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Cold Fusion – Engineering Perspectives

by

Ali F. AbuTaha

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Cold Fusion—Engineering Perspectives[1]

Ali F. AbuTaha[2]

Considerable heat was liberated from a palladium–deuterium (Pd-D) system and this was attributed to cold nuclear fusion of deuterium within the palladium lattice.[1] The primary source of heat in cold fusion was proposed to be the work-of-fracture of cracks in the Pd electrodes, and the mechanism for crack initiation and propagation was identified as deuterium or hydrogen embrittlement.[2] In this paper, comparable characteristics of cold fusion and embrittlement are established, relevant aspects of the extensive engineering database on hydrogen and deuterium embrittlement are reviewed, some areas of study and applications of the cold fusion process are identified, and parameters for controlling the ignition and heat release from metals are specified.

KEY WORDS: Cold fusion; hydrogen embrittlement; palladium–hydrogen; palladium–deuterium; fracture energy.

1. BACKGROUND

In the short period following the announcement of the Pons-Fleischmann discovery, several centers reported the generation of variable amounts of heat in similar experiments. Other centers reported no heat from the process. The disparity of heat output has been enormous, indicating that the controlling experimental parameters of the cold fusion process are not well understood. Unlike the excess heat, the D-D nuclear fusion has not been as widely supported or reported. For example, fusion products initially reported by the original experimenters were revised downward and early reports of fusion byproducts from other centers were retracted.

Careful examination of the reported characteristics of cold fusion revealed outstanding similarities to an esoteric engineering subject: hydrogen embrittlement. This led to correlation of important properties of the two phenomena, explanation for the enormous disparity in heat production in cold fusion, and identification of specific parameters to ignite and control the process.

Hydrogen embrittlement was studied at length in the last three decades to understand, theorize, and control a serious cause of premature failure of aerospace and other structures. The palladium–deuterium system is similar to the palladium–hydrogen system, with the heavier deuterium causing slightly greater damage to metals and alloys than hydrogen.

Failure of metals and alloys by hydrogen embrittlement is comprised of the initiation, growth, and propagation of cracks. The interaction of hydrogen with other hydrogen or metal atoms and residual stresses locked in during processing and manufacturing introduce forces in the vicinity of the cracks. The locked-in stresses can remain in a metal sample for a long time, ready suddenly to release mechanical energy by a variety of mechanisms, including deuterium or hydrogen embrittlement. While only small forces are involved in the process, considerable energies are exchanged within the metal lattice during the fracture process. The most significant energy term was identified as the work-of-fracture.[2] The energy to form two new surfaces in palladium, or other metals, is generally less than 1 J/m^2, while the fracture energy to produce the same new surfaces can be greater than 1×10^6

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[2] Technical Consultant, Herndon, Virginia.

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J/m^2. Actually, the total fracture work that can be done within a metal electrode is greater than the heat reported from cold fusion to date.

2. TEMPERATURE CORRELATION

It is not clear whether Professors Pons and Fleischmann attempted the cold fusion process at high, intermediate, and low temperatures and whether the intermediate room temperature was found to be optimum through tests or not. Maximizing a process, such as cold fusion, can be done by varying parameters, particularly temperature. The hydrogen embrittlement database clearly shows that embrittlement is most severe in intermediate temperature regions, particularly around room temperature, while the effect is negligible at low and high temperatures. A correlation for this important parameter appears to exist between cold fusion and the embrittlement of metals by hydrogen and deuterium.

3. VARIABLE HEAT PRODUCTION

The amount of heat liberated in cold fusion experiments varied greatly; from more than 4 × 10^6 J/cm^3 of palladium electrode volume to no heat at all. Recognizing that the fracture process can be the primary source of the reported heat clarifies the variation of heat output and this can be explained by known characteristics of embrittlement.

Severity of deuterium attack is dependent on the crystallographic structure of metals and alloys. The more open body-centered cubic (bcc) metals are more susceptible to embrittlement than the more closed hexagonal close-packed (hcp) or face-centered cubic (fcc) metals. Most metals and alloys, however, are susceptible to hydrogen and deuterium embrittlement to varying degrees, depending on many complex conditions.

