazard is created by grinding as part of the standard procedure to prepare the electrodes to perform gas tungsten arc welding. Dust particles from this grinding process can cause internal radiation exposure if the dust is accidentally ingested or inhaled, so precaution is necessary. Concern regarding radiation exposure to the external body from these electrodes is minimal. If thoriated electrodes are preferred to be used, the Fact Sheet recommends:

- Read, understand, and follow all information in the Safety Data Sheet (SDS) for the selected tungsten electrode.
- Use a high-efficiency dust collection system to capture particles created during the grinding of electrodes or disturbed during housekeeping.
- Evaluate the ventilation system before acceptance and periodically thereafter to minimize personnel and environmental contamination.
- Develop and implement standard operating procedures for the use of thoriated tungsten electrodes, including proper procedures for storage, grinding, use, housekeeping and disposal, and
- Provide training in the operation of the welding and grinding equipment, personal hygiene, and safety.

Grinding equipment suppliers have noted that wet grinding tungsten electrodes is more effective at capturing grinding debris than dry grinders. When welding, the risk of internal exposure is negligible in most circumstances since the thoriated electrode is consumed at a very slow rate.

The possible harm from thoriated electrode usage has prompted action from the Nuclear Regulatory Commission (NRC) to issue distribution requirements. Effective August 27, 2014, electrode manufacturers and handlers have to possess a certain license for legal distribution, which includes requirements for labeling, quality control, reporting and record keeping (ref.3). The Department of Transportation (DOT) requires all shippers to properly package and label all thoriated electrodes (ref.4). The surfaces of these packages are checked for radioactivity. Other organizations like the European Union, United Nations, and the Gases and Welding Distribution Association (GAWDA) have stressed for industry leaders to discontinue manufacturing and usage of thoriated tungsten electrodes.

Professionals in the industry find the many varying regulations from these authorities complicated to follow, and expensive. Difficulties complying with these regulations have resulted in the stoppage of manufacturing thoriated tungsten electrode in North America. The largest manufacturers in Europe and the IGB Group in Germany and China have stopped using thoriated electrodes.

Another issue manufactures' face when considering changing tungsten electrode type is whether the electrode type is considered an essential or non-essential variable for procedure qualification. Technical codes from the American Society of Mechanical Engineering (ASME) Boiler &

Pressure Vessel Code, Section 9; AWS D1.1 Structural Welding Code – Steel; and D1.2 Structural Welding Code – Aluminum, for example specify the tungsten electrode type to be a non-essential variable for the Welding Procedure Qualification Record (PQR). One AWS code, D17.1 Structural Welding Code - Aerospace Fusion Welding specifies the type of tungsten as an essential variable. The latter code governs the welding of very high integrity structures used in aerospace applications where risks are carefully managed. High quality data is needed to show electrode type is nonessential before risk adverse communities will allow electrode substitution without re-qualification. For standards that specify electrode type as essential, switching to non-thoriated electrodes could cost fabricators large sums to re-qualify welding procedures.

AWS A5.12M/A5.12:2009 - Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting (Table 1), lists a range of electrode types that can carry an AWS marking based on a specified alloy mixture. A mixed oxide tungsten electrode known as E3 has been reported to offer superior electrode performance. It has a chemical composition of 98.34% W +1.5% La_2O_3 + .08% ZrO_2 + .08% Y_2O_3. Internal testing done by a manufacturer (Astaras) shows this tungsten alloy to have better arc starting capabilities and running temperature 1650 deg F lower than conventional 2% thoriated electrodes (ref.5), (ref.6). Lower operating temperatures produces less oxide burn-off, which results in longer electrode life (ref.7). Data also shows the E3 electrode to have a better work function; so much so that in most instances machine current can be lowered around 5%.

Table 1 – Chemical Composition Requirements for Tungsten Electrodes

Classification symbol (*ISO 6848* Classification)	Chemical composition requirements				Colour code, RGB colour value and colour sample[a]
	Oxide addition		Impurities, mass percent	Tungsten, mass percent	
	Principal oxide	Mass percent			
EWP (WP)	None	N.A.[b]	0.5 max.	99.5 min.	Green #008000
EWCe-2 *(WCe 20)*	CeO_2	1.8 to 2.2	0.5 max.	Balance	Grey (formerly orange) #808080
EWLa-1 *(WLa 10)*	La_2O_3	0.8 to 1.2	0.5 max.	Balance	Black #000000
EWLa-1.5 *(WLa 15)*	La_2O_3	1.3 to 1.7	0.5 max.	Balance	Gold #FFD700
EWLa-2 *(WLa 20)*	La_2O_3	1.8 to 2.2	0.5 max.	Balance	Blue #0000FF
EWTh-1 *(WTh10)*	ThO_2	0.8 to 1.2	0.5 max.	Balance	Yellow #FFFF00
EWTh-2 *(WTh 20)*	ThO_2	1.7 to 2.2	0.5 max.	Balance	Red #FF0000
(WTh 30)	ThO_2	2.8 to 3.2	0.5 max.	Balance	Violet #EE82EE
EWZr-1 *(WZr 3)*	ZrO_2	0.15 to 0.50	0.5 max.	Balance	Brown #A52A2A
EWZr-8 (WZr 8)	ZrO_2	0.7 to 0.9	0.5 max.	Balance	White #FFFFFF
EWG	*The manufacturer must identify all additions.*	*The manufacturer must state the nominal quantity of each addition.*	*0.5 max.*	*Balance*	*The manufacturer may select any color not already in use.*

NOTE Intentional additions of "doping oxides" other than indicated for a particular electrode classification is prohibited.

[a] RGB color values and color samples can be found at the following website: *http://msdn2.microsoft.com/en-us/library/ms531197.aspx*

[b] N.A. = Not applicable.

Project Objectives

- Conduct a literature review on tungsten electrode alloy development and performance testing methods
- Develop repeatable, consistent electrode performance testing methods for electrode life and arc starting
- Evaluate other types of electrode performance tests that could be easily replicated and offer benefits to industry
- Establish the electrode life and arc starting performance of two types of tungsten electrodes
- Rank the electrode performance based on the preferred test conditions
- Compare test results with data published by industry and other researchers

Experimental Procedure

Two types of testing were used to assess and compare electrode characteristics: an electrode life (heavy loading) test and a start-stop test. The performance of two electrodes were evaluated with these tests, the Astaras E3 and ThO_2(2.0%)-W electrode. For the heavy loading test, it was imperative that the duty cycle of the power supply and the torch could sustain the high amperage of the test for one-hour intervals. For this reason, an air-cooled, stationary handheld torch was used for the lower amperages, while a machine-held, water-cooled straight torch was needed for the higher amperage tests. The air-cooled torch was sufficient for the start-stop testing. Each electrode was precisely ground with a wet auto-grinder for consistent tip angles. A water-cooled copper block served as the anode for all testing; that is, no filler material was used.

Task 1: Heavy Loading (Electrode Life) Test

Subtask 1.1: Equipment and set-up

Three electrode life tests were performed for each electrode type, totaling six life test trials. The three trials varied only in current, all of which were DCEN: 80 A, 120 A, and 150 A. Before each life test, gas was purged for at least 30 minutes to remove any oxygen that may have built up in the tubing. The gas pre-flow and post-flow times were set at 5 s and 10 s, respectively. 99.998% Ar shielding gas was used at 9 L/min (29 cf/hr). 3/32-inch electrodes were selected as appropriate for these amperages. The electrodes were ground precisely to a 30-degree included angle (not truncated) using an automatic wet grinder. Photographs were taken of each electrode tip after grinding, prior to testing. The electrode to anode distance was set at 3 mm, and the nozzle to tip distance at 5 mm. A composite size 10 torch nozzle with a gas lens was used. The anode (copper block) was filed and cleaned with acetone before each test.

Subtask 1.2: Life Testing

The welder was run continuously for five one-hour intervals with the parameters described in Subtask 1.1. During testing, the temperature of the front edge of the copper block, the current, the voltage, and any relevant observations were recorded every 15 minutes. Between one-hour intervals, the electrode and torch were allowed to cool to room temperature and photographs were taken of the tip of the electrode. No precise quantitative measurements were taken; instead, the photographs served as qualitative data to compare electrode performance.

Task 2: Start-stop Test

Similar parameters were used in the start-stop testing as the heaving loading: 99.998%Ar shielding gas at 9 L/min, 5 mm electrode to anode distance, 3 mm stick-out, 3/32-inch electrodes with 30-degree included angles, and DCEN current. The testing was completed with E3 and ThO_2(2.0%)-W electrodes. After 5 seconds of gas pre-flow, the welder was run with a 3 seconds on-12 seconds off sequence with continuous gas flow until 100 arc strikes were made. Arc start failures were recorded when appropriate. Photographs were taken before and after the 100-start sequence to observe electrode wear due to arc striking.

Results

Electrode Life Test

The results of the life test for the E3 electrode at 80 A are shown in Figure 1. After the first hour, the electrode tip had just begun to dull slightly, and a faint build-up of material is visible about 1 mm below the tip. As the test progressed, the tip remained slightly dulled, with little to no additional degradation occurring just at the tip. The material build-up observed just below it gained some additional thickness by hour 5, but on the macro-scale still appeared mostly flush along the side of the electrode face. Throughout the life test, the arc appeared stable and consistent, and was contained to the lower third of the ground face of the electrode.

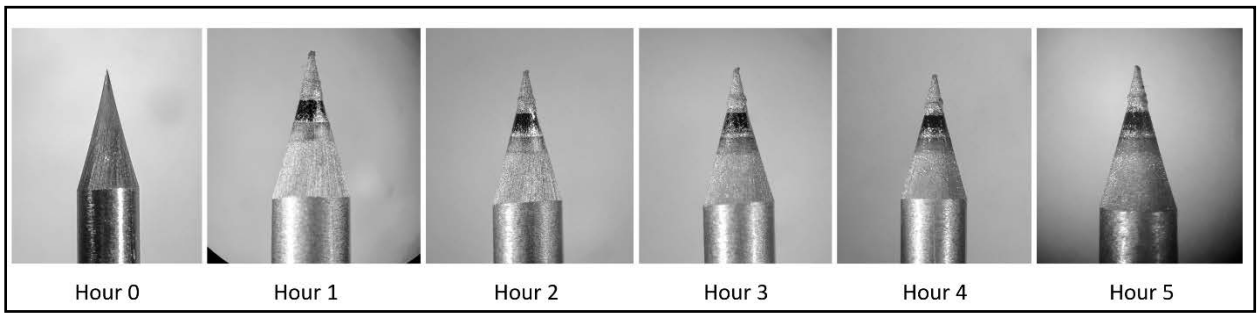

Figure 1: E3 electrode completed life test at 80 A – five 1-hr intervals

Figure 2 displays the five photographs of the ThO_2(2.0%)-W electrode during each hour of the five-hour life test at 80 A. Erosion was observed at the tip of the electrode after the first hour. A small bulb developed in place of the point at the tip, with material build-up beneath it, similar to the E3 results. However, the erosion at the tip for this electrode was more significant than the E3, as was the material build-up. In hours 3 through 5, the rim of material build-up grew down the length of the electrode and developed a rougher, more grainy texture. The bulb at the tip of the electrode became shorter and thicker through hour 5. Despite its more significant erosion and tip rounding, the arc of the ThO_2(2.0%)-W electrode remained stable and consistent throughout the life test.

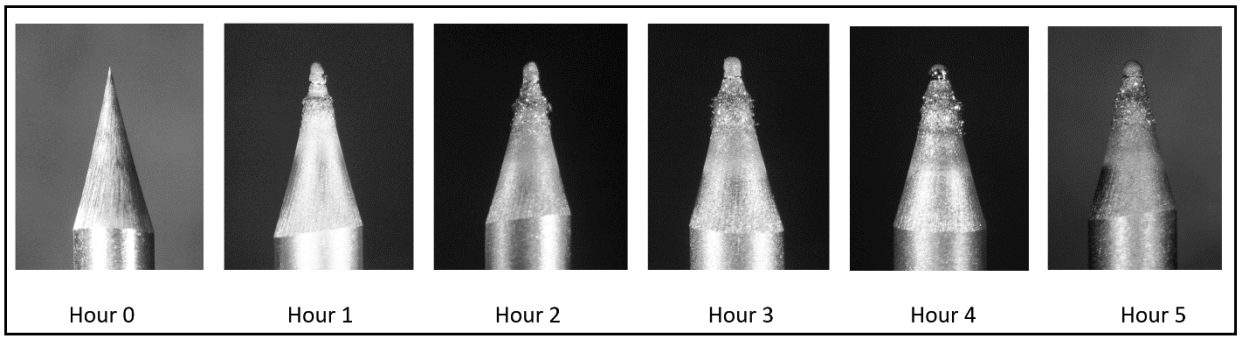

Figure 2: ThO_2(2.0%)-W electrode completed life test at 80 A – five 1-hr intervals

The 120 A life test results of the E3 electrode are shown in Figure 3. More significant rim formation and tip degradation were apparent at this higher current. The rim appeared to exhibit dendritic growth, as thin needles begin to form on the rim's surface after each hour. Figure 4 displays the 5-hour life test for the ThO_2(2.0%)-W electrode at 120 A where the dendritic rim growth was far

more extreme. Hour 1 shows significant tip melting and erosion as well as the longest outward rim growth. As the test progresses, the tip continues to melt away and recede towards the rim. At the same time, the rim itself begins to melt away and decreased in thickness.

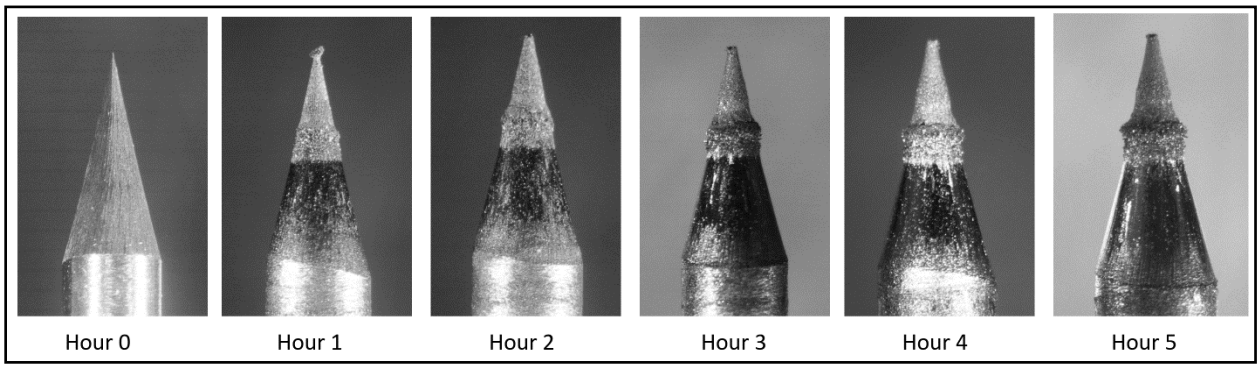

Figure 3: E3 electrode completed life test at 120 A – five 1-hr intervals

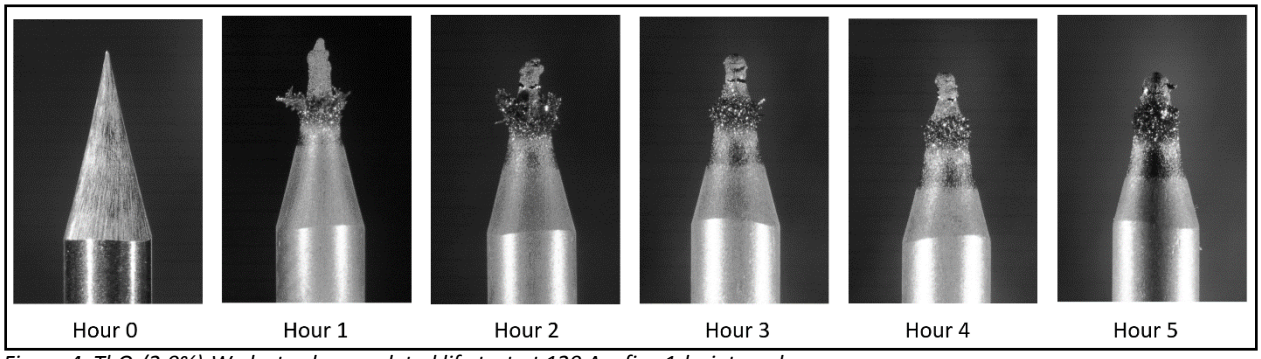

Figure 4: ThO_2(2.0%)-W electrode completed life test at 120 A – five 1-hr intervals

In Figure 5, the results from the 150 A life test for the E3 electrode are displayed. Significant rim formation was apparent in each of the five hours. The tip was immediately flattened after hour 1, and rim formation occurred about 2 mm from the tip. At hour 1, the surface of the rim was relatively smooth and barely thicker than edge of the electrode. The longitudinal grinding lines were still vaguely visible after hour 1. As testing progressed, grinding lines were eliminated and the rim became coarser and more crystalline in appearance. The higher current in this test contributed to the increased erosion and rim formation compared to the 80 A and 120 A tests. No irregularities or changes were observed in the arc throughout the five hours.

