Dispelling the Fears of Hydrogen in Shielding Gases
For Corrosion Resistant Overlays on High Strength Steels

Introduction:

Hydrogen-bearing shielding gases have been used for decades; however, with today’s awareness about hydrogen-induced cracking (HIC) and the need for low hydrogen consumables and welding practices, the suggestion of using a welding shielding gas containing hydrogen is rarely considered. The negativity associated with the use of this gas has long overshadowed its inherent benefits. In an attempt to overcome these inhibitions and prohibition by the welding academic/technical community, it was realized that a study of the effects of hydrogen additions to shielding gases to either confirm or dispel these concerns was justified.

Such a study is especially interesting to the technical community involved with the use of the gas tungsten arc welding process with hot wire filler metal addition (GTAW-HW) for the welding of corrosion-resistant overlays (CROs) on high strength steels like 4130, 8630 and F22, all of which are common alloys used for components in the upstream sector (production) of the oil and gas industry. The CRO alloy of choice for many of these “oil patch” applications is INCONEL® 625 (625).

Another impression one gets when mentioning the use of hydrogen is the fear of explosions. While true that hydrogen is highly flammable, its flammability limit occurs at 4% concentration. For this study, 98% Ar – 2% H₂ was used so the concern for fire or explosion is immediately eliminated.

Hydrogen-induced cracking (HIC), however, is a more legitimate concern among metallurgists familiar with its potentially catastrophic consequences. One of the more vocal groups arguing against the use of hydrogen in shielding gases are those in the oil and gas production community, especially those on the Gulf coast. Damaging effects of hydrogen sulfide on carbon and low alloy steel weldments are well known, and respected, by this group. The risk of hydrogen-induced stress corrosion cracking is real, which is why the use of welded corrosion-resistant overlays (CROs) on oil patch components is so important. Without this protective layer, steel components would fail prematurely potentially causing serious damage, including potential safety and health risks to personnel.

When using the GTAW process, inert shielding gases such as argon and helium are required, with argon being the most common choice. When helium is used, more heat is generated by the welding arc allowing for improvements when welding thick sections or when there is a desire to weld at higher travel speeds. However, the increased cost and limited availability of helium makes argon the gas of choice for typical CRO welding applications in the oil patch.

Compared to argon and helium, hydrogen is reactive as opposed to inert. This reaction, however, creates a reducing atmosphere in the weld zone resulting in the reduction, i.e. elimination, of oxides. Hydrogen readily combines with any oxygen present in the weld zone. Similar to helium, the addition of hydrogen adds heat to the weld pool and has the capability for increased heat transfer, six (6) times that of argon.

With these characteristics, it is easy to see how hydrogen-bearing shielding gases can offer a number of advantages in terms of both weld quality and productivity. Some of those benefits include:

- Higher heat input allows for the use of faster travel speeds, with better edge-wetting, even at lower welding currents.
- Cleaner weld surface is increasingly more important when making multi-layer welds in small bores where cleaning between layers is impractical.
- Cleaner weld metal reduces the potential for creating subsurface oxide inclusions which could subsequently result in surface defects on machined surfaces, requiring repair.
- Removal of oxygen contamination in the shielding gas is evidenced by the presence of a clean electrode. As a result, longer weld times are possible without deterioration of the electrode resulting in fewer tungsten electrode changes.
Two welds made with the same “Dirty” wire at the same welding parameters, both have two (2) layers of 625 wire.

**Top weld -** was made using argon shielding gas. Note the irregular edges and oxide spots on surface of weld.

**Bottom weld -** was made with 98% argon/2% hydrogen shielding gas. Note the clean straight edges on weld beads and the much cleaner weld surface.