Consider the effect of hydrogen on the alloys in Table I. Here, the fracture toughness of precracked specimens was measured[3] in vacuum, molecular, and atomic–molecular hydrogen at the shown pressures. The stress intensities in Table I were calculated in Ref. 3 from measured loads. The results show that atomic hydrogen, molecular hydrogen, pressure, and alloy treatment produce different effects. The results for the titanium samples are of particular importance here. The annealed titanium (Ti-6Al-4V) samples suffered less strength reduction than the solution-treated samples. Since residual stresses are greatly reduced by annealing, the embrittlement effect and the work-of-fracture are smaller, and the liberated heat is minor or absent.

Table I. The Effect of Hydrogen on the Fracture of Different Alloys (Reproduced from Ref. 3)

Alloy	K_{scg}, MN/m^2-m$^{1/2}$		
	Vacuum ($K_{scg} = K_Q$)	$P_{H_2} = 90.6$ kN/m^2)	$P_{H_2} = 1.07$ N/m^2)
Molybdenum alloy (TZM)	123.4	74.6	—
Copper alloy (Cu–Be)[a]	39.3	37.6	37.5
Copper alloy (cu–Be)[b]	82.4	87.9	92.3
Nickel alloy (201)	No failure	No failure	—
Nickel alloy (301)	162.6	54.9	—
Aluminum alloy (7075)	23.5	24.6	24.6
Magnesium alloy (HM21A)	6.12	6.40	5.85
Titanium alloy (6–4)[c]	115.6	105.3	—
Titanium alloy (6–4)[d]	149.7	52.1	—
Steel alloy (4130)	64.0	27.3	48.8
Stainless-steel alloy (310)	No failure	No failure	No failure
Stainless-steel alloy (A286)	No failure	No failure	No failure

[a] Aged at 343°C for 4 h.
[b] Aged at 399°C for 3 h.
[c] Annealed at 704°C.
[d] Solution treated at 1037°C and stabilized.

Professor Pons said that there is "almost no fusion if the palladium rod is machined, or formed from a larger block, for instance; only cast palladium, in which the metal is melted and poured into a form, works" (*Newsweek*, May 8, 1989, pg. 52). Cast metals are generally brittle and weak in tension and are, thus, more susceptible to embrittlement and are more likely to release considerable fracture work and heat.

Also, residual stresses vary across the bulk of the same ignot after cooling, so that samples from the same block can exhibit differing degress of susceptibility to fracture. The work-of-fracture, and the amount of heat that can be liberated, will therefore vary for electrode samples obtained from the same ignot or block. This last observation is amplified by other tests in Ref. 3, where the effect of hydrogen on similar metal samples was tested. The results of these tests are shown in Figs. 1

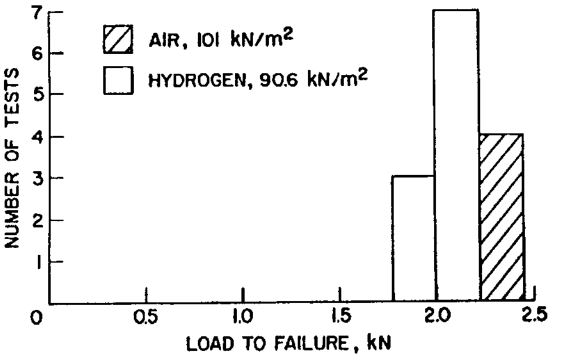

Fig. 1. The distribution of titanium alloy failure load in air and hydrogen (reproduced from Ref. 3).