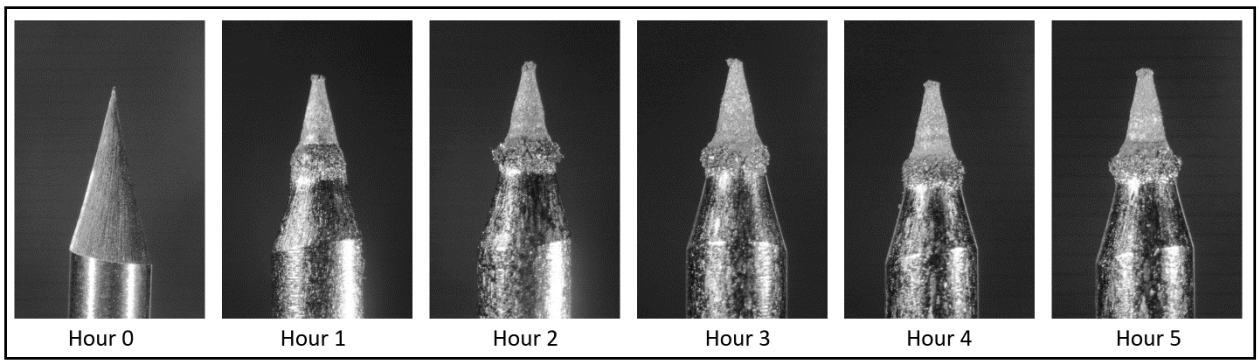

Figure 5: E3 electrode completed life test at 150 A – five 1-hr intervals

Figure 6 shows the 150 A life test for the ThO_2(2.0%)-W electrode. Starting in hour 1, severe flaring of material developed about 2 mm from the electrode tip. This phenomenon is normally attributed to oxidation of the tungsten, usually due to oxygen contamination in the welding apparatus. However, the lines were properly purged with argon gas, and gas flow was monitored throughout the process. The cause of this flaring was attributed to other causes, discussed later in this work. Heavy erosion occurs at the electrode tip from hour 2-5, where the tip completely rounds off and there was evident material loss. The flaring rim became thicker with each additional hour and more crystalline in appearance. Though the arc appeared to be stable throughout testing, this level of erosion in the electrode would not be an acceptable condition for performance welding. A representative welding testing that examines weld cross section should be considered for future work.

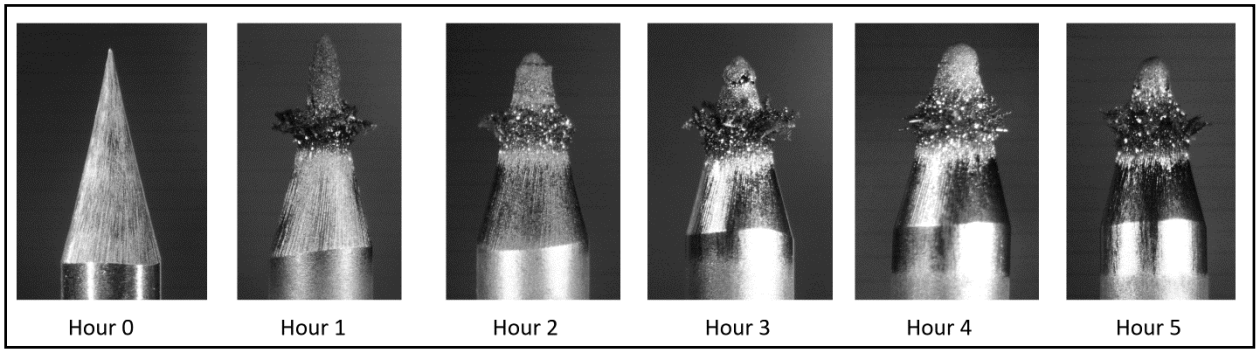

Figure 6: ThO_2(2.0%)-W electrode completed life test at 80 A – five 1-hr intervals

Start-stop Test

100 arc strikes were completed for the start-stop test, during which the E3 electrode had a failure rate of 1%, while the ThO_2(2.0%)-W electrode failed to start 15% of the time. A comparison photo of the electrode tips after the testing is presented in Figure 7. The ThO_2(2.0%)-W electrode experienced more tip degradation than the E3, though both showed no flaring or rim formation as was evident in the heavy loading tests.

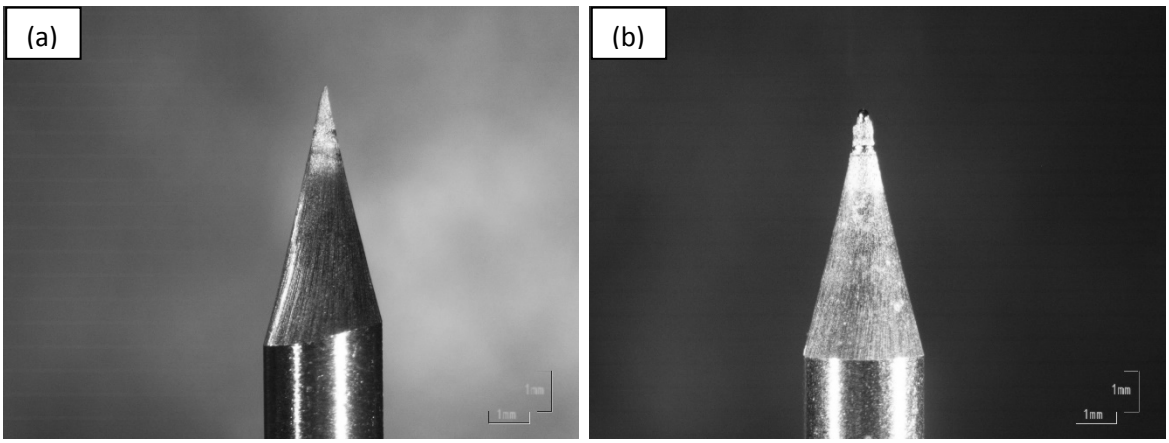

Figure 7: Photographs of the (a) E3 electrode and (b) the ThO_2(2.0%)-W electrode after 100 arc starts

Discussion

Several papers have been published that help explain the mechanism behind the different erosion characteristics of these electrodes after heavy loading and start-stop testing. The most prominent difference between the two electrodes are their alloying oxides – 2% ThO_2 for the thoriated electrode and 1.5% La_2O_3 + .08% ZrO_2 + .08% Y_2O_3 for the E3. These rare earth metal oxides have strong effects on the electrode's microstructure and arc characteristics. Suga, Ogawa, and Matsumoto in their work (ref.8) list common alloying elements along with their boiling and melting point and work functions, which are shown in Table 2. Electron work functions strongly influence the electron emission current density of the arc, governed by the Richardson-Dushman equation (ref.8)

$$J = AT^2 \exp\left(-\frac{e\phi}{kT}\right)$$

where J is the current density, A is a constant, k is the Boltzmann constant, e is the charge of an electron, T is temperature, and ϕ is the work function. A cathode (electrode) must reach a critical temperature in a welding arc system to produce a sufficient current density of emitted electrons necessary to maintain an arc. Lower electron work functions allow the cathode to operate at a lower surface temperature while sustaining a high current density. According to Table 2, Y_2O_3 and La_2O_3 and have lower work functions than ThO_2, so one could conclude that the E3 electrodes which contain Y_2O_3 and La_2O_3, operate at lower surface temperatures than a thoriated electrode. However, it is worth noting that ZrO_2, also found in the E3, is reported having a higher work function than ThO_2 (ref.9), and that work functions can change with temperature and crystal face orientation (ref.10, ref.11). That said, higher alloying composition of the E3 with Y_2O_3 and La_2O_3, and thus an overall lower electron work function, believed to provide lower surface temperatures and lower erosion rates than the thoriated tungsten electrode.

Table 2: Rare earth metal properties (ref.8)

	Melting point (K)	Boiling point (K)	Work function Φ (eV)	A Value kA/m^2K^2
W	3653	5800	4.54	600
WO	1745	2123	9.22	—
Th	2008	5757	3.3	—
W–Th*	—	—	2.63	30
ThO_2	3327	4673	2.6	50
Y	1783	3610	3.3	—
W–Y*	—	—	2.7	70
Y_2O_3	2683	4573	2.4	10
La	1193	3727	3.3	—
W–La*	—	—	2.71	80
La_2O_3	2573	4473	2.5	9
Ce	1073	3530	2.84	—
W–Ce*	—	—	2.71	80
CeO_2	2873	—	3.2	10

*** Thermionic properties of rare-earth metals with adsorbed electropositive layers.**

Sadek, Ushio, and Matsuda corroborated the variance of operating temperatures of electrodes based on alloying elements (and their differing work functions) in a graph shown in Figure 8 (ref.9). They found the operating temperatures of the electrodes from lowest to highest were the 2% yttriated, 2% lanthanated, 2% thoriated, and 2% zirconiated tungsten. Based on this data, the combined presence of Y_2O_3, La_2O_3, and ZrO_2 in the E3 would be expected to cause a lower operating temperature than the 2% thoriated electrode.

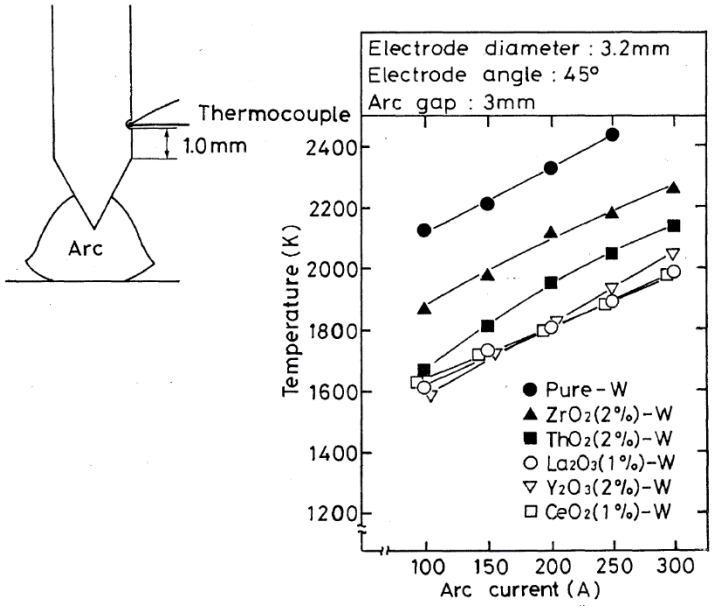

Figure 8: Electrode operating temperatures measured by thermocouple (ref.9)

The more significant erosion seen in the ThO_2(2%)-W electrode can be explained by the higher operating temperatures causing increased sublimation and/or melting of the oxides at the surface of the electrode tip. This sublimation and melting caused mass loss which was studied in ref. 8 and shown in Figure 9. Lanthanated and yttriated tungsten experienced less erosion than the thoriated tungsten, which is consistent with their lower work functions and can be applied to this study's results with the E3 and ThO_2(2%)-W electrodes.

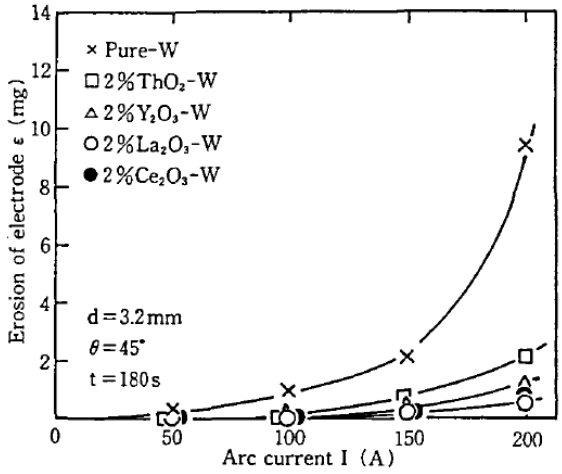

Figure 9: Effect of current and alloying elements on electrode erosion (ref.8)

From the available literature, there is no universal mechanism that describes the rim formation seen in tungsten electrodes under heavy loading. Most agree that rim formation is increased as a function of increasing temperature, current, and oxygen content in the shielding gas. The results in this work validate these relationships. The authors of ref. 12 describe a mechanism of rim formation where tungsten oxide is vaporized at the surface, travels along the path of the shielding gas due to electrostatic forces, and is deposited onto the electrode surface as a rim where the temperature and vaporization rate allow for dendritic growth. A schematic of this mechanism is shown in Figure 10.

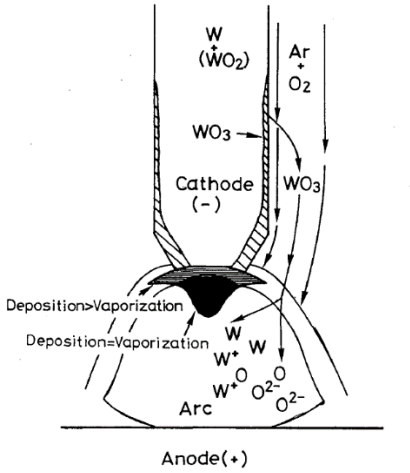

Figure 10: Rim formation mechanism by vaporization and deposition of tungsten oxides (ref.9)

Sadek et al. also studied the temperature profiles of electrodes with differing rare element oxide additions, and how these oxides react with tungsten and behave during arcing (ref.10). The authors found that mobility of Y_2O_3 and La_2O_3 contributed to more stability than ThO_2. In addition to oxide migration, ref. 10 observed differing reactions of the rare metal oxides with tungsten at elevated temperatures. ThO_2 and W experienced a reaction zone where pure thorium was formed and vaporized, which could also explain the increased rim formation of the ThO_2(2%)-W electrode in this report. The reduction of ThO_2 may have created increased presence of tungsten oxides on the surface which vaporized and were redeposited onto the rim beneath the reaction zone. This theory could be validated by compositional and microscopic analysis of the rim in future work. What is generally accepted is that this rim formation could seriously affect arc stability and electrode durability, especially during extended continuous operation.

Conclusions

1. Under continuous heavy loading conditions, the E3 experienced less erosion and tip degradation than the ThO_2(2.0%)-W electrode. This difference is attributed to the lower electron work functions of the E3 electrode's rare earth metal alloying oxides causing it to operate at lower temperatures and undergo less sublimation and melting than the thoriated electrode.
2. Rim formation increased with increasing current and load time.
3. The ThO_2(2.0%)-W electrode experienced more severe rim formation due to the instability of ThO_2 and its reaction with tungsten that promoted tungsten oxide and/or pure thorium vaporization and subsequent deposition onto the rim.
4. Tip degradation for both the E3 and ThO_2(2.0%)-W electrode was not severe enough to affect the arc stability of the 80 A heavy loading test, though the extent of rim build-up in the 150A life test for both electrodes, and the 120A life test for the ThO_2(2.0%)-W electrode, would be considered unacceptable.
5. After 100 arc starts, the E3 electrode experienced less tip degradation than the ThO_2(2.0%)-W electrode and a lower arc-start failure rate.
6. Better guidelines are needed to define 100% current duty for combinations of electrode type, diameter, and tip geometry

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Appendix

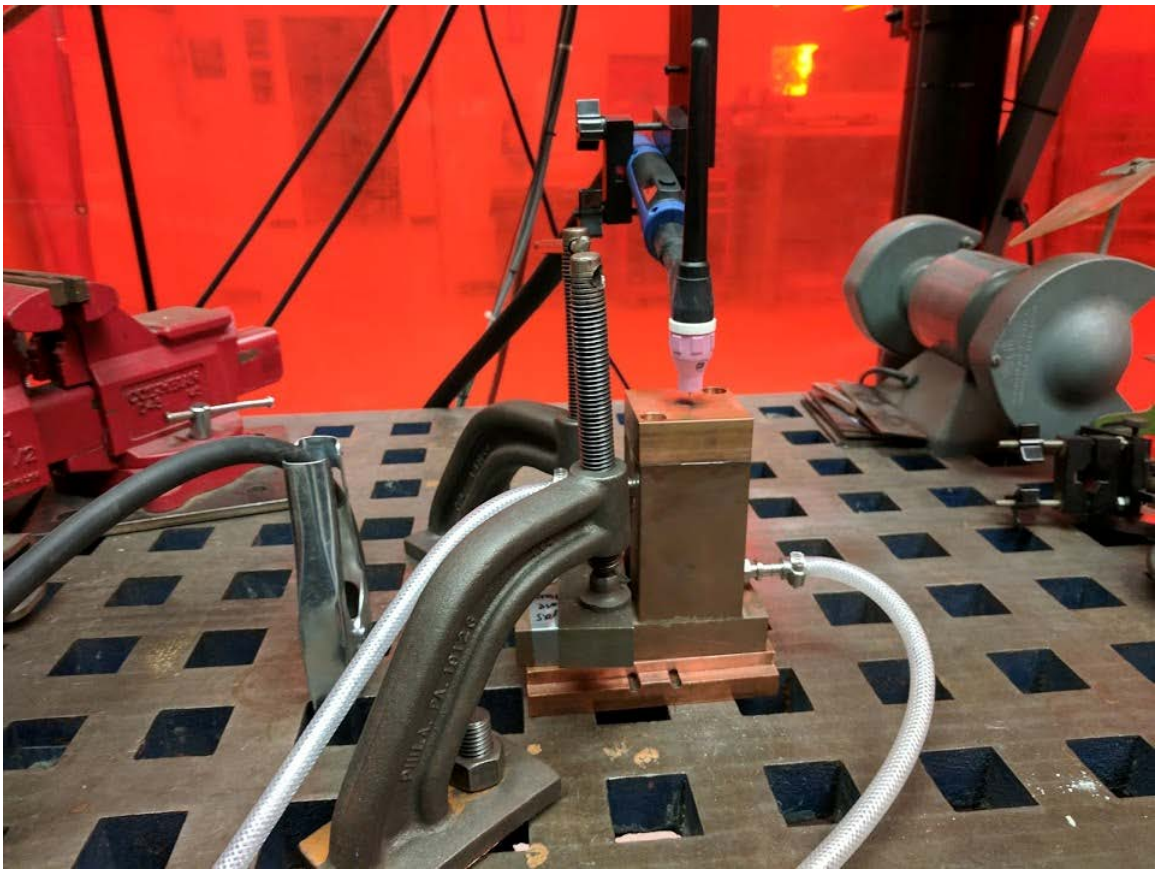

Figure A1: Equipment set-up with air-cooled torch for 80A life tests. Copper block (anode) is water-cooled and was used for all testing.