**History of hydrogen in welding:**

Hydrogen was the first gas used for shielding of an arc welding process. Introduced in the 1930s, the atomic hydrogen welding (AHW) process used hydrogen for shielding. It produced higher welding temperatures than any of the welding processes available at the time. Not only does it have a high temperature arc, but it has a very high thermal conductivity. The heat of the arc ionizes the hydrogen, separating the atoms of the hydrogen molecule. When the ionized gas cools in the weld zone, the atoms recombine, releasing the absorbed energy. Another beneficial characteristic is the reducing potential of hydrogen. Oxygen has a greater affinity for hydrogen than molten steel, so if oxygen-bearing contaminants are present in the arc atmosphere, they will combine with the hydrogen and evolve instead of becoming surface oxides or entrapped oxide inclusions. Atomic hydrogen welding has been used for welding tool steels and hard facing of high strength steel rock bits for decades with no detrimental effects. Through the years, hydrogen has been added to shielding gases for GTAW, GMAW, and PAW to take advantage of its high heat transfer and reducing atmosphere. When one observes a weld made with hydrogen additions, it is clearly evident the surface is cleaner.

To better understand the concerns related to the presence of hydrogen during welding, it is appropriate to briefly discuss the conditions leading to hydrogen-induced cracking (HIC). While the presence of hydrogen is a necessary factor for this damage, there are other contributing elements. For HIC to occur in steel weldments, three (3) conditions must coexist: 1) the presence of a crack-susceptible microstructure (HAZ hardness greater than 20 HRc); 2) the presence of applied stress (residual stresses from welding are sufficient); and 3) the presence of hydrogen. For the applications cited here where CROs are welded to hardenable steels such as 4130, 8630 and F22, the presence of a high HAZ hardness and residual stress are expected. One might ask with those two (2) factors present, how can HIC be avoided when hydrogen is present as a component of the shielding gas? To answer that, we need to understand what happens to the hydrogen during the welding operation.

As mentioned above, some of the available hydrogen is converted to monatomic hydrogen which is highly soluble in molten steel. This diffusible hydrogen (monatomic hydrogen dissolved when the steel is molten) must be allowed to evolve from the steel so it does not become trapped in the solidified steel or it could potentially lead to HIC. Hydrogen is not a concern for stainless steels and nickel alloys because the atomic structure of these metals provides for the hydrogen to remain mobile. The higher the temperature, the faster the hydrogen will diffuse from the steel and into the CRO. Most of the hydrogen, however, will be consumed in the reduction of oxygen in the weld zone. Therefore, the increased hydrogen mobility at elevated welding temperatures, and the elimination of hydrogen as a result of the
Testing Program:

As stated above, the primary goal of this study was to measure the amount of hydrogen present in the weld metal and prove that the addition of a small amount of hydrogen to the shielding gas does not result in any degradation of mechanical properties of the weld metal zone (WMZ), heat-affected zone (HAZ), or base metal zone (BMZ). A related concern is the potential for hydrogen-induced cracking (HIC) due to the introduction of hydrogen during the welding operation.

All three (3) materials previously mentioned are considered to be hardenable, so the potential for a HAZ microstructure with a hardness above the 20 HRc threshold is virtually guaranteed. While the use of preheating and postweld heat treatment (PWHT) will tend to reduce hardnerness and residual stresses, the potential still exists that even with these measures, one (1) or two (2) of the contributing conditions could exist. These thermal treatments also play a key role in removal of diffusible hydrogen from the weld zone, with both temperature, and time at temperature, being key factors.

The risk of HIC is minimal as long as proven procedures are followed and the welding operation is properly controlled. The testing program presented here is an attempt to show the use of hydrogen-bearing shielding gases does not introduce enough hydrogen into the weld or base metal to be detrimental.

The testing program was separated into three (3) specific parts: determination of hydrogen content, resulting weld mechanical properties, and inclusion content. For each of these, the welding parameters were held constant to minimize variability in the resulting welds. All welding was done using pulsed gas tungsten arc welding (GTAW-P) with hot wire (AC-energized) filler metal addition. Only the first part of this program will be reported here.

Hydrogen Content Testing:

The purpose of these tests was to measure the amount of diffusible and residual hydrogen remaining in the weld when using a hydrogen-bearing shielding gas. In addition to those welds made with the argon/hydrogen shielding gas, control welds were made (using the same welding parameters for tests #1 and #2) with argon only.

