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Hydrogen and Internal Residual Stress Gear Failures – Some Failure Analyses and Case Studies

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Hydrogen and internal stress failures are relatively rare; however, when they occur they are always spectacular, often very costly and sometimes quite catastrophic. While hydrogen and internal stress issues are generally recognized as significant in the design and manufacture of larger gears, they are also important for smaller gears as well. Unfortunately, such failures are difficult to diagnose and, because of their often catastrophic nature, may well go unrecognized.

This paper presents, via illustrated actual case studies, the mechanisms by which these failures occur, the manner in which they progress and methods for testing finished gears for the possibility of internal problems. In addition, precautionary steps that can be taken during design, manufacture, heat treatment and quality control to minimize the possibility of these problems occurring in a finished part along with similar steps required to prevent any flawed gears from entering service are also presented and discussed.

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Introduction

Unlike most fatigue failures, hydrogen and internal stress related failures almost always occur with virtually no warning at all. No debris is generated and, since the cracks progress from deep within the part to the surface, there is generally no observable change in noise or vibration level, until the very last moment when a spectacular fracture failure occurs. The very large, double helical, carburized pinion shown here (figure 1), for example, operated satisfactorily for many months before suffering a catastrophic failure (the shaft fractured into two halves, stopping the mill immediately and causing ancillary damage as well). While this fracture occurred after a period of successful service time, it is more common for such failures to occur very early in the life of the part. In some instances, dramatic failures have occurred while post heat treatment processing was under way in the factory!



Figure 1. Large mill gear failure
(note leg at left for scale)

We tend to think of steel as a solid medium, however, given the right conditions, nascent

hydrogen will actually migrate interstitially through the steel matrix to gather in a common location that will then form the nucleation site for a crack that leads to the dramatic failure events that typify these problems. Internal residual tensile stresses can act alone to cause similar failures or they can work in concert with hydrogen to accelerate the “fatal” crack propagation.

The hydrogen problem

Controlling the hydrogen content in gear steels is important because hydrogen entrapment can have a very detrimental effect on service performance of steel gears. Only a few parts per million of hydrogen dissolved in steel can cause internal hairline cracks (flakes), hydrogen embrittlement, hydrogen blistering and loss of tensile ductility, particularly in large steel gears with thick cross-sections.

When the hydrogen content of the molten steel used to cast the ingot from which a gear blank will ultimately be fabricated is in excess of the solubility limit of hydrogen in solid iron, the hydrogen will be rejected during the solidification process. The failure mode which results is often called a “hydrogen burst” because of the visual characteristics of the fracture face, as will be described below.

Hydrogen can be entrapped in a steel gear blank during the initial steel melting process, during processing operations during the manufacturing process (e.g., acid etch inspection for hard finishing burns) and during subsequent electroplating processes. Internal residual tensile stresses are generated during solidification of the molten steel as well as during heat treatment, particularly during the quench operation. It is also quite possible, and in some cases likely, that both hydrogen entrapment and internal residual tensile stresses may occur together.

As the thick slab that will be used to fabricate a heavy section steel gear is rapidly cooled, there will be little diffusion of hydrogen out of resultant bar. This type of cooling can also result in increased internal residual tensile stresses. Hydrogen solubility

decreases with a decreasing temperature, but if the hydrogen is internal it will migrate to tensile stress locations, and form hydrogen gas. Thus if hydrogen is present in the steel as it is being poured, there will be a build up of H₂ gas pressure in the steel matrix during rapid cooling. For the limiting case of no hydrogen diffusion, the pressure generated by the entrapped hydrogen will be as shown in Figure 2 (data obtained from Reference 1). Clearly, as even very small hydrogen concentrations as low as 4 ppm can generate significant internal gas pressures. As the hydrogen content increases, the internal gas pressure increases at an exponential rate. Even at concentrations as low as 8 ppm, the pressure increase is obvious. At double digit concentrations, the pressure can literally “blow” a steel gear apart.