Figure A2: E3 electrode at hour 0 of 80 A life test

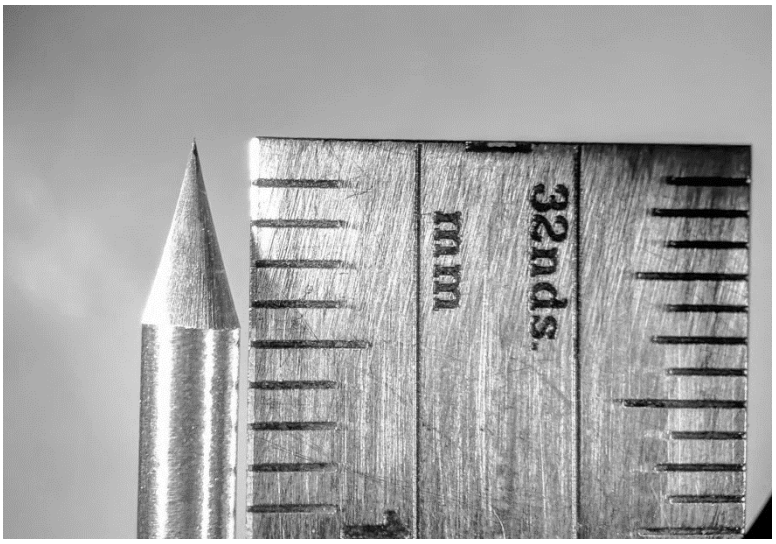

Figure A3: E3 electrode at hour 0 of 80 A life test with scale

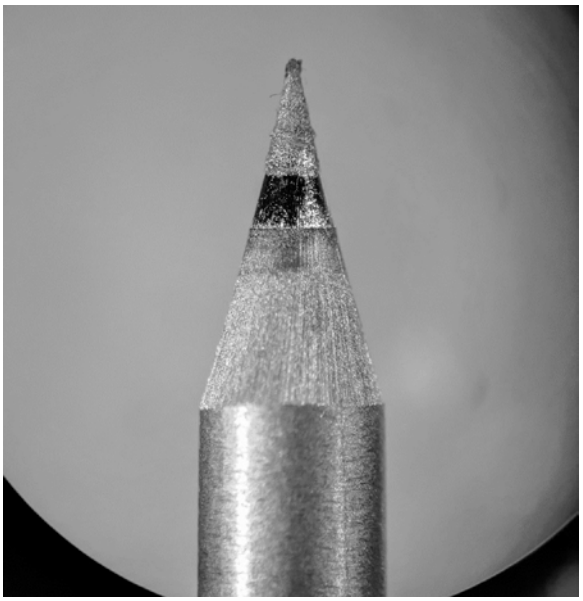

Figure A4: E3 electrode at hour 1 of 80 A life test

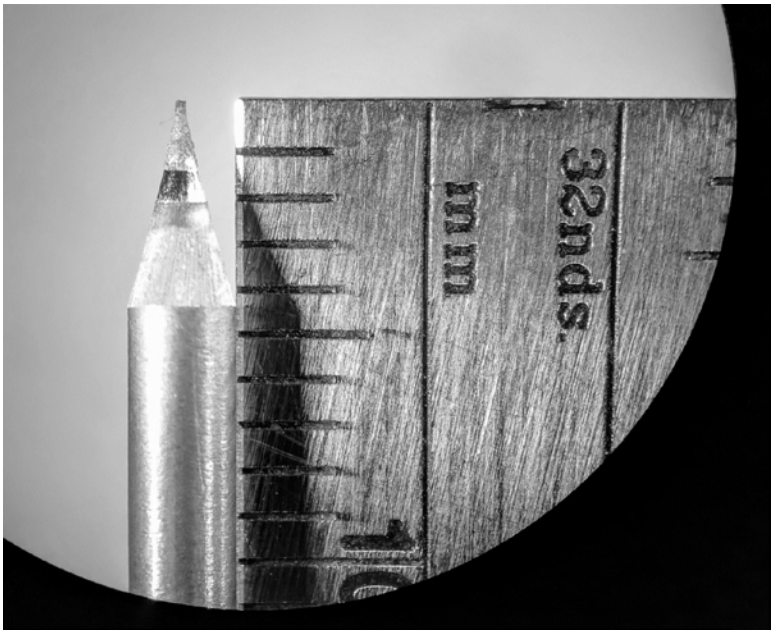

Figure A5: E3 electrode at hour 1 of 80 A life test with scale

Figure A6: E3 electrode at hour 2 of 80 A life test

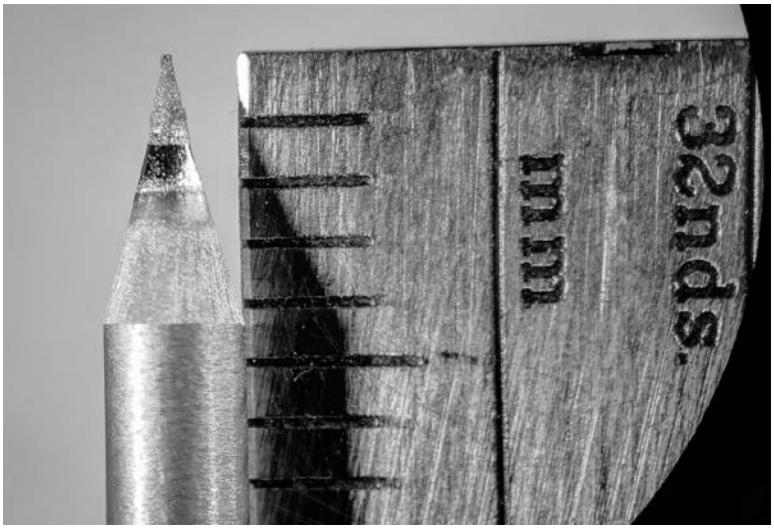

Figure A7: E3 electrode at hour 2 of 80 A life test with scale

Figure A8: E3 electrode at hour 3 of 80 A life test

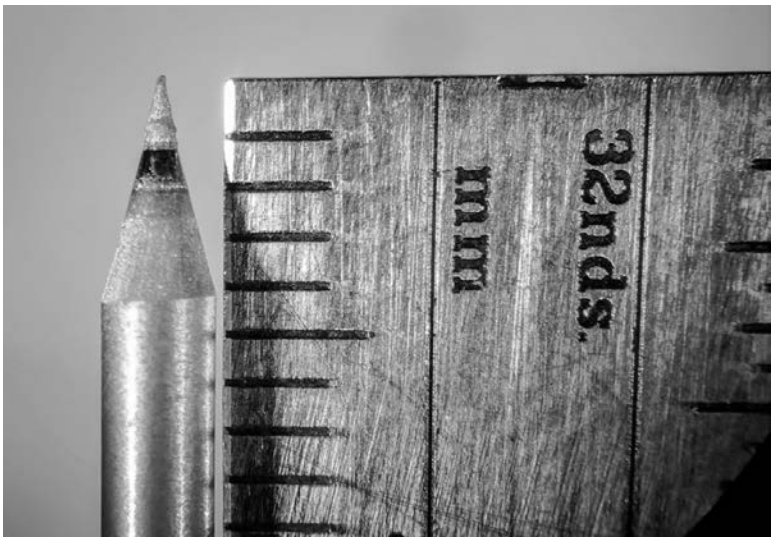

Figure A9: E3 electrode at hour 3 of 80 A life test with scale

Figure A10: E3 electrode at hour 4 of 80 A life test

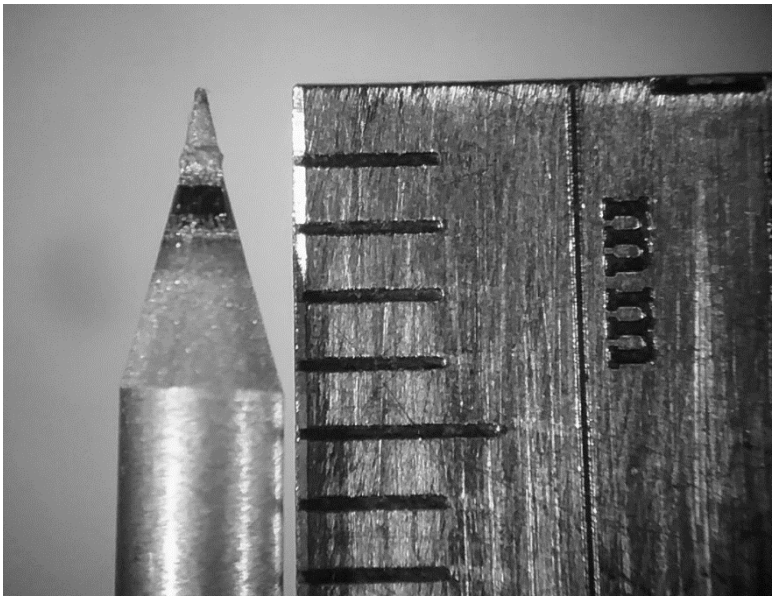

Figure A11: E3 electrode at hour 4 of 80 A life test with scale

Figure A12: E3 electrode at hour 5 of 80 A life test

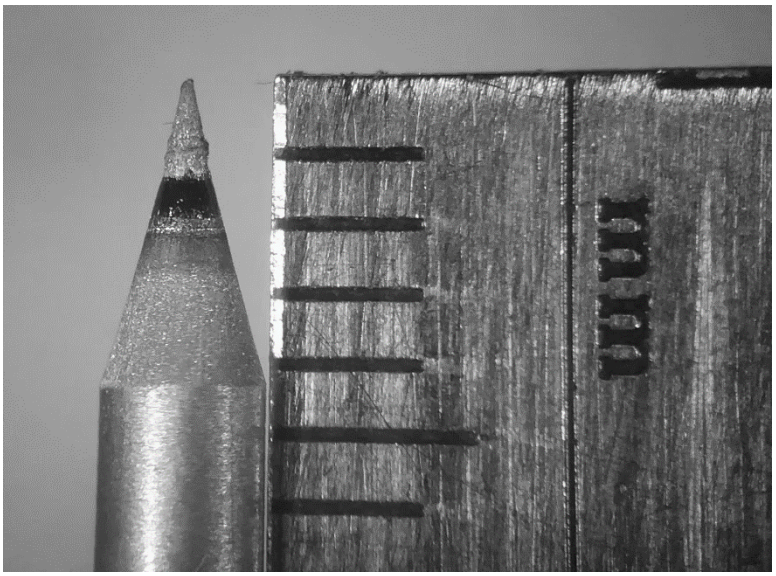

Figure A13: E3 electrode at hour 5 of 80 A life test with scale

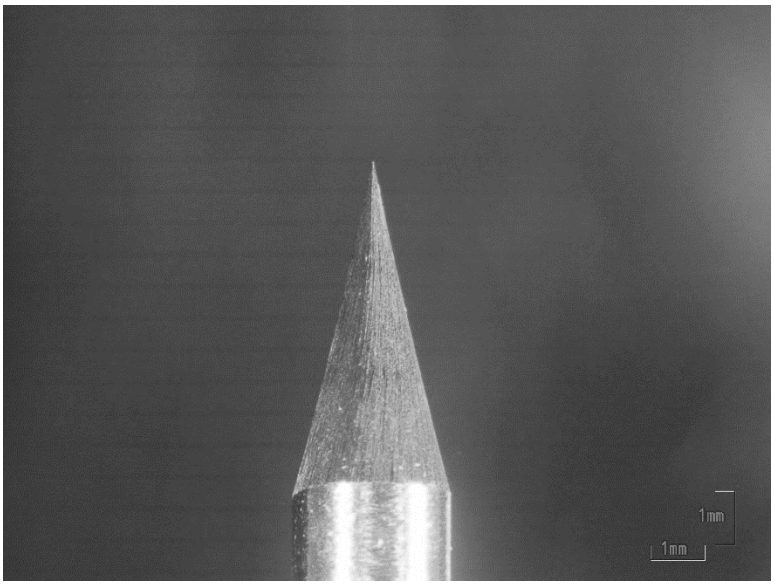

Figure A14: E3 electrode at hour 0 of 120 A life test

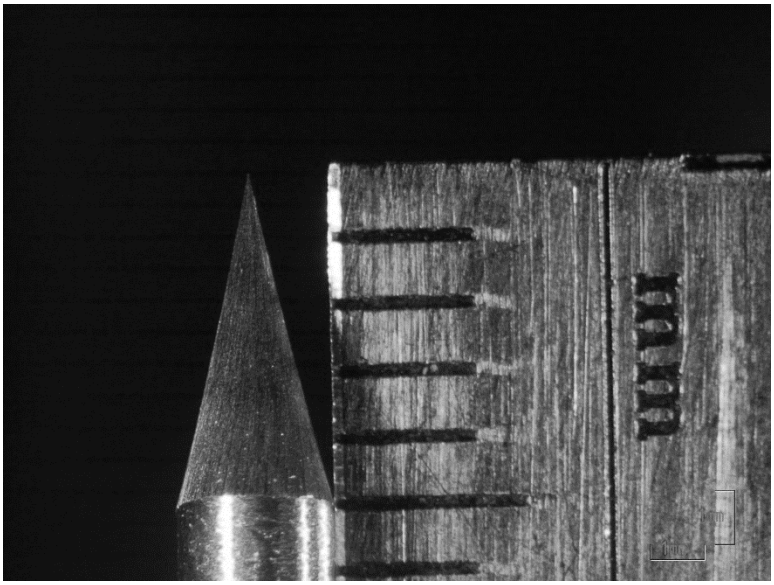

Figure A15: E3 electrode at hour 0 of 120 A life test with scale

