Section 10.0: Electrode Erosion

The primary reason for failure of plasma torches usually involves the inability of the electrodes to operate as they were designed, or operation under adverse conditions. This includes carbon deposition in the anode constrictor, electrode erosion and electrode fusion where the electrodes become electrically connected through the buildup of electrode particles on the anode. This section discusses the effects on electrode wear of operating under different conditions. For each test, the electrode gap, current and feedstock flowrate were kept constant. Tests were conducted with methane, ethylene and propylene. Each anode and cathode was weighed before and after each test to quantify the amount of electrode loss. The time each test took to complete and the number of starts needed to achieve steady operation were also recorded.

10.1: Material Review and Plasma Torch Electrode Background

The original goal of the latest Virginia Tech Plasma Torch design was to attain the ability to operate on pure argon for a period of at least twenty hours without failure (Stouffer, 1989). Hydrocarbon feedstocks significantly reduce this operating time by quickly eroding electrodes. This effect was also discovered by Hruby et al. (1997) with his methane arcjet experiments. He reported that electrode erosion was much more severe when his plasma torch operated on methane as compared to argon. Generally, hydrocarbon feedstocks require much more voltage to maintain the arc than pure argon. High voltages have been associated with arc instability and high electrode erosion rates.

The Virginia Tech Plasma Torch uses electrodes made from 2% thoriated tungsten. To produce thoriated tungsten, pure tungsten is contaminated with thorium, an electropositive element, using a special heat treatment. This process enhances the electron emission ability of pure tungsten (Smithells, 1953). Tungsten and its alloys are often used in high temperature environments, since it provides an exceptionally high melting point (≈3800K) and good electrical conductivity at high temperatures. This is due in part to its body-centered-cubic crystalline structure. Its ability to withstand high temperatures and still maintain desirable chemical, mechanical and electrical properties

make tungsten desirable for many different applications, including various types of electrodes. A study of arc discharges (Hardy, 1985) showed that among six different materials tested, thoriated tungsten and pure tungsten had the lowest anode mass loss rates. Even though thoriated tungsten had a slightly higher mass loss rate than pure tungsten, the electrodes were constructed from it because of its superior machineability. Figure 10.1 is a graph of tungsten thermal conductivity versus temperature. The Virginia Tech Plasma Torch usually operated with a body temperature between 550-800K (depending on the feedstock and current level) with the anode bulk temperature being somewhat higher. As the thermal conductivity of an electrode decreases, it has a tendency to form higher thermal gradients because heat can not be transferred away from the point of arc attachment as quickly.

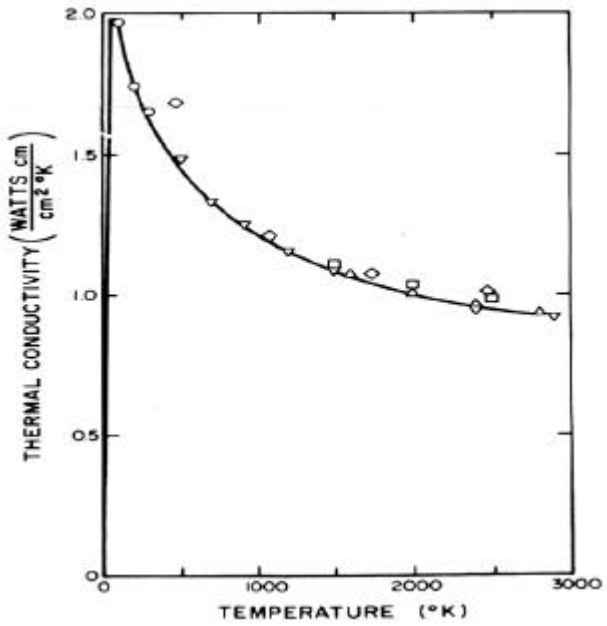


Figure 10.1: Thermal Conductivity of Tungsten vs. Temperature (Yih, 1979)

High thermal conductivity and heat tolerance would allow the electrode material, in this case, tungsten, to function with minimal loss in mass. As an electrode material, tungsten is an ideal choice for use in a plasma torch.

In addition to material considerations, the arc mode is also important. Recall from Section 3 that a plasma torch can operate in either high or low-voltage modes. Of the two modes, the low-voltage mode is most damaging to the anode. This is because the

heat flux to the anode is greater in the low-voltage case due to a smaller arc diameter. The amount of heat flux is directly proportional to the rate of electrode wear. This concept is analogous to the use of a hammer and chisel. Although the momentum of the swinging hammer is the same, the use of a chisel allows the force to be directed onto a smaller area thereby causing more damage. In the case of the plasma torch, higher pressures intensify the 'chisel effect'.

