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Review of Hydrogen Induced Disbond Testing

Explosion Welding is an Excellent Choice for Resisting Hydrogen Induced Disbond of Clad Materials

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ABSTRACT

Clad materials are regularly used in corrosive, high temperature, high pressure process environments. When high partial pressures of hydrogen are also present the stakes are raised considerably. Clad disbonding becomes a valid concern when hydrogen charging conditions in combination with subsequent operations cause rapid cooling. The ability of clad material to resist disbonding is a key consideration when selecting appropriate materials of construction for critical process equipment. This paper reviews multi-year sampling test data of hydrogen induced disbonding comparing the three primary cladding techniques for these purposes. To build a foundation for the discussion, a brief examination of the American Society of Testing and Material (ASTM) G146-01 standard practice, is presented. The results will provide equipment designers and materials selection experts guidance on which cladding techniques are appropriate for the materials of construction in high stakes environments.

INTRODUCTION

Processes with high partial pressure of hydrogen, like the ones found throughout oil refineries, are regularly associated with high temperature and high pressure, corrosive applications. Hydrotreaters or hydrocrackers of varying operating specifications are the most common equipment in these instances. The temperature, pressure and service factors outlined above all contribute to selection of materials in the construction of vessels and heat exchangers. The typical result are designs with relatively thick walls of alloy steel (ASTM A387) clad with stabilized grades of austenitic stainless steel (ASTM 240 grade 321 or 347).

Designers recognize that for optimal equipment performance, the bond between the alloy steel backing plate and the corrosion resistance alloy cladder must be robust and reliable. Failure of the bond can cause problems with the vessel wall blistering or issues with the integrity of pressure vessel internals. To evaluate the propensity of clad material disbonding, ASTM has developed the standard practice designated as G146-01. This practice outlines test procedures and inspection criteria used to evaluate and rank the performance of clad material at certain process conditions.

A number of trials have been conducted by industry professionals to evaluate clad metal combinations and cladding techniques to the G146-01 practice or related test regimes. A select group of those tests are discussed here, specifically the testing that set the standard for the specimen used today. While some of the testing discussed here is not based on the ASTM standard, it is important to discuss those test results and evaluations for similar hydrogen induced disbonding.

Ultimately, a conclusion can be reached that explosion welded clad metal is a suitable, and in some cases, a preferred technique for producing clad plate for an aggressive service environment.

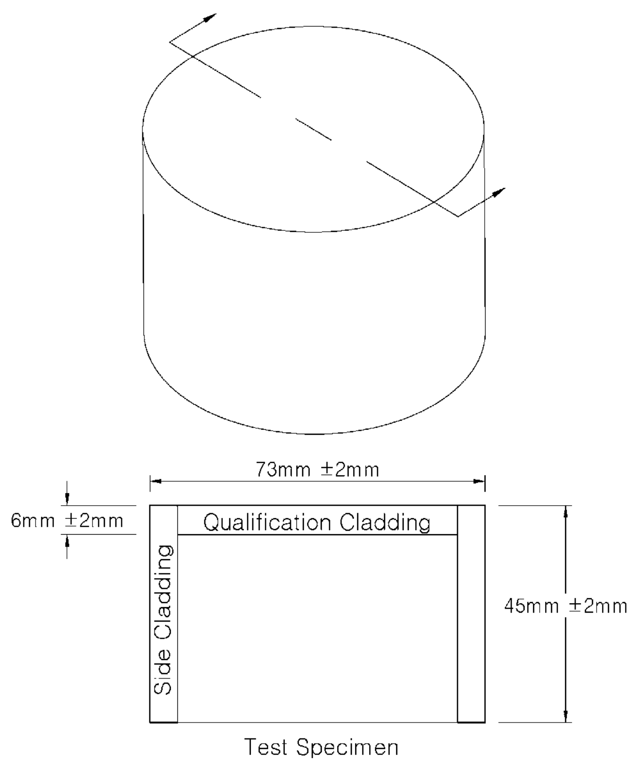
OVERVIEW OF ASTM G146-01, 2013

The ASTM G146-01 standard is used to evaluate bimetallic steel plate clad with stainless steel used in high pressure, high temperature gaseous hydrogen applications. Evaluating ASTM G146-01 allows for a comparison of data among different testing results. In this case, the evaluation is based on the susceptibility of different types of clad material, in different process conditions, to exhibit hydrogen induced disbonding. The standard allows for testing across a broad range of temperatures, pressures and cooling rates to demonstrate the response of the clad material in various environments.

The cooling rate used in testing is a key variable to be specified. Rates as high as 260°C/h are used to intentionally produce disbonded areas. Cooling rates proximate to 150°C/h are often invoked to mimic real world conditions. The speed of cooling can be used to simulate shutdown conditions of the equipment in critical environments.

The samples used in ASTM testing are configured as a short cylinder, with the cladding to be evaluated on one flat face, the other flat face left uncladded and the sides of the specimen covered in weld overlay. The purpose of the overlaid sides is to help simulate a response in the sample as though it were still part of a contiguous plate in service, limiting the pathways for hydrogen to exit from the sides of the sample. A representative test specimen is depicted in Figure 1. This test specimen was first introduced in *Review of Test Data and Published Papers*, a 1994 paper written by John Banker and Michael Cayard (Banker).