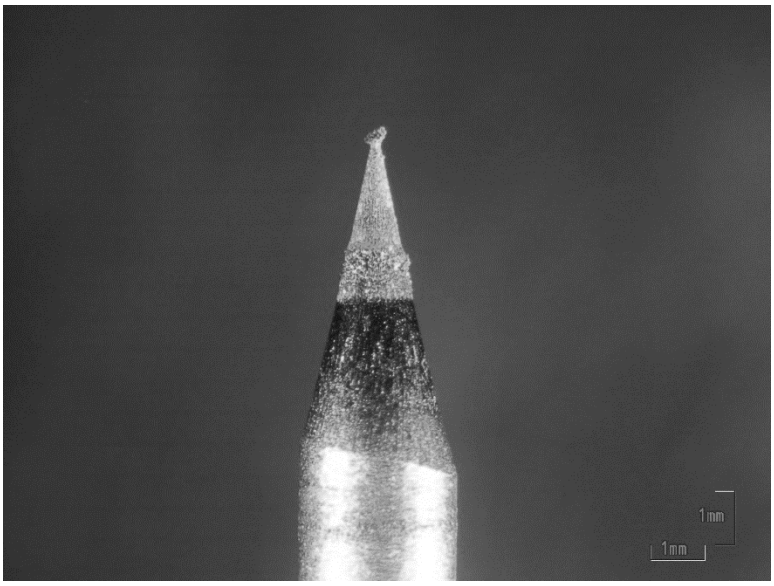

Figure A16: E3 electrode at hour 1 of 120 A life test

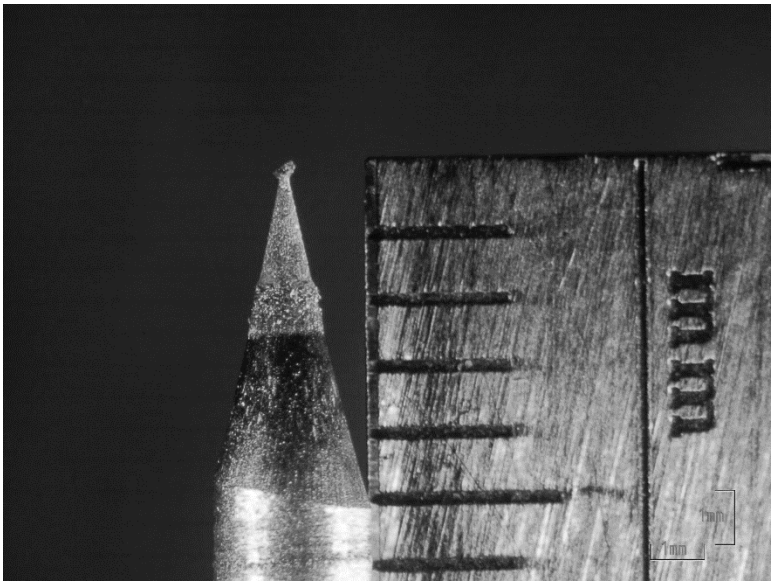

Figure A17: E3 electrode at hour 1 of 120 A life test with scale

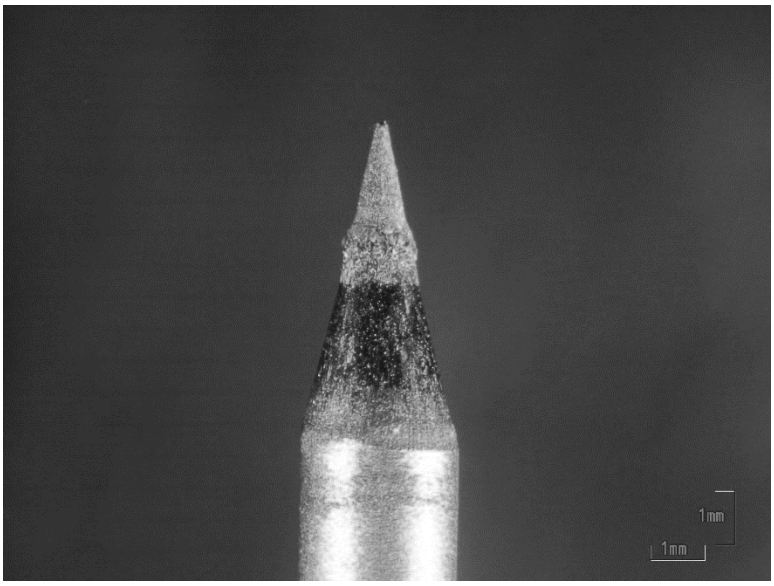

Figure A18: E3 electrode at hour 2 of 120 A life test

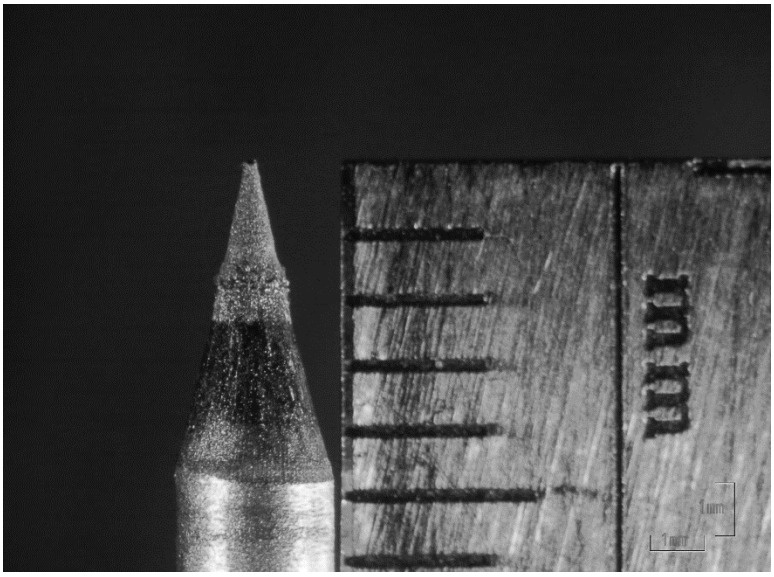

Figure A19: E3 electrode at hour 2 of 120 A life test with scale

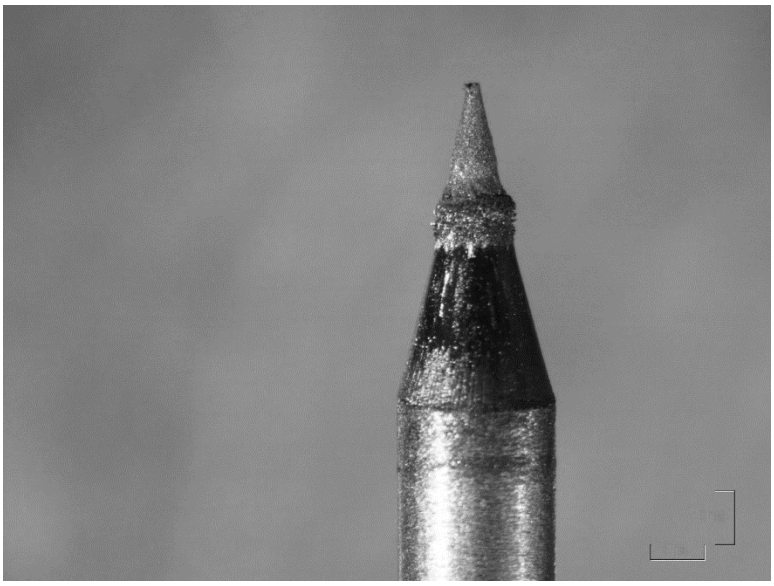

Figure A20: E3 electrode at hour 3 of 120 A life test

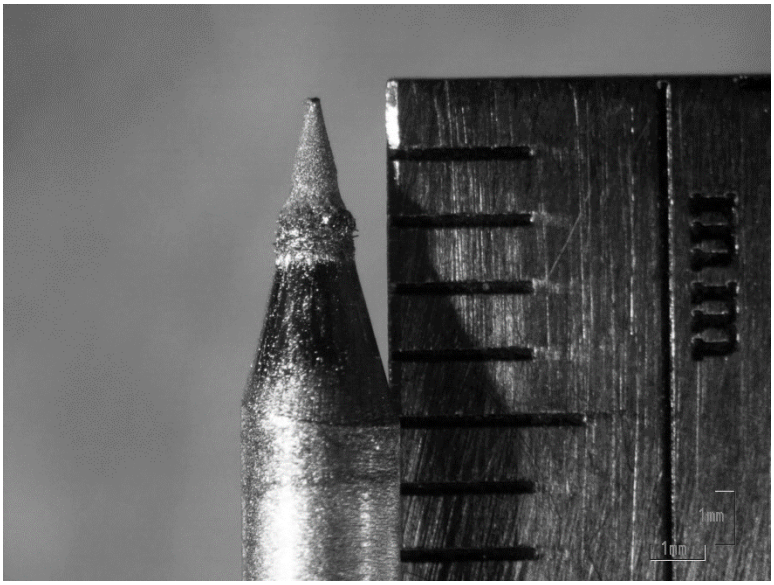

Figure A21: E3 electrode at hour 3 of 120 A life test with scale

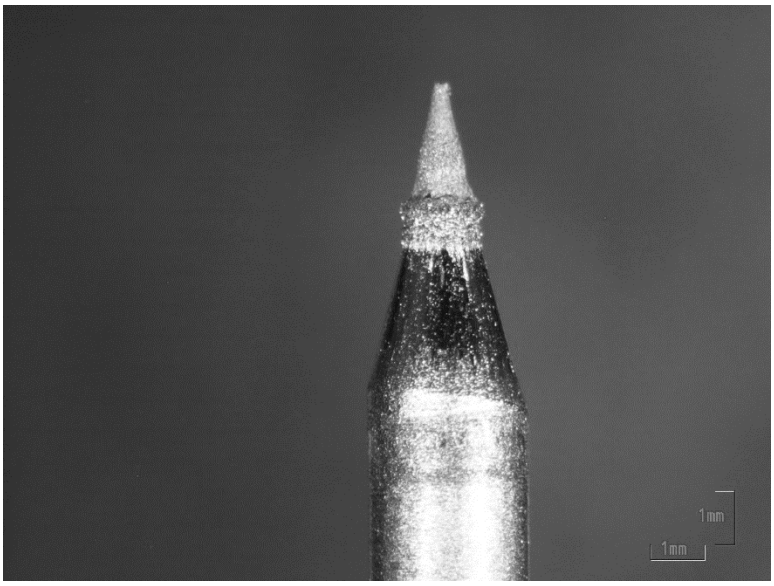

Figure A22: E3 electrode at hour 4 of 120 A life test

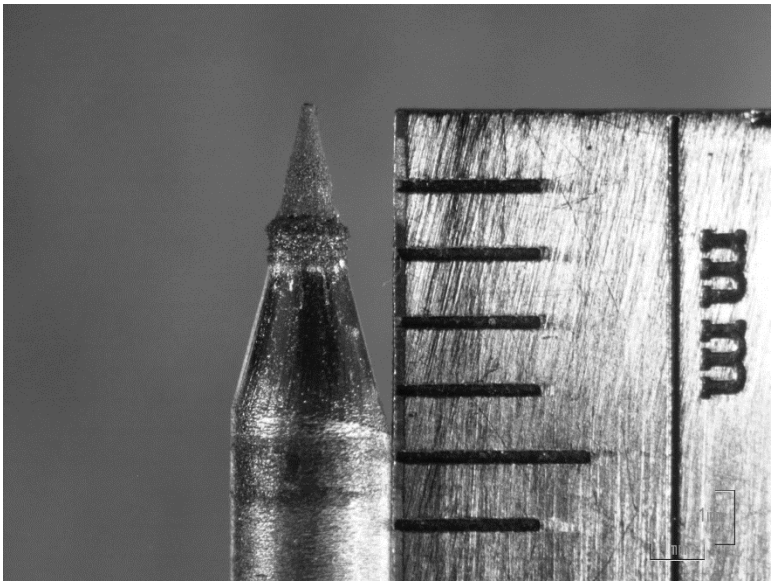

Figure A23: E3 electrode at hour 4 of 120 A life test with scale

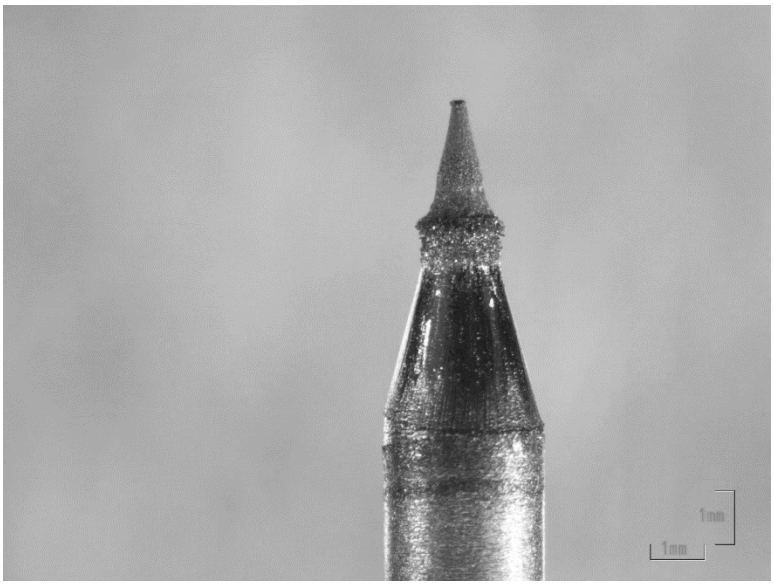

Figure A24: E3 electrode at hour 5 of 120 A life test

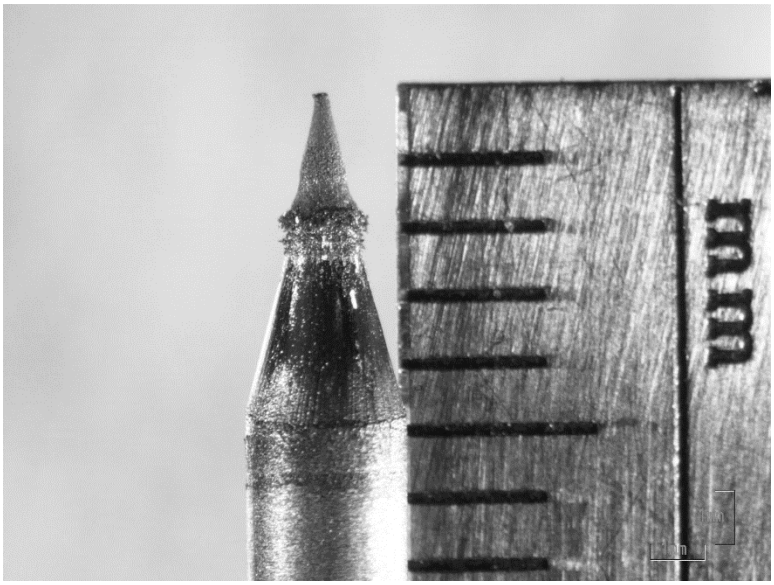

Figure A25: E3 electrode at hour 5 of 120 A life test with scale

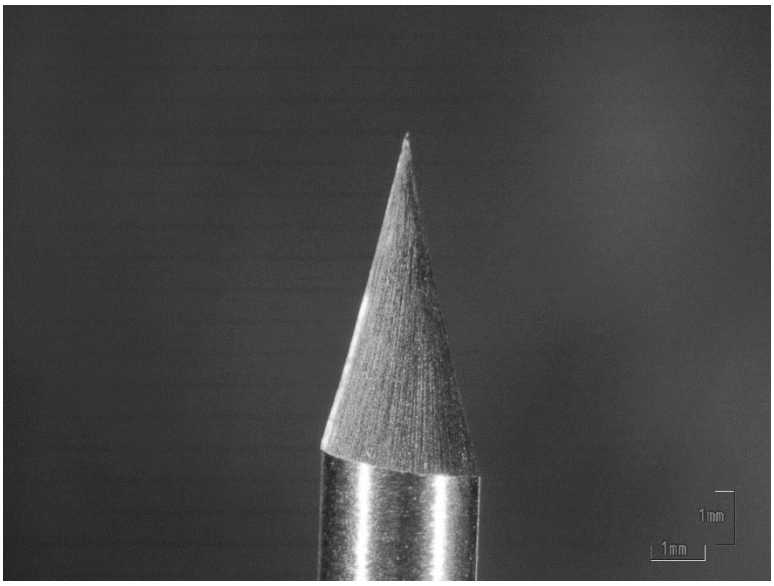

Figure A26: E3 electrode at hour 0 of 150 A life test

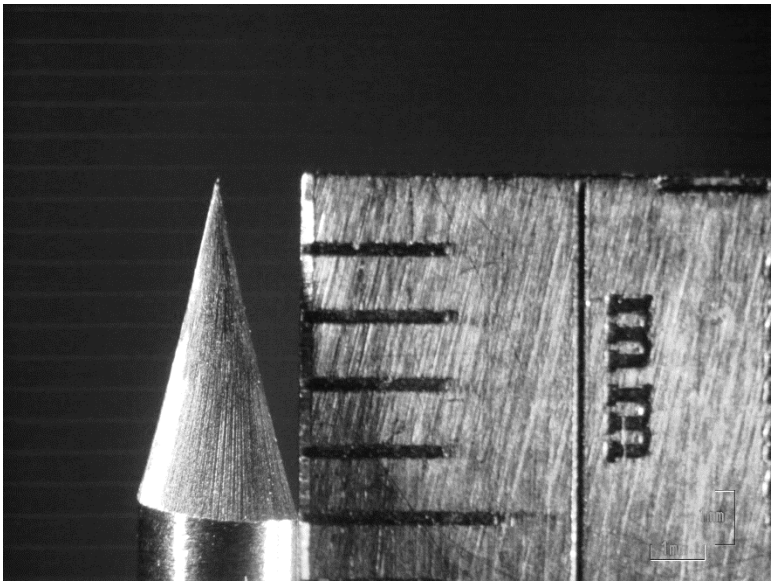

Figure A27: E3 electrode at hour 0 of 150 A life test with scale