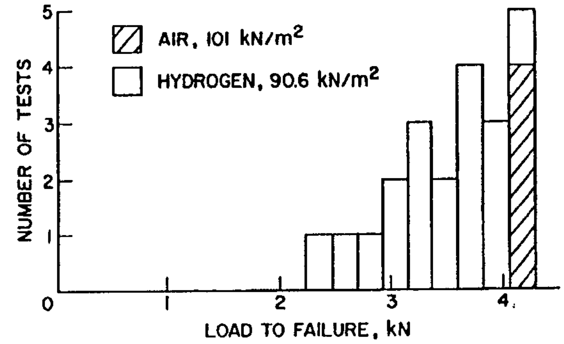

Fig. 2. The distribution of steel alloy failure load in air and hydrogen (reproduced from Ref. 3).

and 2. Here, all the titanium specimens were slightly affected by the hydrogen environment (Fig. 1). The steel samples exhibited greater variation in strength reduction (Fig. 2). If the 26 similar steel specimens were used in calorimetric tests to measure the amount of heat that can be liberated through strength reduction and fracture energy, then a normal distribution is observed. No heat would be obtained from five samples in hydrogen (corresponding to samples in air), one to three experiments would produce considerable heat (corresponding to samples which failed between 2 and 3 kN), and most of the tests (14 specimens) would give intermediate results. Other tests demonstrated variation of ultimate strength of palladium for hydrogen–palladium atom ratios of 0.0 to 0.6, while the reduced ultimate strength remained constant from 0.6 to 1.0 ratios.[4] The release of fracture energy from the same sample can then vary as the concentration of hydrogen or deuterium in the specimen changes.

The heat output of cold fusion appears to correlate to strength reduction caused by hydrogen or deuterium environments. The strength reduction was not measured in cold fusion experiments and the proposed correlation went undetected. The embrittlement process is complex and is sensitive to minor deviations in one of many parameters as discussed in the next section.

4. OTHER CONTROLLING FACTORS

Correlation of hydrogen embrittlement to the cold fusion process uncovers an extensive data base to study the process. Many important characteristics of hydrogen embrittlement were studied and identified before. For example, the embrittlement process was found to have little or no correlation to hydrogen diffusion and the activation energy for hydrogen diffusion, the effective radius of the hydrogen electron shell in metals, the effective radius of hydrogen ions and the radius of interstices, the heat of chemisorption, and the activation energy of desorption, while no correlation, or conflicting results, were reported for hydrogen solubility and heat effects.[3] Other characteristics were carefully tested in the same reference, including the effects of hydrides and phase formation in metals, kinetics of hydrogen transport, stress intensity, cyclic loading, strain rates, pressure, and temperature. The inconsistent behavior of embrittlement in some metals led the author of Ref. 3 to propose that "A correlation with a common parameter may never be possible."

Thermodynamics of palladium–hydrogen, –deuterium, and –tritium systems and electrochemical and calorimetric measurements were surveyed and summarized in Ref. 5. In general, the enthalpy and entropy of Pd-H, -D, and -T systems were based on the heats of absorption, desorption, formation, and other chemical, physical, or thermodynamics processes. Correlation of enthalpies and entropies to the concentration of H, D, or T in palladium was reported. The study noted that anomalies exist in the enthalpy measurements of the Pd-H system, but the substantial work-of-fracture and the heat that can result from the work were not included.

On the other hand, the significant energy involved in the fracture work was reported in other studies, but these were not correlated to the embrittlement process or to heat production. In the energy balance for the formation of a crack, Ref. 6 includes the energy of superdislocation, surface energy, distortion energy, and the work done in opening a crack. Conditions at the crack tip, for example, were noted to increase the energy by a factor of 100 to 1000.[2,6]

The study of crack initiation, growth, and propagation uncovers other intricacies. The severity of deuterium attack on metals and alloys is further influenced by the microstructure of the material, stress intensity, method of load application, and whether hydrogen or deuterium is in the atomic, molecular, gaseous, liquid, or other states.

The embrittlement process explains the arbitrary "ignition" of the fracture process and the ignition of heat generation from cold fusion. Many microcracks are introduced into metals and alloys during the manufacturing process. These cracks provide many sites for the nucleation of other cracks, and the fracture process is significantly influenced by complex factors acting singly or in combination. To ignite the fracture process, the experimenter must know the conditions above plus the stress concentration at the crack tip, heterogeneity of deformation, orientation of planar defects, yield and ultimate strengths of the material, and surface and lattice bond energies. Uncontrolled, this complex composite of conditions makes the ignition of cold fusion a random process.