The feedstock is also an important factor in electrode erosion rates. Electrical conductivities of monatomic gases tend to fluctuate little with temperature, unlike diatomic gases. Electric arcs in diatomic gases generally tend to be narrower because of the tendency of diatomic gases to have higher rates of heat transfer and electrical conductivity. Noeske and Kassner (1962) determined that the current carrying cross-section of a monatomic gas is nine times greater than for a diatomic gas with the same current. This narrow arc will drastically increase the heat flux to the anode, and hence the electrode erosion rate.

10.2: Materials, Methods and Test Procedure

Seven newly machined anodes and cathodes were used to conduct the electrode erosion tests. Each anode and cathode was labeled and grouped in pairs. Each electrode was weighed with a digital analytical balance before and after each test. The analytical balance had an accuracy of ±0.001g. Each set, consisting of an anode and cathode, was used only once. The time period for each test was recorded to provide the rate of erosion. The number of high frequency starts required to obtain steady operation of the torch was also recorded, since a significant amount of electrode loss occurs during startup. All tests were conducted using high frequency current and operating in the high voltage mode. The original goal was to run each test for fifteen minutes and then shut off the power to end the test. However, the plasma torch was unable to run on ethylene for more than nine minutes due to the high rate of electrode erosion. A tungsten plug formed on the diverging section of the anode nozzle and ended the ethylene tests prematurely. Methane ran quite easily and was allowed to run up to twenty-six minutes before power was turned off. A tungsten plug never formed while the plasma torch was operating with methane.

The same current and gap setting were used for each test. Methane and ethylene were both run at 30 SLPM, while propylene tests were conducted with 15 SLPM of propylene and 10 SLPM of argon to stabilize the arc. One test using ethylene was conducted without the use of a flow swirler to determine the true effectiveness of swirling the arc. Of the seven tests, three were performed with ethylene, two with methane and two with propylene.

10.3: Results and Discussion

Overall, propylene was found to cause a much higher rate of electrode erosion than either ethylene or methane. The results of the seven electrode erosion tests are shown in Table 10.1.

Table 10.1: Electrode Erosion Results

Feedstock	Run Time (min)	Anode Erosion (mg)	Cathode Erosion (mg)	Total Erosion Rate (mg/min)
Test #1 Ethylene (no flow swirler) 1 start	3.00	27	34	20
Test #2 Ethylene 3 starts	4.17	40	6	11
Test #3 Ethylene 1 start	8.67	11	1	1.4
Test #4 Methane 1 start	26.00	10	1	0.42
Test #5 Methane 1 start	26.00	2	2	0.15
Test #6 Propylene 2 starts	2.17	140	11	70
Test #7 Propylene 3 starts	2.83	247	10	91

Throughout the entire testing series, it was observed that a large amount of electrode emission occurred during initial startup. Electrode emission is characterized by yellow streaks of light emanating from the plasma torch nozzle, caused by ejected molten tungsten particles. A picture of electrode emission during startup is shown in Fig. 10.3.

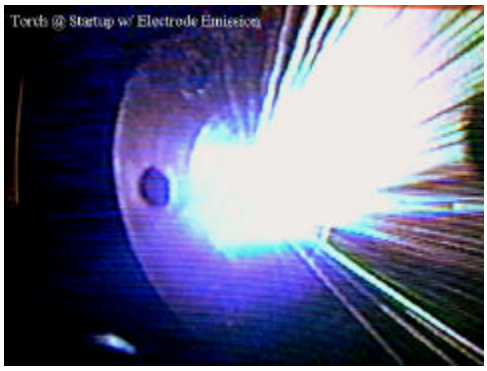


Figure 10.3: Heavy Electrode Emission at Startup

Once the torch was operating under steady conditions, electrode erosion diminished significantly. One of the tests conducted using ethylene, test #2, required three starts in order to get the torch operating. This test experienced four times the amount of electrode loss as did the ethylene test requiring only one start, test #3, and it ran for roughly one-half of the time. Also, test #7, propylene with three starts, produced 70% more electrode loss than test #6, propylene with two starts. Test #7 was only 30% longer than test #6. Therefore, it can be concluded that a significant portion of electrode loss occurs during startup. This deduction is supported by the findings of Miller and Winstead (1996) who measured the copper emission from their copper electrode torch. They discovered that electrode emissions are initially very high, but rapidly decrease over the first five minutes of operation.

It is clear from Table 10.1 that a plasma torch operating with propylene would have a much shorter operating lifetime than a plasma torch operating with methane. The electrode erosion experienced when the torch was operated with propylene was severe. Electrode erosion rates for propylene were approximately 700% greater than for the next best test gas, ethylene. Ethylene tests were also quite short when compared to methane. Arc failure occurred in every test conducted with ethylene and propylene due to severe electrode erosion. Methane ran smoothly and exhibited very little electrode erosion. Methane tests were stopped at 26 minutes, still exhibiting no signs of even moderate electrode erosion.