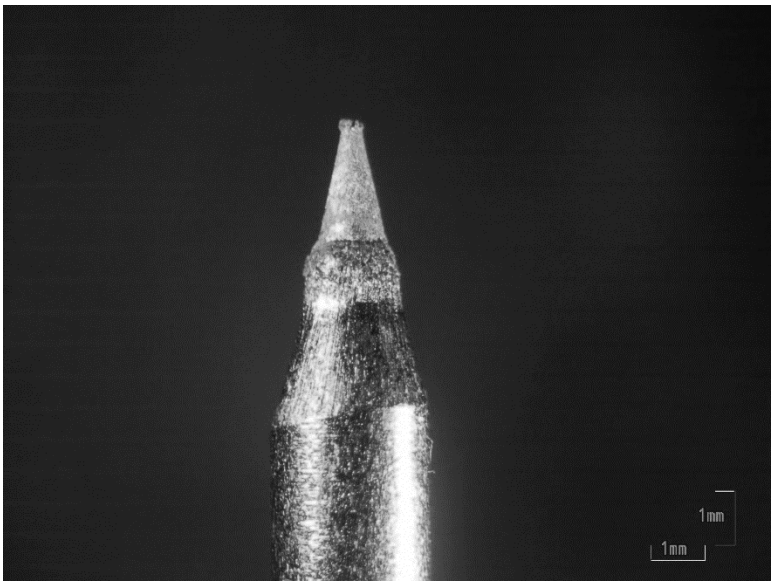

Figure A28: E3 electrode at hour 1 of 150 A life test

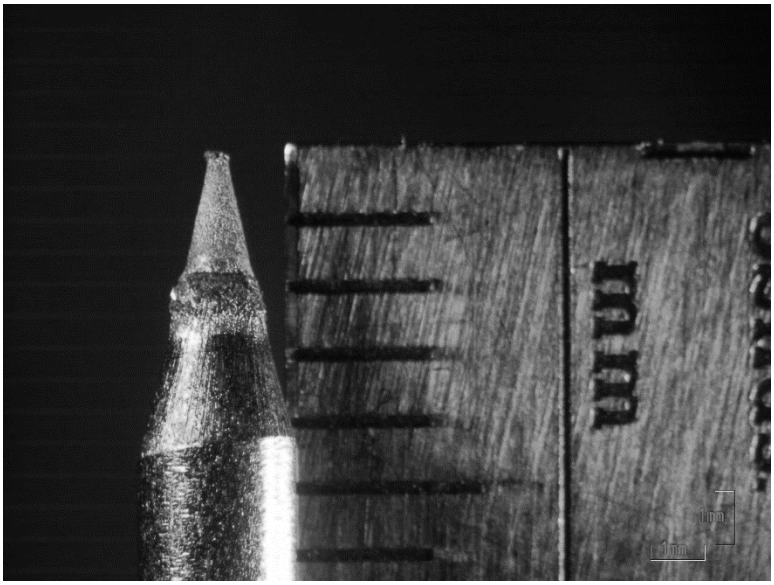

Figure A29: E3 electrode at hour 1 of 150 A life test with scale

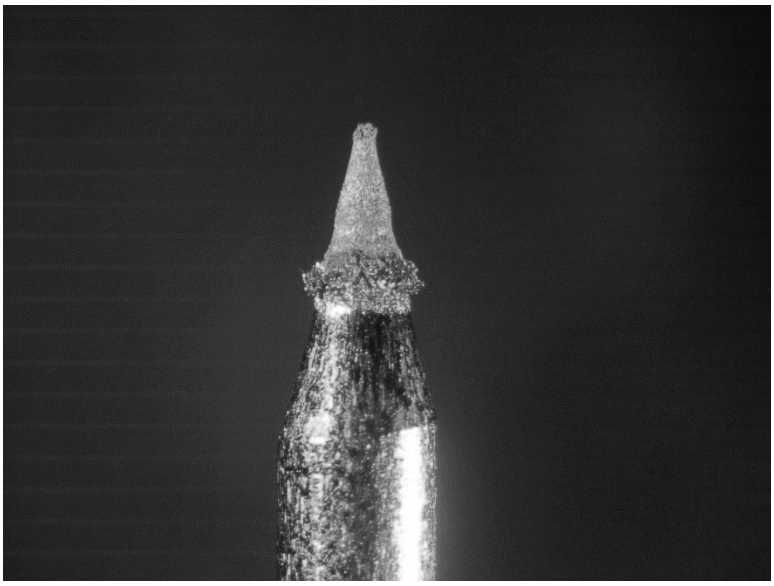

Figure A30: E3 electrode at hour 2 of 150 A life test

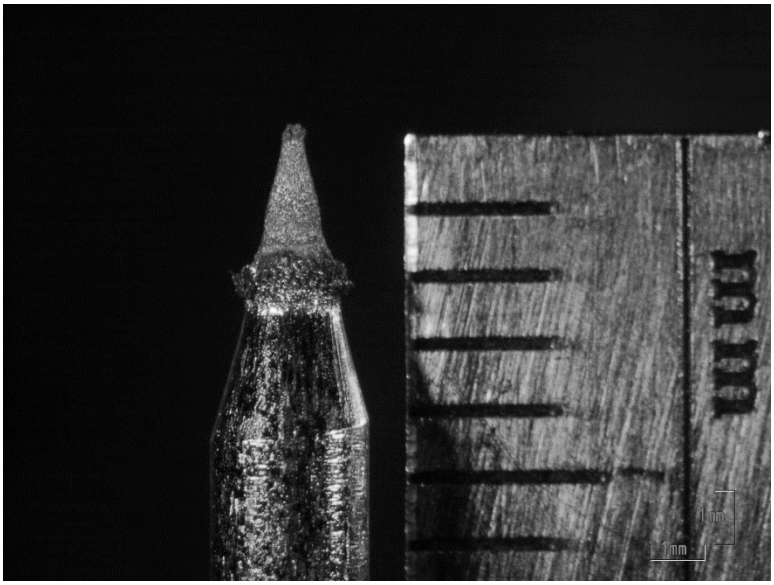

Figure A31: E3 electrode at hour 2 of 150 A life test with scale

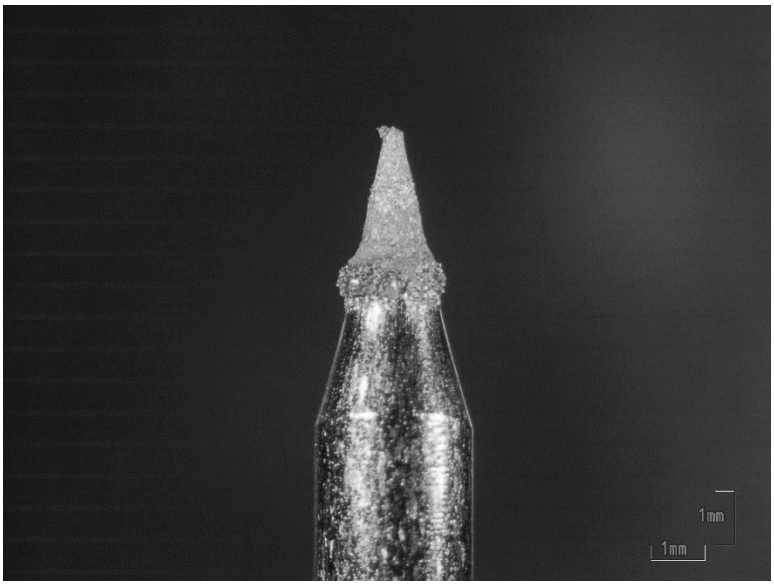

Figure A32: E3 electrode at hour 3 of 150 A life test

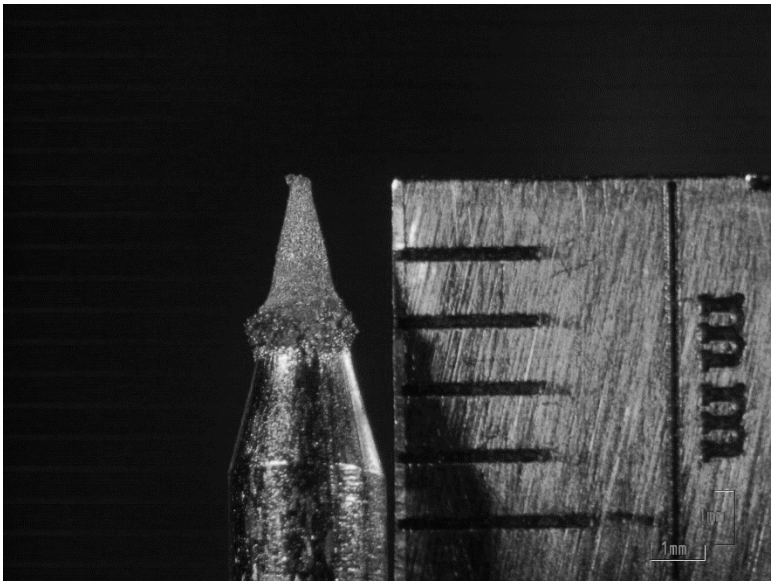

Figure A33: E3 electrode at hour 3 of 150 A life test with scale

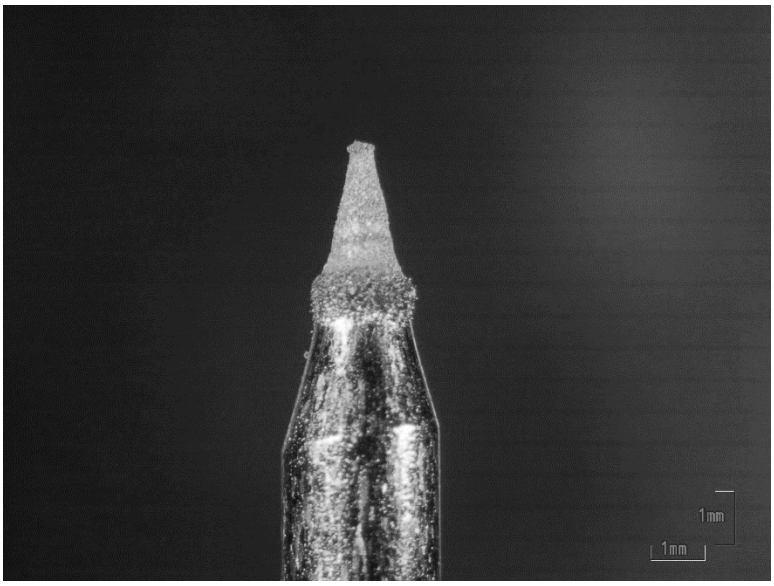

Figure A34: E3 electrode at hour 4 of 150 A life test

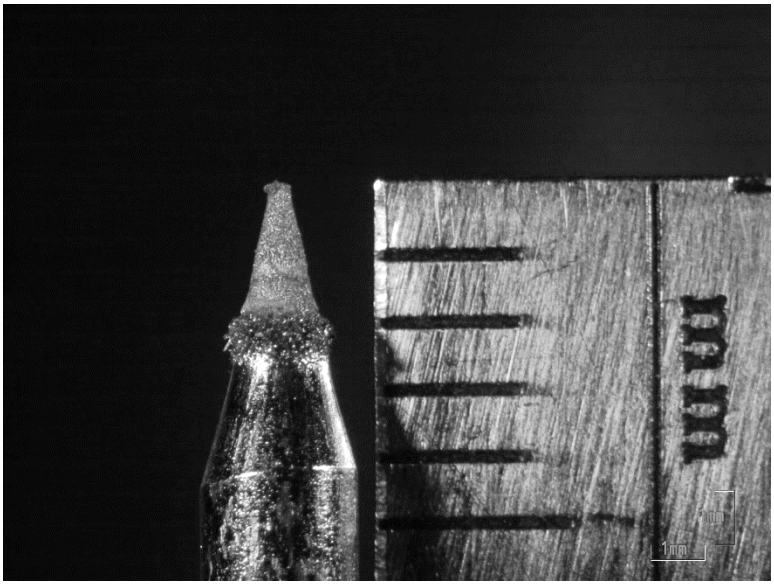

Figure A35: E3 electrode at hour 4 of 150 A life test with scale

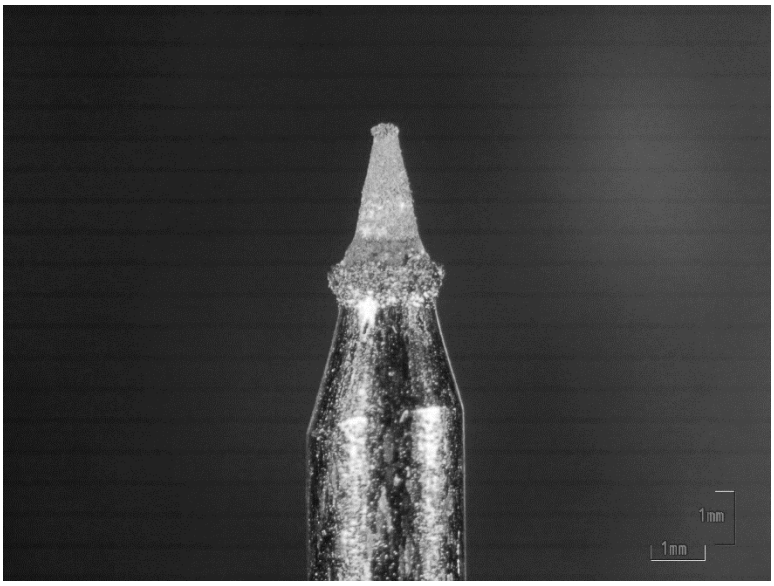

Figure A36: E3 electrode at hour 5 of 150 A life test

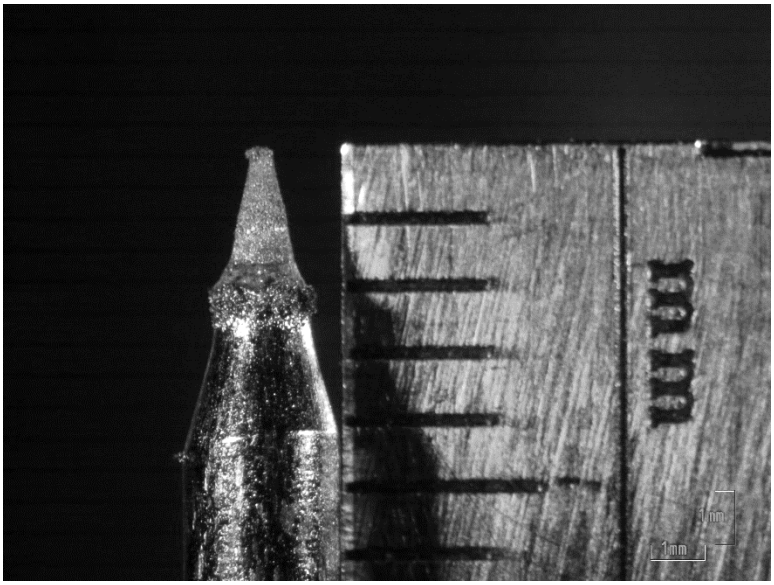

Figure A37: E3 electrode at hour 5 of 150 A life test with scale

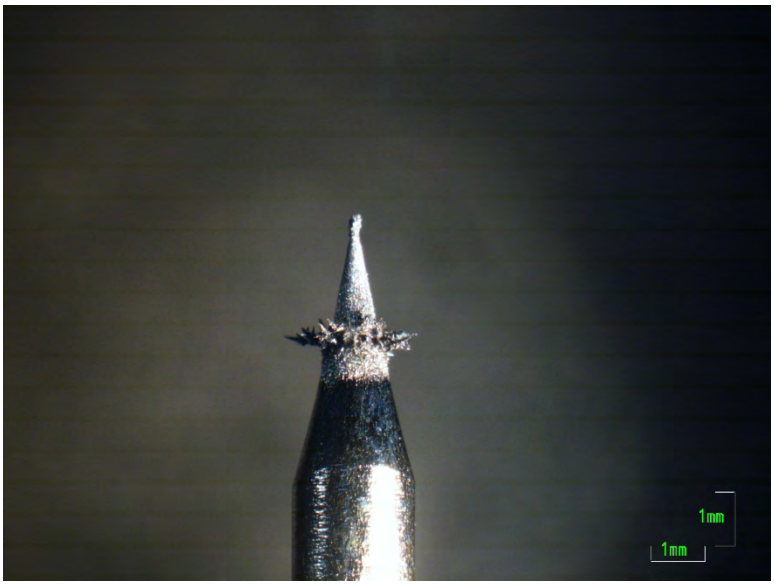

Figure A38: E3 electrode at hour 2 of 150 A life test with excessive gas flow rate (30cfh) causing increased flaring

