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Opening Remarks

Hydrogen embrittlement of metals is an old, a frequently encountered, and often misunderstood phenomenon. Metals processing, chemical, and petrochemical industries have experienced various types of hydrogen problems for many years. More recently, however, the aerospace industry has experienced new and unexpected hydrogen embrittlement problems. There are many sources of hydrogen, several types of embrittlement, and various theories for explaining the observed effects. For purposes of this symposium, hydrogen embrittlement will be classified into three types:

1. Internal reversible hydrogen embrittlement (IHE).
2. Hydrogen environment embrittlement (HEE).
3. Hydrogen reaction embrittlement (HRE).

The definitions of these three types of embrittlement are as follows. If specimens have been *precharged* with hydrogen from any source or in any manner and embrittlement is observed during mechanical testing, then embrittlement is due to either internal reversible embrittlement or to hydrogen reaction embrittlement. If hydrides or other new phases containing hydrogen form during testing in gaseous hydrogen, then, for the purpose of the symposium, embrittlement will be attributed to hydrogen reaction embrittlement. For all embrittlement determined during mechanical testing in gaseous hydrogen other than internal reversible and hydrogen reaction embrittlement, hydrogen environment embrittlement is assumed to be responsible.

1. *Internal reversible hydrogen embrittlement* (*IHE*)—Internal reversible hydrogen embrittlement has also been termed slow strain rate embrittlement and delayed failure. This is the classical type of hydrogen embrittlement that has been studied quite extensively. Widespread attention has been focused on the problem resulting from electroplating—particularly of cadmium on high-strength steel components. Other sources of hydrogen are processing treatments, such as melting and pickling. More recently,

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the embrittling effects of many stress-corrosion processes have been attributed to corrosion-produced hydrogen. Hydrogen that is absorbed from any source is diffusable within the metal lattice. To be fully reversible, embrittlement must occur without the hydrogen undergoing any type of chemical reaction after it has been absorbed within the lattice.

Internal reversible hydrogen embrittlement can occur after a very small average concentration of hydrogen has been absorbed from the environment. However, local concentrations of hydrogen are substantially greater than average bulk values. For steels, embrittlement is usually most severe at room temperature during either delayed failure (static fatigue) or slow strain rate tension testing. This time-dependent nature (incubation period) of embrittlement suggests that diffusion of hydrogen within the lattice controls this type of embrittlement. Cracks initiate internally, usually below the root of a notch at the region of maximum triaxiality. Embrittlement in steel is reversible (ductility can be restored) by relieving the applied stress and aging at room temperature, provided microscopic cracks have not yet initiated. Internal reversible hydrogen embrittlement has also been observed in a wide variety of other materials including nickel-base alloys and austenitic stainless steels provided they are severely charged with hydrogen.

2. *Hydrogen environment embrittlement* (*HEE*)—Hydrogen environment embrittlement was recognized as a serious problem in the mid 1960's when the National Aeronautics and Space Administration (NASA) and its contractors experienced failures of ground based hydrogen storage tanks (Refs *1* and *2* of author's paper in text). These tanks were rated for hydrogen at pressures of 35 to 70 MN/m^2 (5000 to 10 000 psi). Consequently, the failures were attributed to "high-pressure hydrogen embrittlement." Because of these failures and the anticipated use of hydrogen in advanced rocket and gas-turbine engines and auxiliary power units, NASA has initiated both in-house (Refs *3* through *5* of author's paper in text) and contractural (Refs *6* through *14* of author's paper in text) research. The thrust of the contractural effort generally has been to define the relative suscepibility of structural alloys to hydrogen environment embrittlement. A substantial amount of research has been concerned with the mechanism of the embrittlement process (Refs *4*, *5*, *15* through *26* of author's paper in text). There is marked disagreement as to whether hydrogen environment embrittlement is a form of internal reversible hydrogen embrittlement or is truly a distinct type of embrittlement. Some background information regarding this controversy will be presented later in this publication.

3. *Hydrogen reaction embrittlement* (*HRE*)—Although the sources of hydrogen may be any of those mentioned previously, this type of embrittlement is quite distinct from that discussed in the previous section. Once hydrogen is absorbed, it may react near the surface or diffuse substantial distances before it reacts. Hydrogen can react with itself, with the matrix,

or with a foreign element in the matrix. The chemical reactions that comprise this type of embrittlement or attack are well known and are encountered frequently. The new phases formed by these reactions are usually quite stable and embrittlement is not reversible during room temperature aging treatments.

Atomic hydrogen (H) can react with the matrix or with an alloying element to form a hydride (MH_x). Hydride phase formation can be either spontaneous or strain induced. Atomic hydrogen can react with itself to form molecular hydrogen (H_2). This problem is frequently encountered after steel processing and welding and has been termed flaking or "fish-eyes." Atomic hydrogen can also react with a foreign element in the matrix to form a gas. A principal example is the reaction with carbon in low-alloy steels to form methane (CH_4) bubbles. Another example is the reaction of atomic hydrogen with oxygen in copper to form steam (H_2O) resulting in blistering and a porous metal component.

Although HRE is not a major topic of discussion in this symposium, its definition is included for the sake of completeness and in the hope of establishing a single definition for each of the various hydrogen embrittlement phenomena in order to avoid problems with semantics.