The capricious behavior of deuterium and hydrogen embrittlement and, more importantly, the complex conditions required to ignite or maintain the fracture process explain some of the chaos that surrounded the early attempts to reproduce the results of the Pons–Fleischmann experiments. The objective of the earlier embrittlement studies was to minimize the fracture process. The objective of the cold fusion experiments, on the other hand, is to maximize the same process. Minimizing the embrittlement effect is a complex task, as the engineers who designed systems to operate in hydrogen or deuterium environments have already discovered. The same complexity will be present in the effort to maximize the effect for heat generation from cold fusion. If only one of the many factors mentioned above is neglected or miscalculated, then the results will be haphazard and random.

5. THE FUSED AND MELTED ELECTRODES

The incremental heat generation in the Pons–Fleischmann experiments was correlated to the well-known discontinuous propagation of cracks in hydrogen and deuterium embrittlement.[2] In addition to the intermittent release of energy, Pons and Fleischmann reported that "a substantial portion of the cathode fused (melting point 1554°C), part of it vaporized, and the cell and contents and part of the fume cupboard housing the experiment were destroyed,"[1] in a cold fusion experiment. The sudden release of substantial energy from palladium in the hydrogen environment can be correlated to the explosive crack propagation phenomenon. A comparable scene to the palladium electrode meltdown was seen in titanium, a similar transition metal, electrode in the early 1970s. During the study of surface hydride formation on titanium[3] (the same tests in Fig. 1), "in one test run, however, a violent reaction occurred between the titanium alloy and the hydrogen environment immediately following the introduction of hydrogen into the chamber. This reaction continued for approximately 3 min, ejecting material continuously, with a resulting crater. . . ." A photograph of the crater is reproduced from Ref. 3 in Fig. 3. Also, "Similar observations have been made at room temperature in columbium and in tantalum where severe fragmentation has been observed as the result of hydride formation originating at a thermocouple attachment" (ibid).

The resemblance of these embrittling phenomena to the Pons–Fleischmann palladium electrode meltdown is apparent. The explosive crack propagation results from the short-time release of the significant fracture work, or energy.

6. OTHER RELEVANT CORRELATIONS

I found other characteristics of the cold fusion process which are analogous to features in hydrogen embrittlement. Whereas initially it was reported that heat generation occurs only with deuterium, and not hydrogen, it

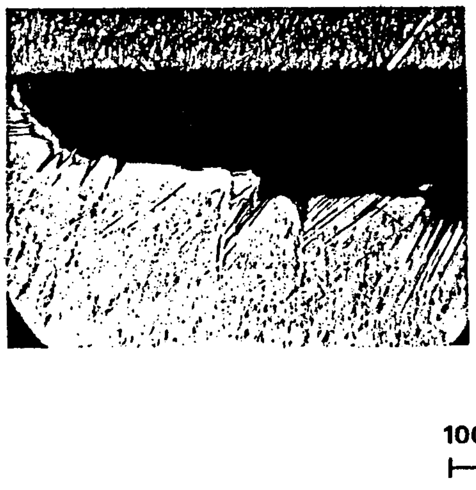

Fig. 3. Crater formed by violent reaction of titanium with hydrogen (reproduced from Ref. 3).

has already been reported that hydrogen produced a similar, though smaller, effect. This compares with the slightly greater effect of deuterium, than of hydrogen, on the fracture of metals and alloys. And whereas it was not clear at the outset whether heat can be liberated from materials other than palladium, it has already been reported that heat was liberated from titanium and nickel alloys in similar experiments. These and other alloys are susceptible to embrittlement, crack initiation and propagation, release of varying amounts of fracture work, and hence, heat. Also, the need for an electric current to enhance the "fusion" process inside of the electrode bulk was proposed, but it has already been reported that the phenomenon is reproduced without an electric current. While hydrogen or deuterium may be introduced into the bulk of metals during processing steps, these atoms are transported onto the surface through physisorption or chemisorption and are then diffused into the bulk, in time and without the need for an electric nudge, where they cause embrittlement. There are other characteristics of cold fusion which correlate directly with similar characteristics of the embrittlement phenomenon, such as the delayed start of heat generation, the incremental release of heat, and others. The similarities between the two phenomena are indeed many.