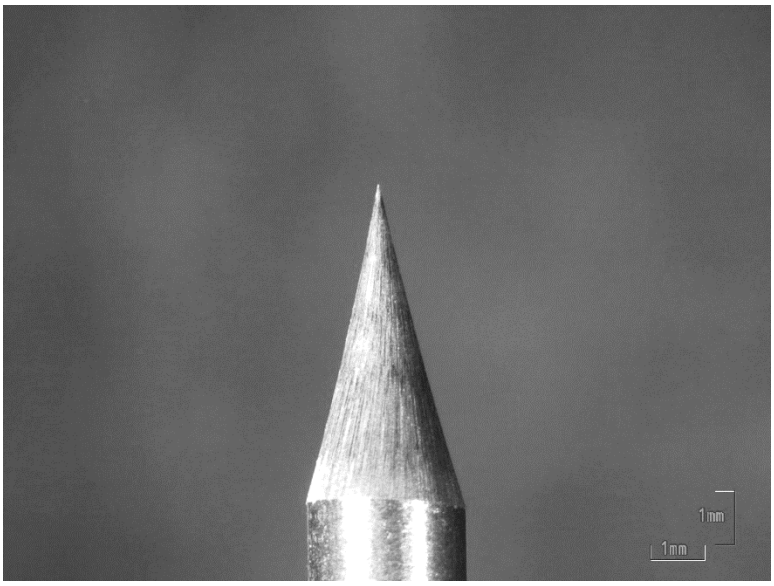

Figure A39: ThO_2(2%)-W electrode at hour 0 of 80 A life test

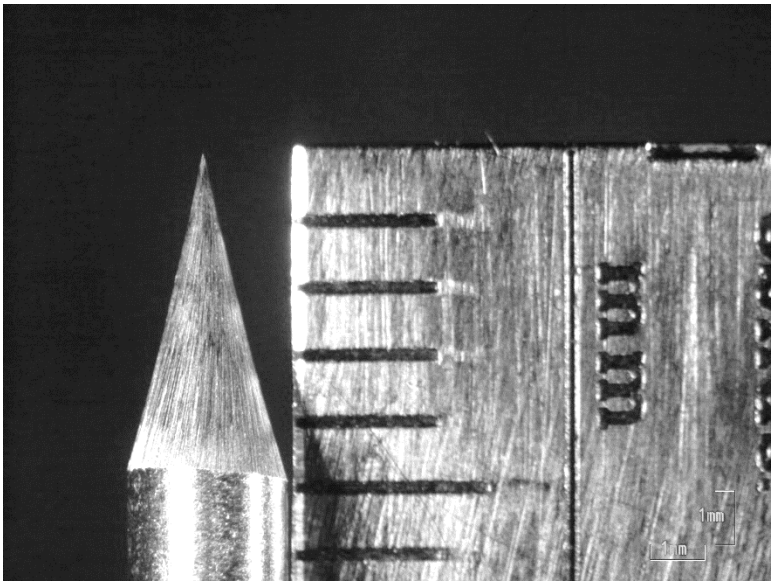

Figure A40: ThO_2(2%)-W electrode at hour 0 of 80 A life test with scale

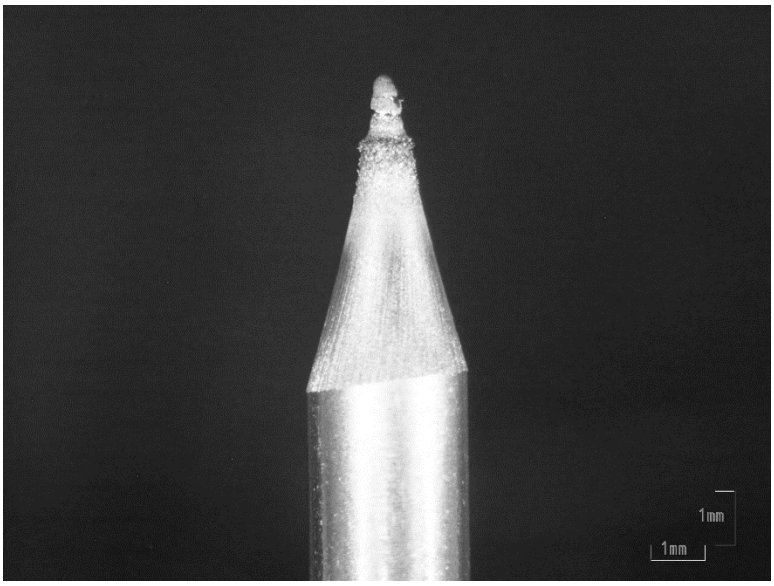

Figure A41: ThO_2(2%)-W electrode at hour 1 of 80 A life test

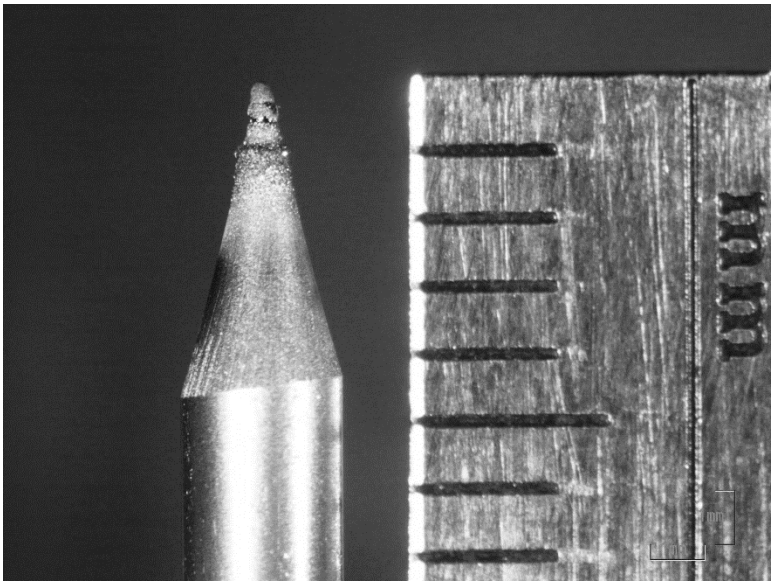

Figure A42: ThO_2(2%)-W electrode at hour 1 of 80 A life test with scale

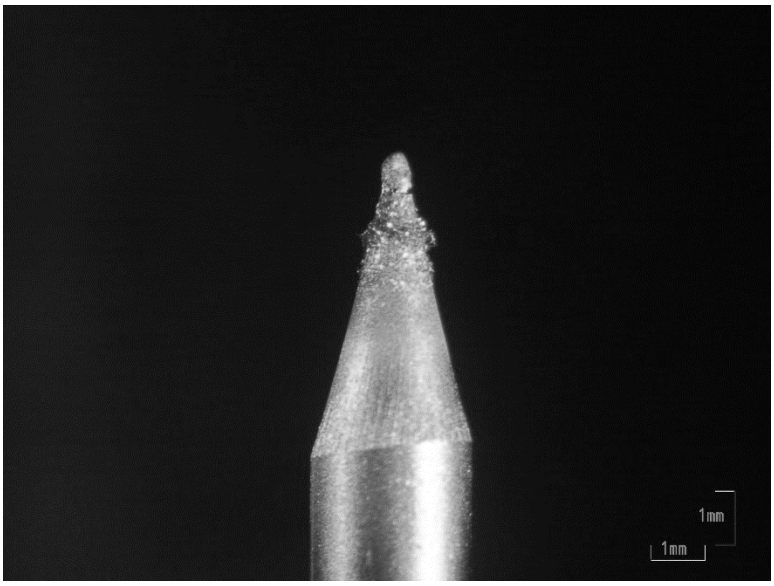

Figure A43: ThO_2(2%)-W electrode at hour 2 of 80 A life test

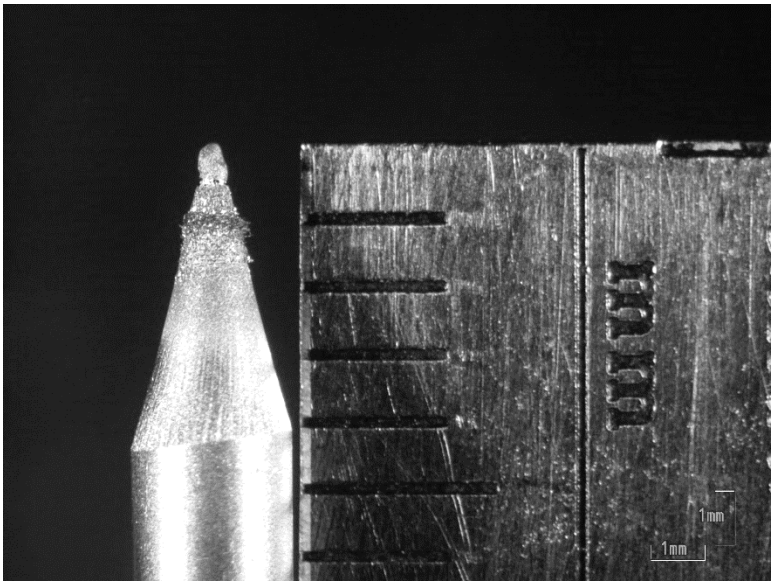

Figure A44: ThO_2(2%)-W electrode at hour 2 of 80 A life test with scale

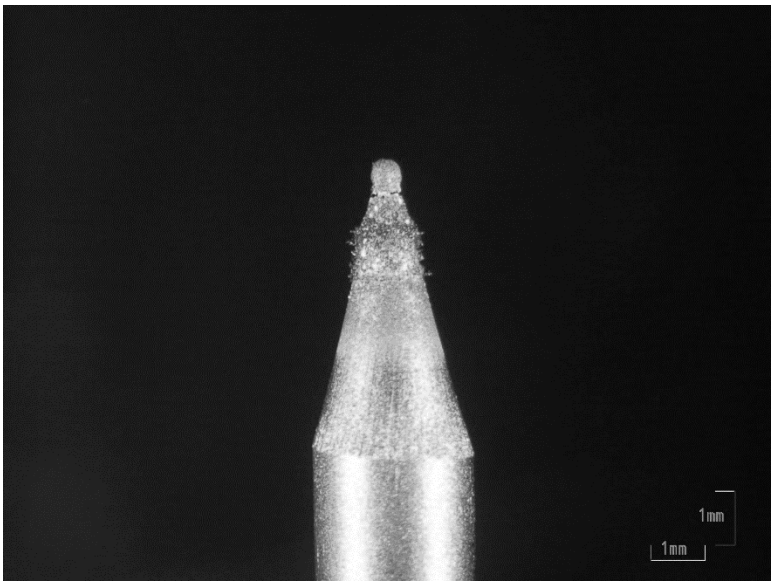

Figure A45: ThO_2(2%)-W electrode at hour 3 of 80 A life test

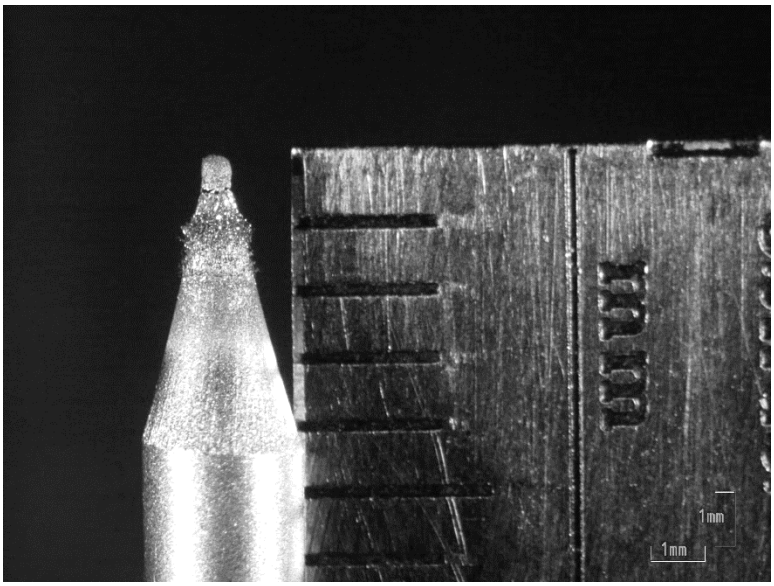

Figure A46: ThO_2(2%)-W electrode at hour 3 of 80 A life test with scale

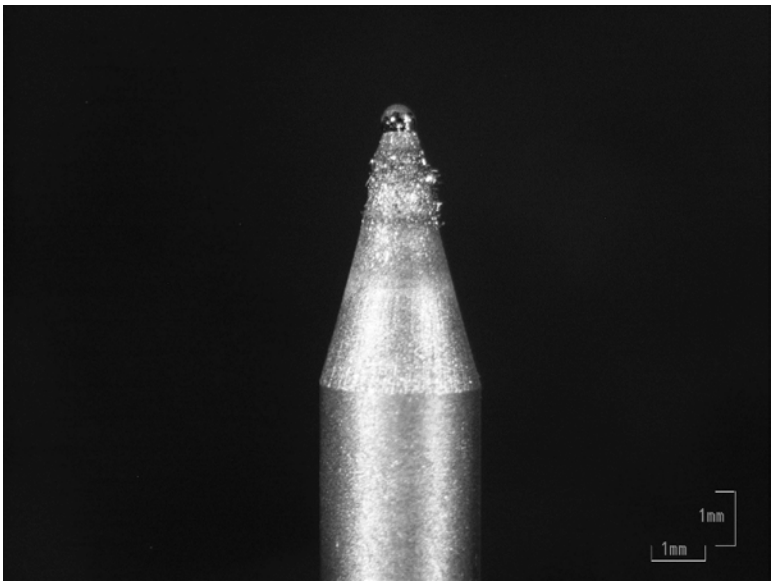

Figure A47: ThO_2(2%)-W electrode at hour 4 of 80 A life te

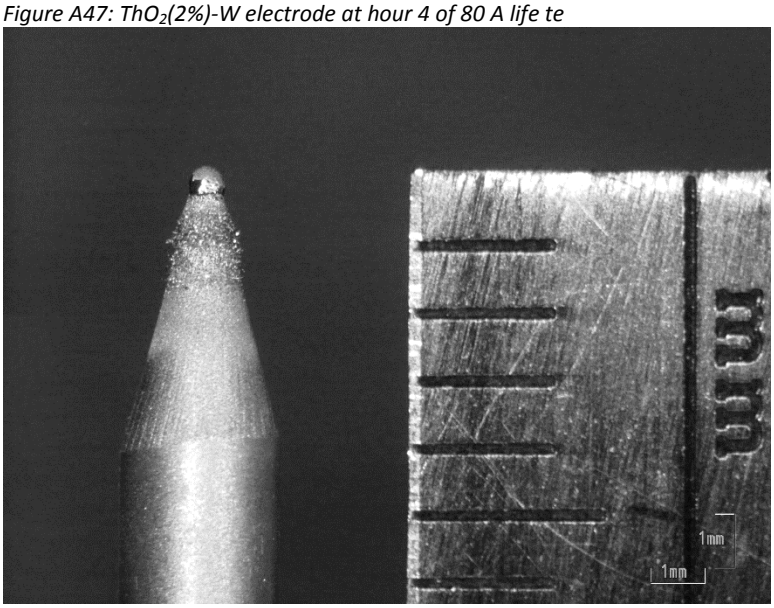

Figure A48: ThO_2(2%)-W electrode at hour 4 of 80 A life test with scale

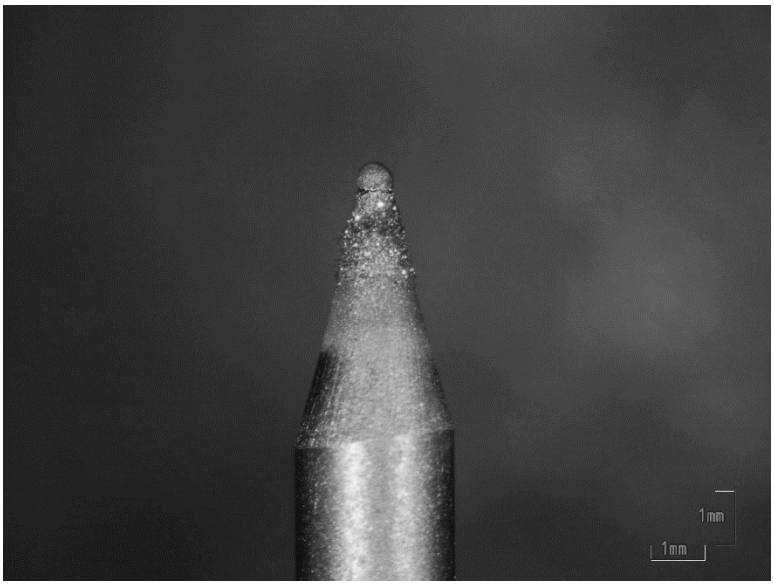

Figure A49: ThO_2(2%)-W electrode at hour 5 of 80 A life test

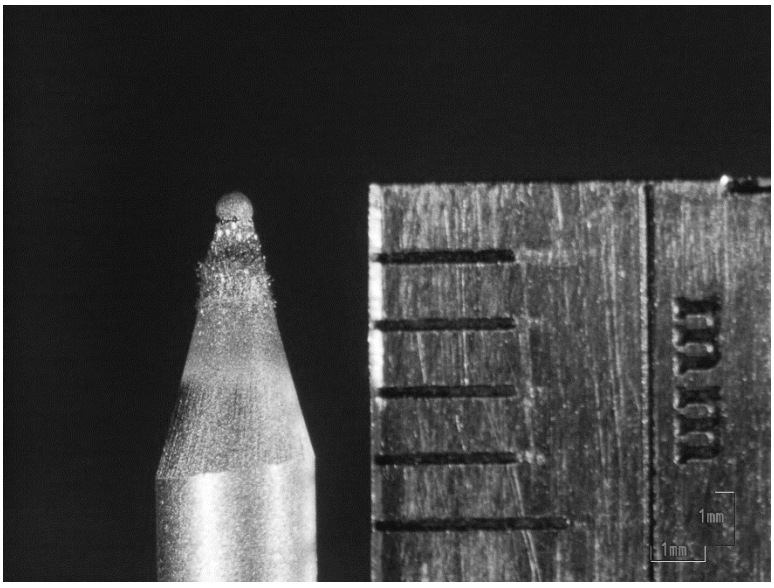

Figure A50: ThO_2(2%)-W electrode at hour 5 of 80 A life test with scale