Knowing preheat and PWHT are always requirements of the welding procedure, the first series of tests was designed to simulate normal production welding. The weld coupons were preheated to 500° F [260° C], welded, and then subjected to PWHT for four (4) hours at 1,175° F [635° C]. Welds for Test #1 were made using 100% Ar shielding and those for Test #2 were made with the 98% Ar/2% H₂ shielding gas. Test #3 was conducted to measure the residual hydrogen in the welding wire in its as-received condition. Test #4 was conducted using the standard AWS A4.3 / ISO 3690 procedure for capturing and measuring diffusible hydrogen, which is considered to be the most stringent measure of entrapped hydrogen in weld metal and is the standard method for evaluation of hydrogen content in welding filler metals. All of these tests were conducted using the gas chromatograph method.

To better understand the test results reported here, it is important to realize there are two different types of hydrogen in weld metal. First, there is diffusible hydrogen, which is the hydrogen released from the weld metal over time. The rate of release is increased at higher temperatures. The other form of hydrogen is the non-diffusible or residual hydrogen. This form of hydrogen is not as mobile as diffusible hydrogen, so it becomes trapped, remaining in the solid weld metal, unable to escape.

Hydrogen Test Results:

When reviewing these results, it is important to note that the lowest (most stringent) hydrogen classification used by AWS to indicate the permissible amount of hydrogen is “H4”, which designates the amount of hydrogen as 4 ml/100 g. As described above, the first two (2) tests were welded using the same (production) welding conditions with the only difference between the two (2) being the shielding gas. Sample #1 was welded with argon, and Sample #2 was welded...
with the argon/hydrogen mixture. The table below shows the average of four (4) weld samples from each test group for the diffusible hydrogen and the average of three (3) weld samples for each residual hydrogen test group.

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<th>Hydrogen Determination</th>
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<tbody>
<tr>
<td>Test Number/Gas</td>
</tr>
<tr>
<td>#1 - Preheat &amp; PWHT – Ar</td>
</tr>
<tr>
<td>#2 - Preheat &amp; PWHT – Ar/H₂</td>
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These results are quite revealing. The first observation, the amount of diffusible and residual hydrogen, is virtually the same when comparing the welds made with argon shielding and those made with argon/hydrogen shielding. Of even greater importance is the magnitude of the diffusible hydrogen results. In both cases, the amount of diffusible hydrogen present is roughly six (6) times less than the 4 ml/100 g limit of the H4 designation.

The fact that the amount of hydrogen present in these samples is virtually the same leads one to ask about the source of the hydrogen. While the diffusible hydrogen amounts are close, the residual hydrogen amounts are virtually identical, leading one to suspect the wire itself as the source. In the manufacture of stainless steel and nickel alloy wires, the wire must be annealed as it moves through the sequential reducing dies since these materials tend to harden due to the cold working. In most filler metal manufacturing operations, this annealing is accomplished in a hydrogen atmosphere since the hydrogen inherently cleans the surface of the wire by removing oxides. As a result, there is a tendency for some hydrogen to be absorbed in the wire as a natural result of the annealing operations applied during the drawing process.

To confirm this theory, a third series of tests (Test #3) was conducted. In this series of tests, samples of the filler metal wire were melted to determine the amount of residual hydrogen present. As shown in the table below as Test #3, the average of the tests performed revealed the amount of residual hydrogen present in the wire was 8.57 ppm, which is roughly 2.5 times the amount of hydrogen present in the weld deposit. So during the welding process, when the wire was taken to a full melt in a protected atmosphere, some of the hydrogen present in the wire is actually removed. It must be noted that this was the hydrogen level in the heat of wire used for our testing. Amounts of hydrogen present in wires from other manufacturers may vary, but it is suspected those levels will also be higher than the resulting amounts of hydrogen in welds made with these wires. This test confirms the amount of hydrogen in the filler metal wire is greater than the amount that ends up in the weld deposit.

Test #4 was conducted using the standard procedure for measurement of diffusible hydrogen, as defined in AWS A4.3 and ISO 3690. This test was only applied to test welds made using argon/hydrogen shielding gas. The weld metal residual hydrogen level was also measured. The amounts of diffusible and residual hydrogen are reported in the table below as Test #4.