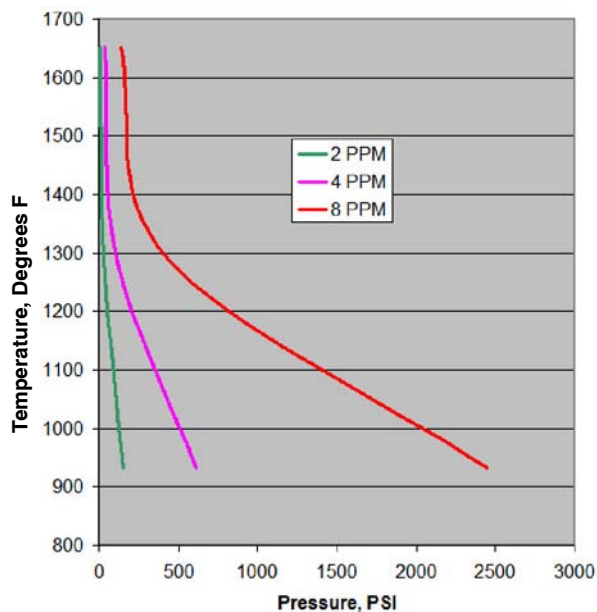


Figure 2. Hydrogen pressure buildup during rapid cooling

While the temperature range of this data is limited, it is clear that higher concentrations of nascent hydrogen can produce very significant internal hydrogen gas pressure as the steel cools, especially as it reaches room temperature. As nascent hydrogen migrates these stresses build up and over time and may not produce any effect at all until the gear is well along in either its manufacturing processing or even after being placed in loaded service. This is one of the primary problems with a hydrogen type of failure

– there is no known time limit for when fracture will initiate.

The authors have participated in failure investigations where massive fractures occurred while a large gear (usually a solid on shaft pinion) was simply sitting on the floor awaiting the next processing operation (most frequently after tooth finishing by grinding or hard cutting has been accomplished) and after the gear had been in loaded service for several years. The sound of a hydrogen burst on the shop floor is something similar to the report of a high powered hunting rifle discharge. It does not take much imagination to realize that such a failure in the shop is, to say the least, a bit unnerving!

In service hydrogen burst failures, while not as readily observable as those that occur on the shop floor, are equally spectacular in that they usually result in a sudden, complete gear blank fracture failure. This type of failure is most often observed on large solid on shaft pinions and when the “shaft” fractures, consequential damage can be and often is very extensive. The pinion shown in Figure 3, for example, fractured due to a hydrogen burst after about one year of loaded service.

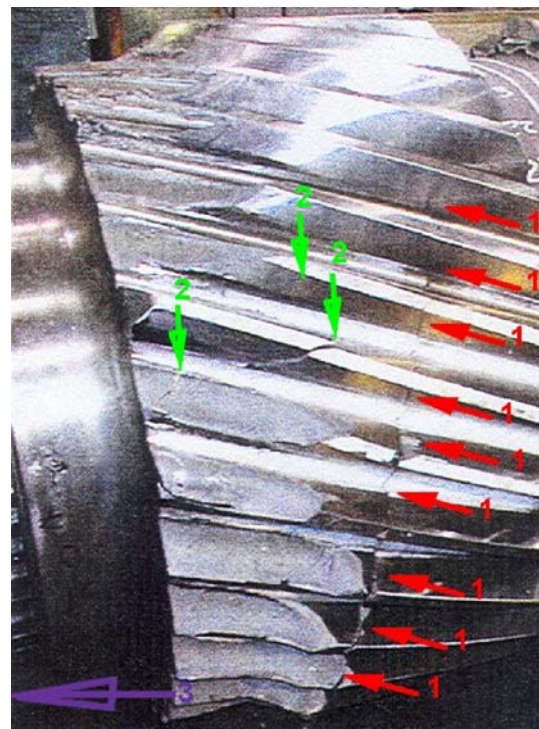


Figure 3. Complete pinion “shaft” fracture due to hydrogen burst