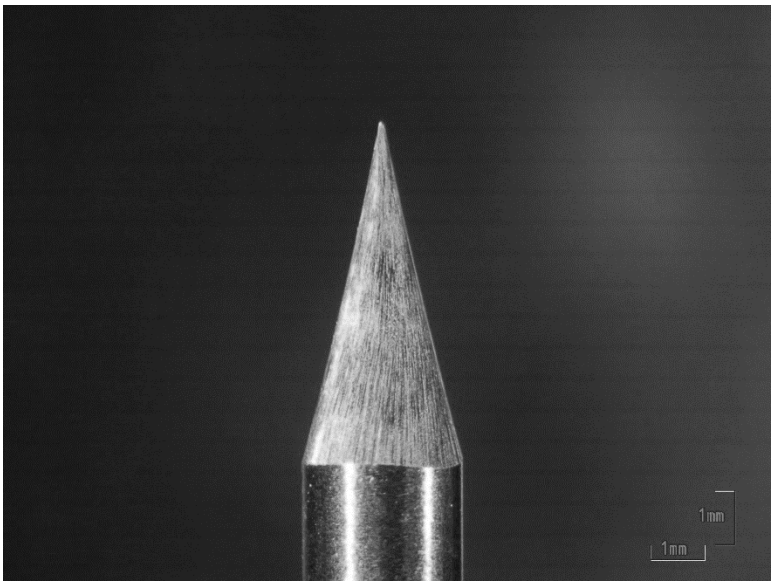

Figure A51: ThO_2(2%)-W electrode at hour 0 of 120 A life test

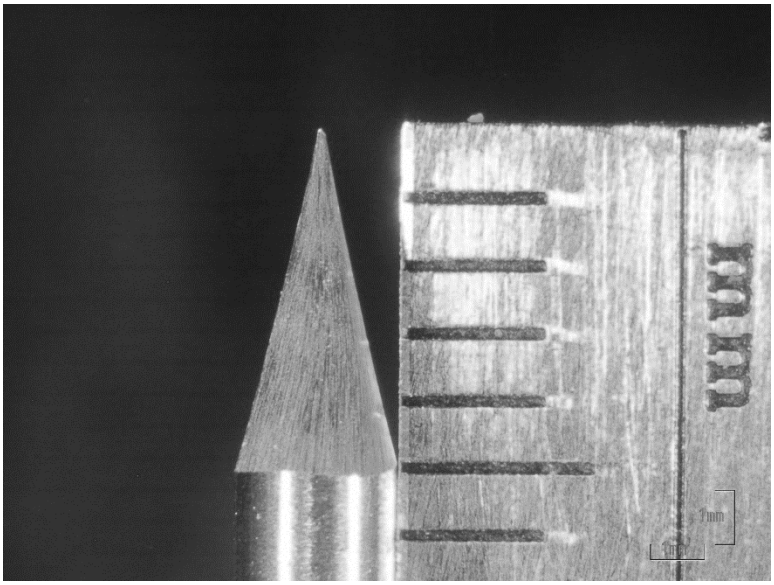

Figure A52: ThO_2(2%)-W electrode at hour 0 of 120 A life test with scale

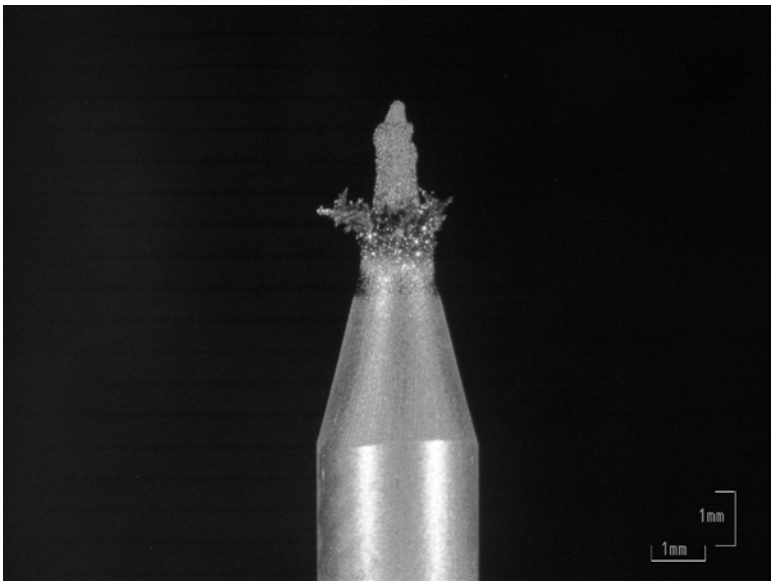

Figure A53: ThO_2(2%)-W electrode at hour 1 of 120 A life test

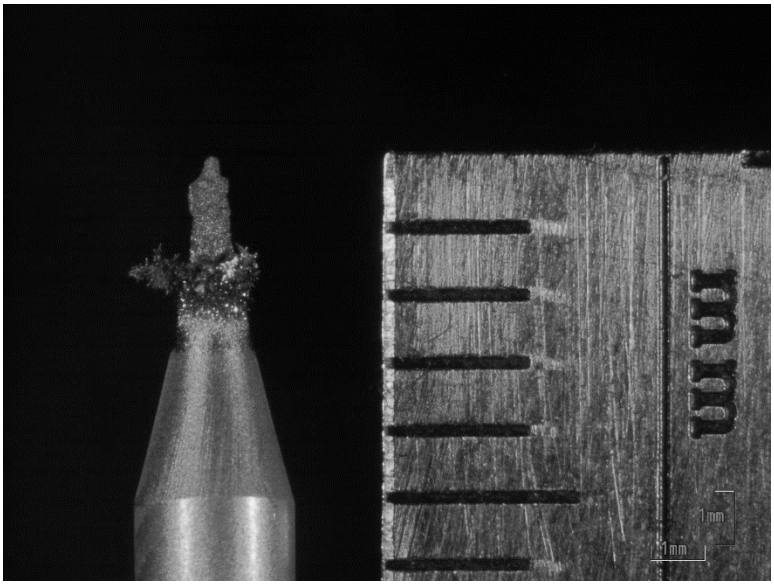

Figure A54: ThO_2(2%)-W electrode at hour 1 of 120 A life test with scale

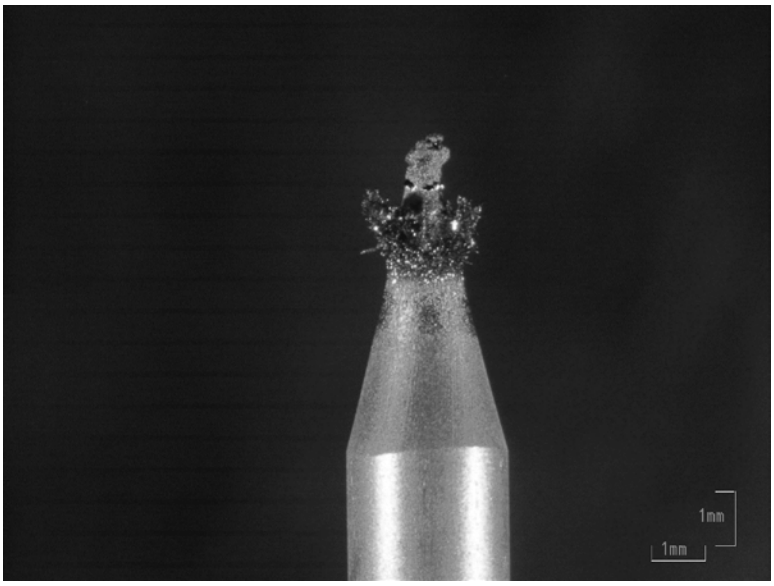

Figure A55: ThO_2(2%)-W electrode at hour 2 of 120 A life test

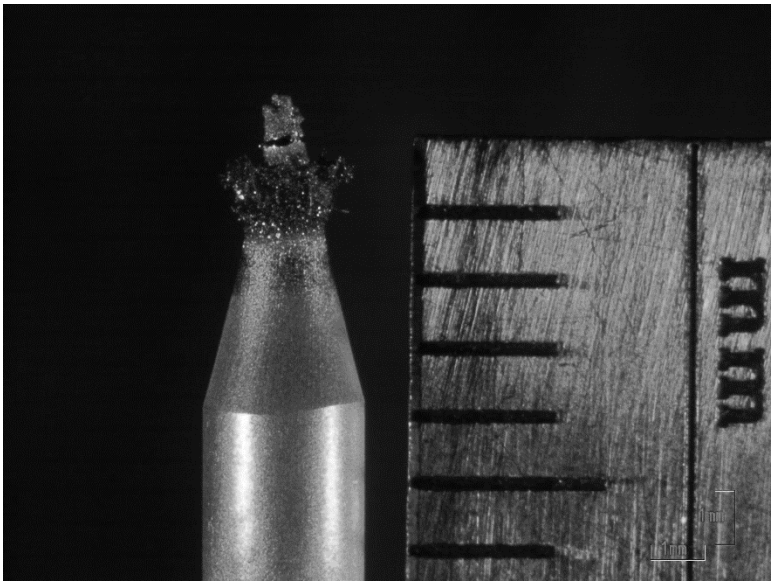

Figure A56: ThO_2(2%)-W electrode at hour 2 of 120 A life test with scale

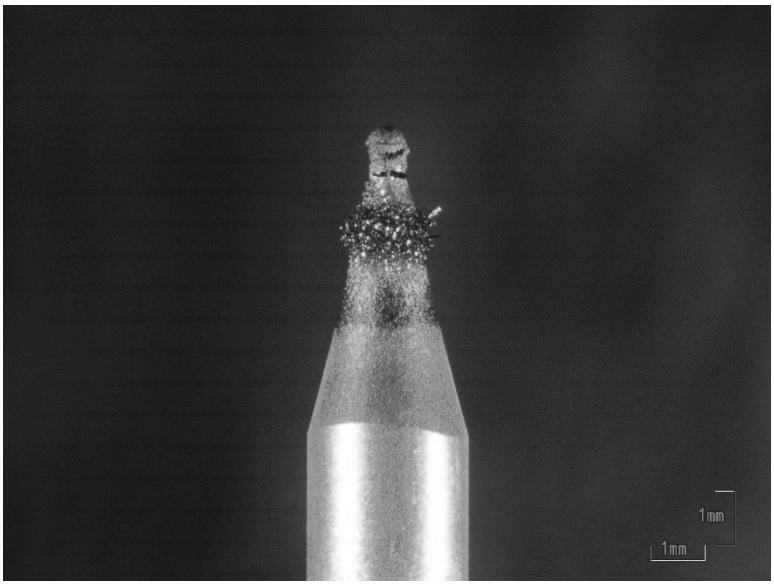

Figure A57: ThO_2(2%)-W electrode at hour 3 of 120 A life test

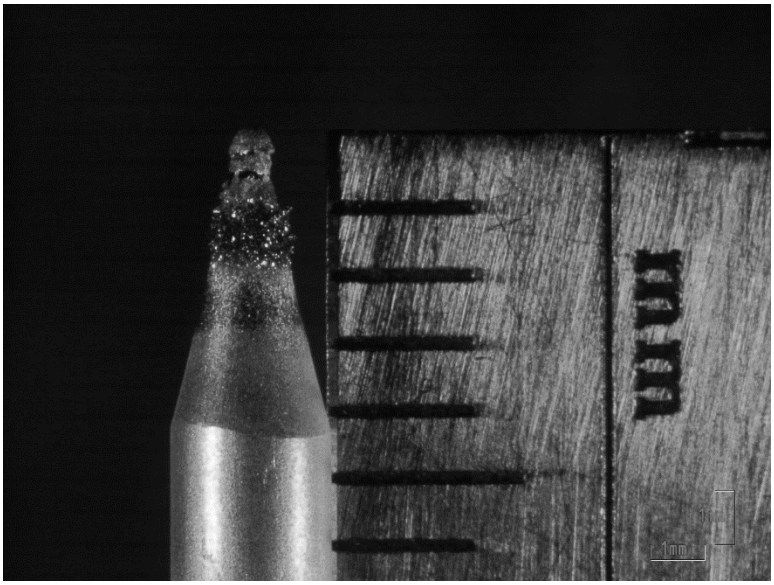

Figure A58: ThO_2(2%)-W electrode at hour 3 of 120 A life test with scale

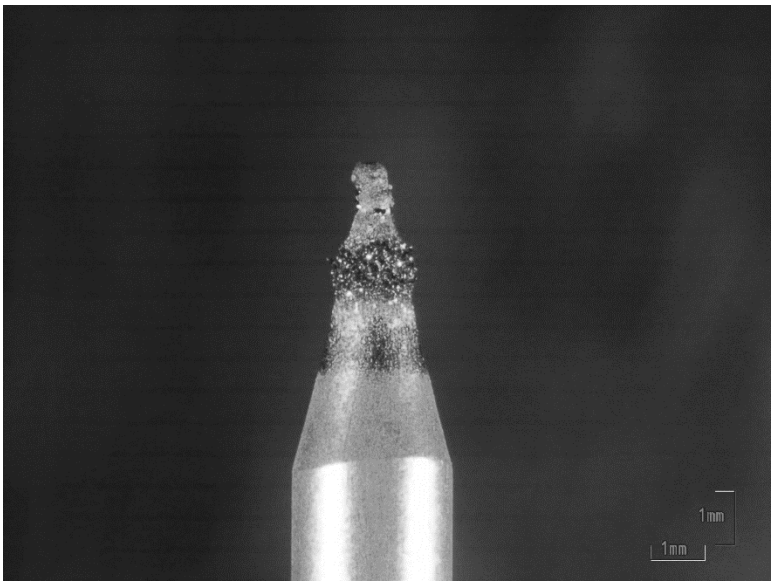

Figure A59: ThO_2(2%)-W electrode at hour 4 of 120 A life test

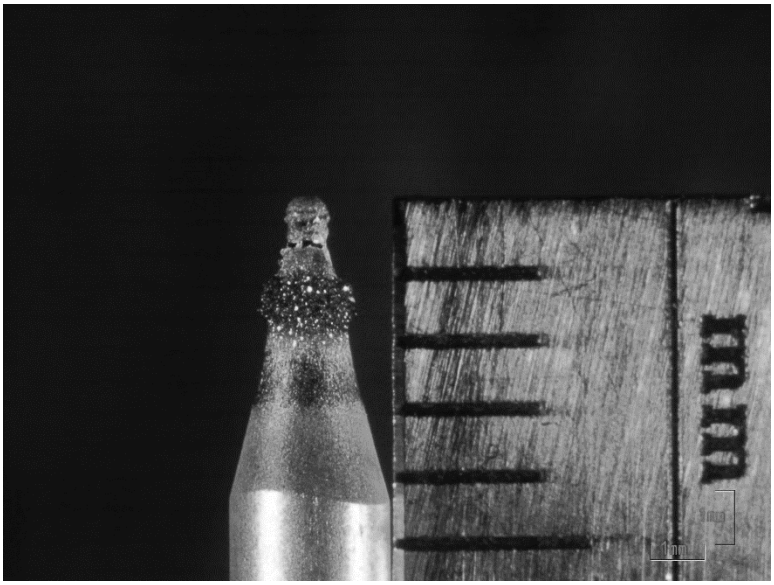

Figure A60: ThO_2(2%)-W electrode at hour 4 of 120 A life test with scale

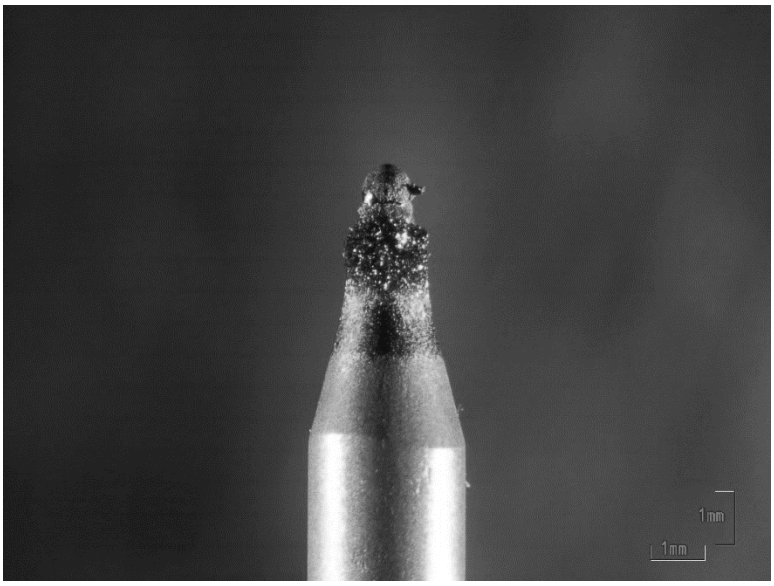

Figure A61: ThO_2(2%)-W electrode at hour 5 of 120 A life test

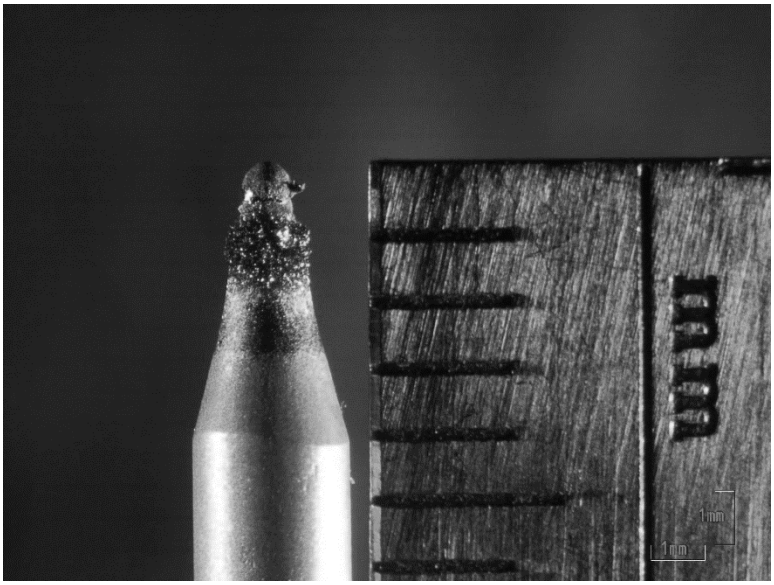