<table>
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<th>Hydrogen Determination</th>
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<tbody>
<tr>
<td>Test Number</td>
</tr>
<tr>
<td>#1 - Preheat &amp; PWHT – Ar</td>
</tr>
<tr>
<td>#2 - Preheat &amp; PWHT – Ar/H₂</td>
</tr>
<tr>
<td>#3 - NiCrMo-3 wire * 8.57 ppm</td>
</tr>
<tr>
<td>#4 - ISO 3690 – Ar/H₂</td>
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Since Test #4 was conducted using standardized procedures typically used for measurement of diffusible hydrogen in weld filler metals, the reported amount of diffusible hydrogen can be directly compared to other filler metals. As discussed above, the lowest classification of hydrogen content for filler metals is H4, which means there is less than 4 ml/100 g of diffusible hydrogen. Therefore, the results of Test #4 show the amount of diffusible hydrogen present was less than 25% of this classification limit. Compared to Test #2, the amounts of diffusible and residual hydrogen present in this test were about 40% and 15% higher, respectively. This clearly shows the methods used for determination of hydrogen content are more stringent because all of the hydrogen is retained in the sample. With these measures, the results from Tests #1 and #2 show that some of the hydrogen will naturally evolve.

With it now proven that the presence of hydrogen in the shielding gas does not significantly increase the amount of diffusible or residual hydrogen in the weld deposit, another question has been raised regarding the potential for
hydrogen remaining in the weld metal to diffuse into the carbon steel. To address this concern, one must consider the potential for hydrogen to migrate through the solid metal. It should be noted that nickel has a high affinity for hydrogen and the equilibrium path is easier for the hydrogen to diffuse thru the nickel alloy rather than into the HAZ of the high strength low allow steel. The mobility of hydrogen is based upon its solubility, which is dramatically reduced as the temperature of the steel decreases. At an elevated temperature 1,300° F [705° C] the solubility of hydrogen in carbon steel is about 8 ppm compared to less than 1 ppm at room temperature. As the temperature of the steel decreases, the pressure of the hydrogen in the steel increases due to the reduced solubility. To avoid HIC damage, any hydrogen introduced into the steel must be removed. This is where the time and temperature become important. Hydrogen will migrate out of the steel 250 to 400 times faster at 400° F [205° C] than at room temperature. Therefore, the use of preheat and allowing the weld zone to cool slowly gives the hydrogen more mobility and time to move out of the carbon steel and into the more soluble CRO weld metal. To reverse this process, significant amounts of time, temperature and pressure would be required.

**Summary and Conclusions:**

This study has primarily been conducted to dispel impressions that the use of a hydrogen-bearing shielding gas will cause hydrogen pickup in the weld and base metals. In the process of dispelling these fears, it shows there are numerous benefits associated with the addition of 2% hydrogen to the shielding gas.

Below are some of the points confirmed in this study:

- In a worst-case scenario with weld metal in the as-welded condition, diffusible hydrogen levels were one fourth the AWS H4 classification for filler metal hydrogen content.
- When using argon/hydrogen shielding gas for joining high strength steels, there is no evidence of any degradation of mechanical properties in the weld metal and heat-affected zones.
- The study shows argon/hydrogen shielding significantly reduces the inclusion content of the weld deposit.

The benefits of using hydrogen as a component of welding shielding gases have been well known for decades; however, these potential benefits have been quickly ignored due to the overriding concern for potential damage or even failures. It was with this in mind that this study was conducted. Years of experience had prompted the need to show that using argon/hydrogen shielding gases for applying CROs to high strength steels was indeed safe. When using argon/hydrogen shielding gas and normal low hydrogen practices, top quality welds can be produced with high productivity resulting in desirable mechanical properties and improved cleanliness.

This article only covered the test results showing the hydrogen content of welds made with an argon/hydrogen blend shielding gas. The study also included the effects of hydrogen on the mechanical properties and the effects on weld metal inclusions. For the full report covering all the details on test weld parameters, comparison of mechanical properties and weld metal inclusion comparisons, readers are encouraged go to the ARC Specialties web site ([https://arcspecialties.com/resources/white-papers/](https://arcspecialties.com/resources/white-papers/)) and download the complete report.