These results support qualitative observations made throughout the entire testing series. A possible explanation for this phenomenon is that propylene and ethylene both have more complex chemical structures than methane. Propylene and ethylene have

double covalent bonds and a number of single covalent bonds, while methane only has single covalent bonds. The chemical structures of propylene, ethylene and methane are shown in Fig. 10.4.

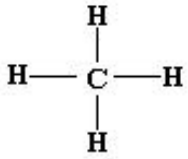
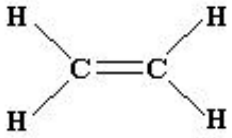
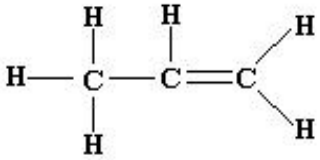
Methane	Ethylene	Propylene
		

Figure 10.4: Chemical Structures of Hydrocarbon Feedstocks

It is possible that the chemical dynamics of the fuel molecules somehow constrict the arc creating a higher heat flux to the anode and destabilizing the arc. An effect similar to this was observed by Noeske and Kassner (1962), who believed the diameter of an arc was related to the heat transfer capabilities of the gases. In the present case, the electrode erosion rate was observed to increase as the chemical complexity of the feedstock was increased, but the specific cause for this is unknown.

A majority of electrode erosion was confined to the anode. Intuitively, this is reasonable, since the arc passes from the cathode to the anode. As the arc strikes the anode it dislodges pieces of electrode, caused both by electron bombardment and large thermal gradients. After the arc is initiated and the electrode reaches a steady state temperature electrode erosion rates reduce. The cathode would experience the brunt of the electrode loss if the polarity was reversed and current passed from the anode to cathode. Combining the effects of arc characteristics and the nature of the feedstock being used provides a clearer picture to why electrode erosion occurs and how to minimize it.

The use of a flow swirler reduced the amount of cathode erosion in ethylene tests by as much as 700%. The anodes did not experience this amount of reduction, but did see some improvement, on average. Reduction in electrode erosion using a flow swirler could not be truly quantified, because the number of new cathodes and anodes available severely limited the number of electrode erosion tests. However, it is still quite evident that swirling the flow does improve plasma torch performance by producing steady operation, while lengthening the lives of the electrodes, particularly the cathode. The

cathode must have flow swirling because of its small thermal mass and dependency on arc rotation and convective cooling. Observations made during the three ethylene tests verified that the use of a flow swirler produced smoother operation and less electrode emission.

10.4: Recommendations and Final Remarks

The electrode erosion tests yielded several important results that must be considered when operating a torch with hydrocarbon feedstocks. First, hydrocarbon feedstocks will significantly reduce the life of an electrode due to the high rate of electrode loss when compared to operation with argon or nitrogen. Among the three hydrocarbon gases tested, propylene produced the highest rate of electrode erosion, followed by ethylene and finally by methane. Propylene tests produced, on average, an electrode erosion rate 750% higher than ethylene. Ethylene had an average erosion rate of 11 mg/s, exceeding that of methane by about 400%. The rate of electrode erosion appears to be strongly related to the chemical complexity of the feedstock. More complex gases were observed to produce higher erosion rates. This high rate of electrode erosion experienced with hydrocarbon feedstocks may warrant the use of an early warning electrode failure device such as the one designed by Miller and Winstead (1996). In their experiments, they impregnated a copper cathode with a thin layer of silver, located a set distance from the cathode tip. When the electrode had been sufficiently worn, silver particles could be detected in the torch exhaust using spectrometry methods and the electrode was replaced.

During most of the tests, the anode experienced considerably more mass loss than the cathode, experiencing about 85% of the total electrode wear. Also, the use of a flow swirler to induce rotation in the arc, significantly increased the life of the electrodes, particularly the cathode, regardless of the feedstock being used. The electrode life is of utmost importance when considering the purpose and mission time of the plasma torch. Purely from an electrode-life analysis, methane is the most feasible hydrocarbon feedstock to be used in a plasma torch. Future testing may need to focus on trying to improve the electrode life while the torch is operating with more complex hydrocarbon

gases if they are found to be superior ignitor/flameholders in a supersonic environment. The Virginia Tech Plasma Torch was designed to operate on argon, hydrogen and nitrogen at power levels up to 2.0 kW. A torch designed for hydrocarbon feedstocks should be designed to be capable of handling power requirements up to 5 or 6 kW. Cooling will be a major issue and can be provided with a larger thermal mass to act as a heat sink or cooling water. Also, since electrode erosion rates will be high, a larger diameter cathode is recommended as well as an electrode geometry which can maintain a constant arc length, independent of moderate electrode wear.