Figure A62: ThO_2(2%)-W electrode at hour 5 of 120 A life test with scale

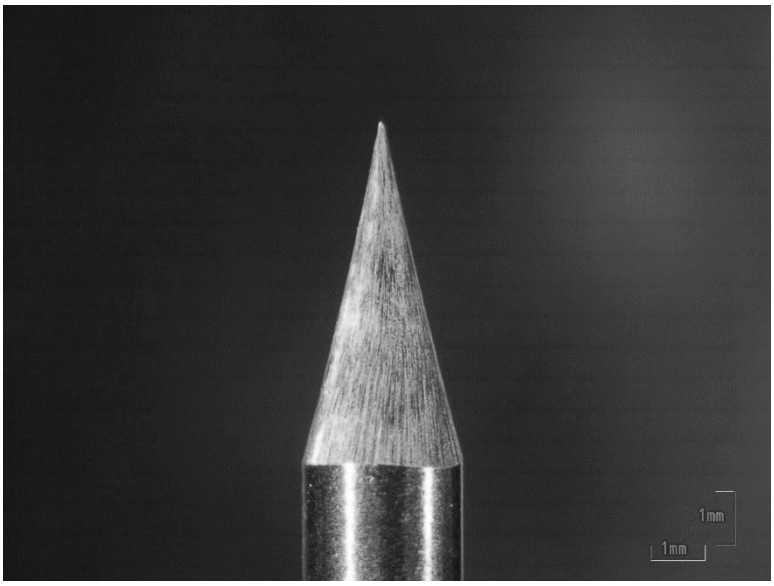

Figure A63: ThO_2(2%)-W electrode at hour 0 of 150 A life test

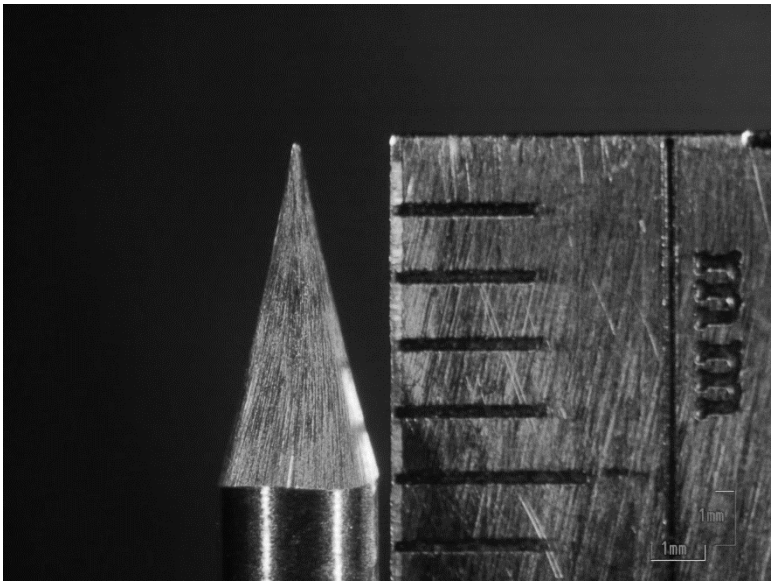

Figure A64: ThO_2(2%)-W electrode at hour 0 of 150 A life test with scale

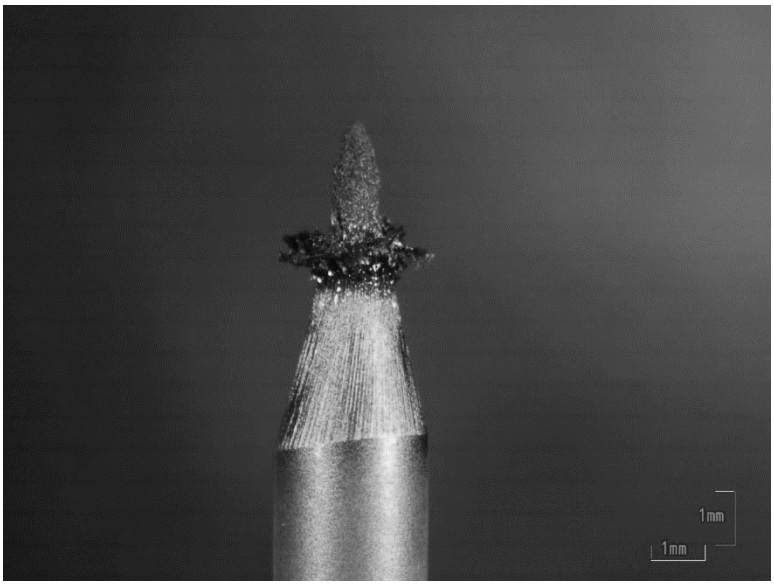

Figure A65: ThO_2(2%)-W electrode at hour 1 of 150 A life test

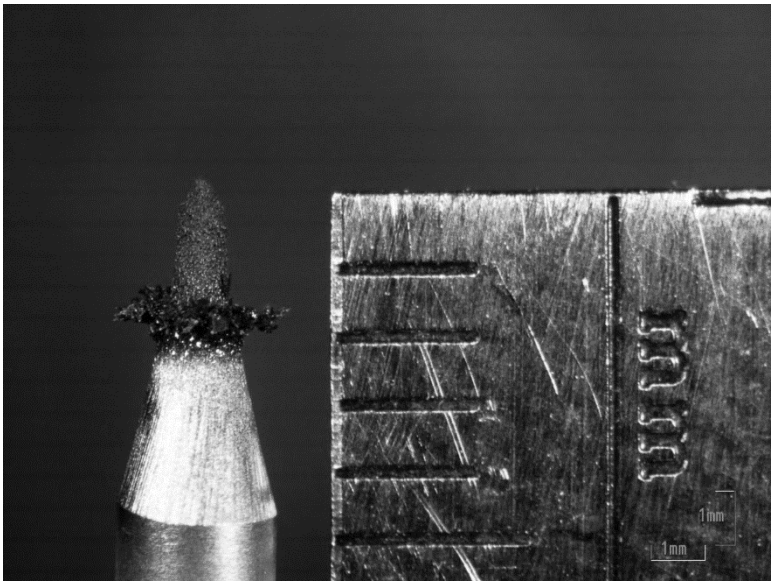

Figure A66: ThO_2(2%)-W electrode at hour 1 of 150 A life test with scale

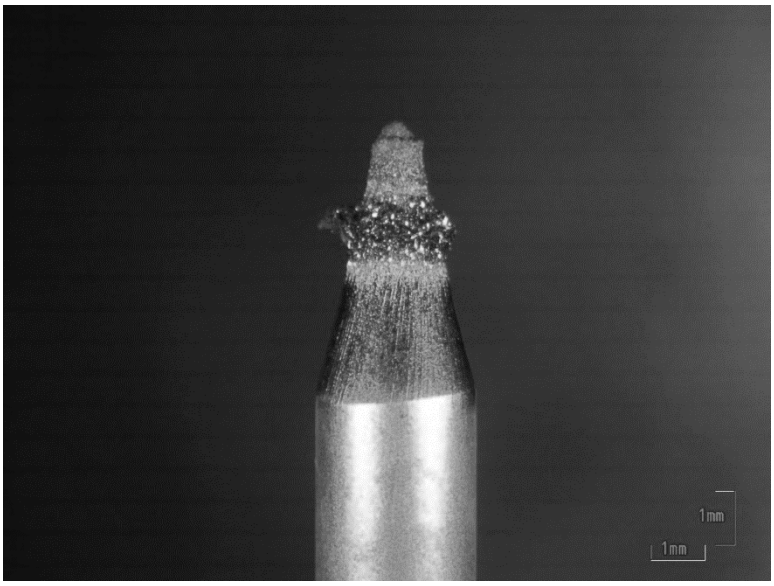

Figure A67: ThO_2(2%)-W electrode at hour 2 of 150 A life test

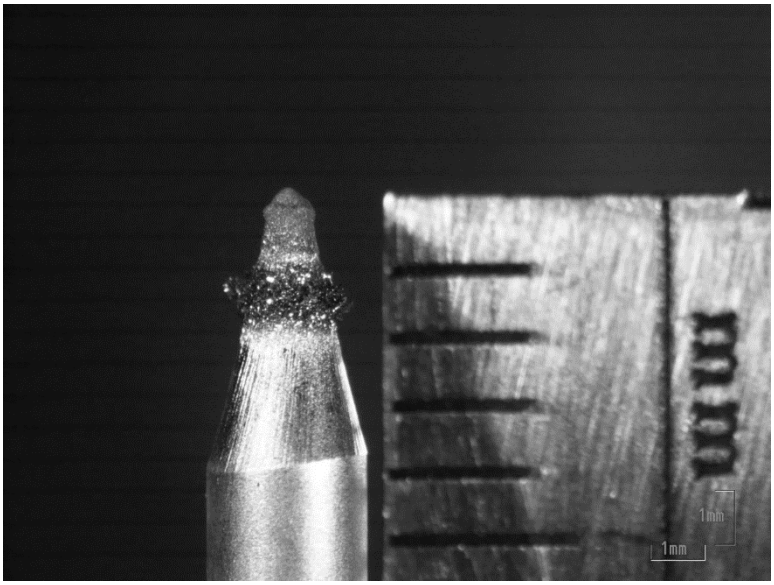

Figure A68: ThO_2(2%)-W electrode at hour 2 of 150 A life test with scale

Figure A69: ThO_2(2%)-W electrode at hour 3 of 150 A life test

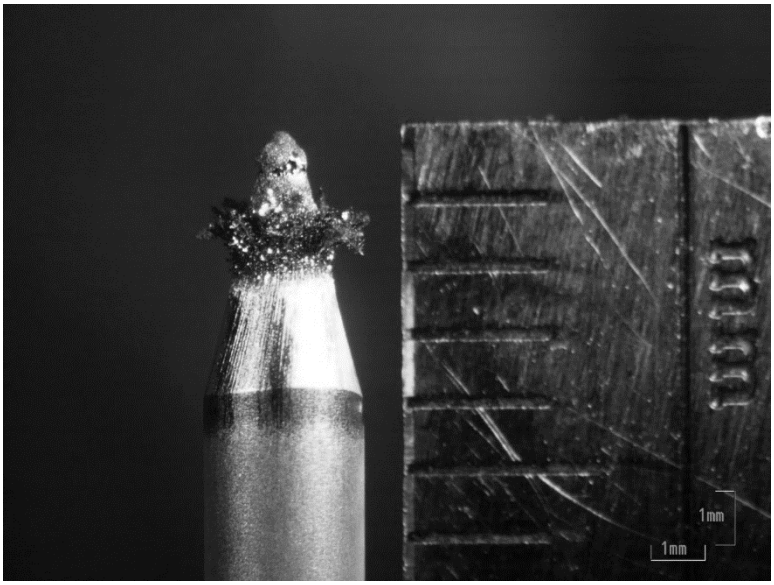

Figure A70: ThO_2(2%)-W electrode at hour 3 of 150 A life test with scale

Figure A71: ThO_2(2%)-W electrode at hour 4 of 150 A life test

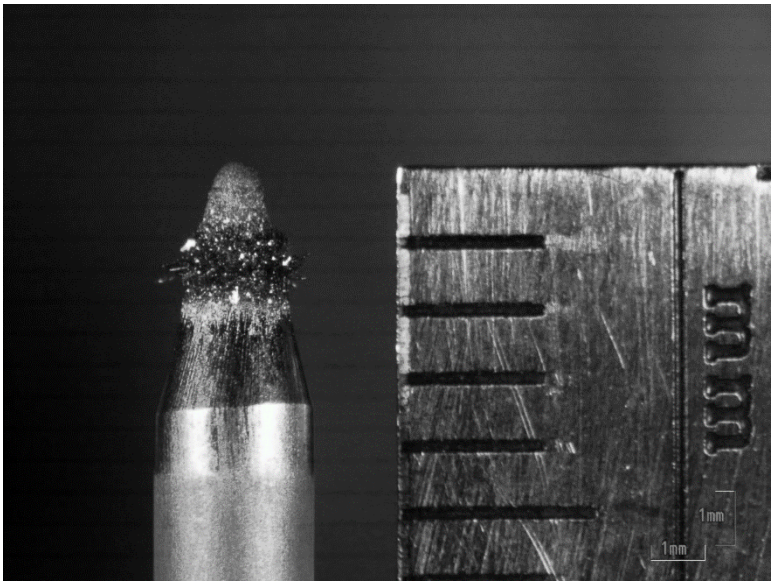

Figure A72: ThO_2(2%)-W electrode at hour 4 of 150 A life test with scale

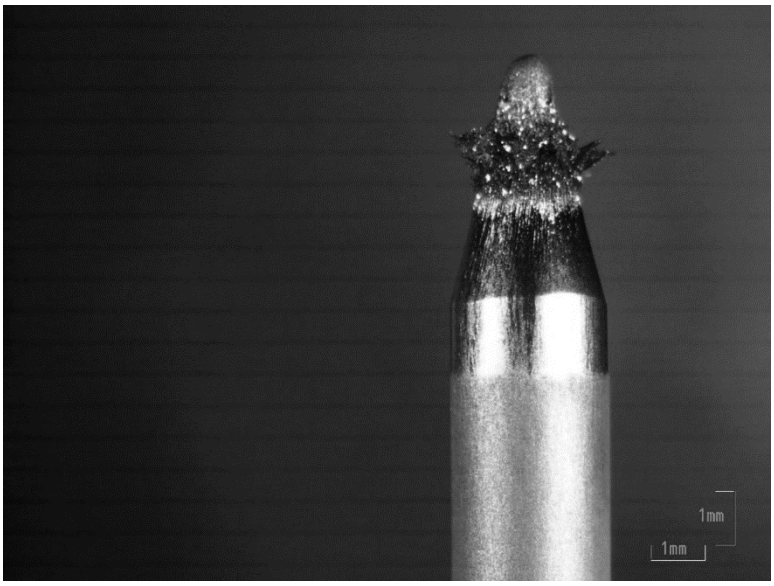

Figure 73: ThO_2(2%)-W electrode at hour 5 of 150 A life test

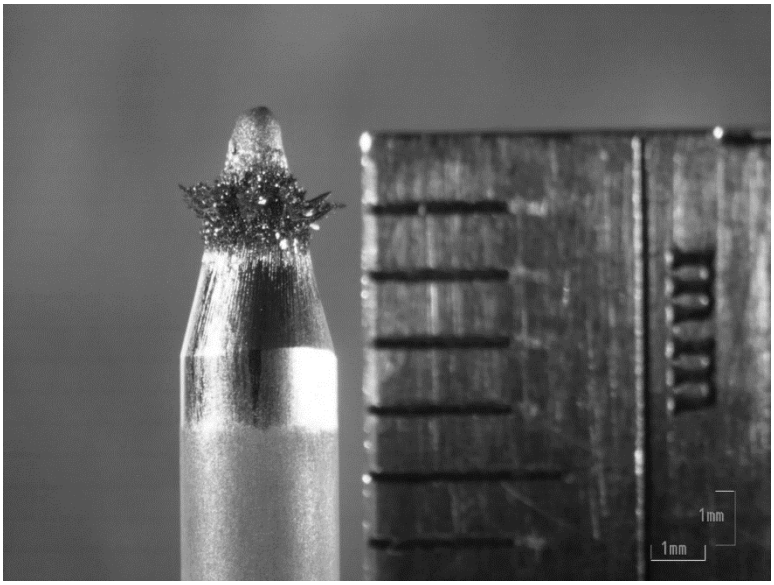

Figure 74: ThO_2(2%)-W electrode at hour 5 of 150 A life test with scale