7. ENGINEERING DESIGN CONSIDERATIONS

The cold fusion phenomenon leads to new vistas for scientific research and study. The reported phenomenon should also rejuvenate understanding of hydrogen and deuterium embrittlement in the design of modern engineering systems. The prevailing practice in the design of spacecraft, aircraft, rockets, and other systems is to analyze the loads, deflections, stresses, strains, fatigue, and other parameters in the system, with little attention given to the energy exchanges in materials and structures.

My two papers, in this journal, illustrate the critical role of energy exchanges in engineering materials and structures. The random behavior of hydrogen- and deuterium-induced cracks and the sudden release of the large fracture energy can lead to premature failure of an aircraft wing or hull, or the unexpected breakdown of a spacecraft. Engineering systems are designed to positive safety margins, but some of these systems experienced occasional premature failures in the last few years. In most instances, the positive safety margins are based on loads, stresses, and strains. Hydrogen and deuterium, and other corrosive elements, are abundant in the environment, and many lightweight systems may have to be designed on the basis of the significant energy exchanges identified in my papers to avert major accidents.

8. COMMERCIALIZATION—ENERGY STORAGE DEVICES

During the congressional hearing on the cold fusion phenomenon,[9] the Utah experimenters proposed that heat generation from the calorimetric process can be made continuous by circulating deuterium in calorimetric cells in a closed system. As I proposed in my papers, heat generation is dependent on the fracture of the palladium electrodes in the deuterium environment and, hence, circulation of deuterium into the all-cracked Pd electrodes cannot continue the heat process.

The capacity of the Pd-D system to liberate heat is significant,[1,2] and the process will be useful for energy storage devices for use in space systems and in remote terrestrial locations and for special applications. This is evident from a comparison of the heat content of coal, less than 10 kcal/cm^3, with the more than 1,000 kcal/cm^3 (the 4 MJ/cm^3 liberated in the Pons–Fleischmann experiments) that can be released from a comparable metal cube. While fine control of embrittlement is complex as described in this paper, some basic parameters can be monitored to control the initiation and suspension of the process. For example, the fracture process is greatly dependent on the microstructure of the electrode material and the strain rate. Carefully applied external forces can be used to alter (start or stop) the fracture process by changing the microdistances within the lattice.[8]

9. ENVIRONMENTAL CONSIDERATIONS

The enormous heat that can be liberated by the fracture of metals may have a detrimental effect on local and worldwide environments. Massive piles and large storage fields of discarded cars, planes, trains, and other metal structures can be a source of enormous heat in concentrated locale. Such stockpiles were introduced around major cities in the last half century and their heat-generation impact on local and world environment may have gone undetected to date. The seriousness of the problem is demonstrated below.

Cast iron, heavily used and discarded in the last century, is susceptible to corrosion by environmental hydrogen, deuterium, and, most importantly, salt seawater and other agents. Approximation of the heat generated from a stockpile of discarded cars indicates that the metal piles may act as small, but invisible, volcanos. If 1 cm^3

of cast iron produces 0.4 MJ, i.e., 10% the heat released from cast Pd, then the heating effect can be calculated. The corrosion of 100,000 cars can produce more than 5×10^{15} J. If the cars corrode in 100 years, then the average daily heat release from the pile is 1.37×10^{11} J. When the corrosion rate is accelerated by stresses due to daily thermal cycles and other factors, the amount of heat that can be liberated from the exposed metal can be enormous. While these values are small on a global scale, their effect can be noticeable in major cities, such as, Los Angeles, Baltimore, and Houston. When the weather is hot and stagnant in these or other cities, the heat production from the discarded metal can intensify and strengthen the stagnation effect. Such effects on local weather can be studied by charting temperature variations around major cities from Earth Resources Satellites and other weather systems.

10. CONCLUSION

This paper is a synopsis of notes from a 3-day course on the subject. The mainly qualitative description briefly demonstrates discernible correlations between the cold fusion process and the hydrogen or deuterium embrittlement of metals and alloys and identifies important parameters to control the ignition and release of heat from the process.

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