FIGURE 1: REPRODUCTION OF TEST SPECIMEN FROM ASTM G146-01 (ASTM)



A review of the ATSM G146-01 standard provides a complete understanding of the process, including test conditions, specimen preparation and procedures.

CHOICES FOR CLAD METAL

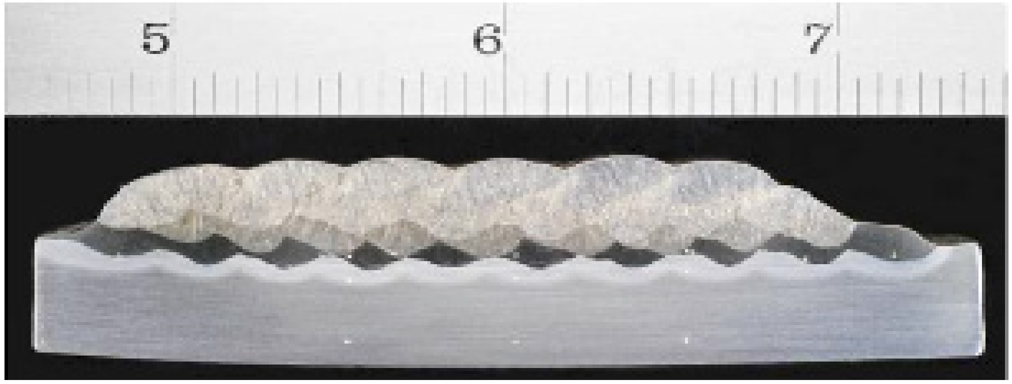
Clad material is the typical choice for high stakes environments and is an economical alternative to solid alloy steel or solid stainless steel. The corrosion resistant alloy is selected specifically for its performance in the process conditions of the equipment and the alloy steel backing metal is designed to contain the pressure at the operating temperature. Once the materials are chosen, a metallurgical bonding technique must be selected to join the two materials. There are three typical choices when metallurgically bonded clad metal is desired; hot roll bond, weld overlay and explosion welded clad material. All of these choices come with advantages and disadvantages that must be well understood before a selection is made. In some cases these techniques are interchangeable, however in critical environments like hydroprocessing equipment selecting the right clad is a critical variable. Table 1 reviews and highlights the differences between the three cladding techniques.

	Explosion Welding	**Hot Roll Bond**	**Weld Overlay**
Full Chemistry of Corrosion Resistant Alloy	Yes	Yes	No
Unaltered Corrosion Resistance	Yes	No	No
Easy to Inspect	Yes	Yes	No
Resists Hydrogen Induced Disbonding	Yes	No	Yes

TABLE 1: COMPARISON OF METALLURGICAL CLADDING TECHNIQUES FOR HYDROGEN SERVICE.

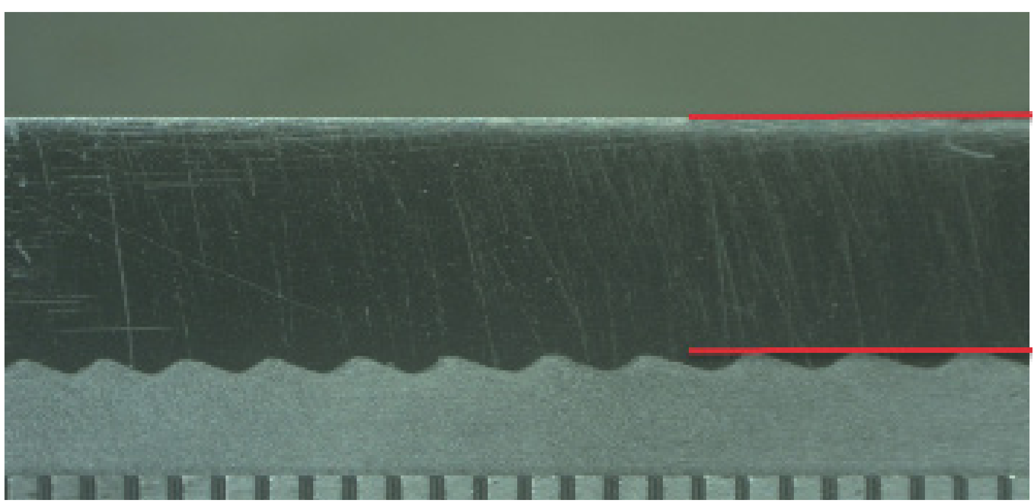
Roll bonded clad is produced when a steel mill heats the steel and corrosion resistant alloy together and rolls them as one package. The rolling, under high temperature and pressure, causes the two metals to clad together. It is generally accepted that a roll bond clad plate has the lowest bond shear strength of the three techniques described here. It is also understood that the resulting roll bonded clad plate, has a significant portion of the interface area containing the oxides that were present on the parent metals before cladding began. During rolling, these oxides are distributed broadly within the interface area of the clad (Xie). While the oxide areas are significant in aggregate, they are generally too small and too widely dispersed to be easily detectable during standard straight beam ultrasonic evaluation with a 25.4 mm transducer. The result is small undetected oxide pockets, and generally lower shear strength of the composite plate. It is possible the lower shear strength of roll bond and the behavior of hydrogen as it accumulates in these small oxide inclusions could lead to disbonded areas. This may cause hot roll bonded clad material to not be considered for hydrocarbon processing. Another issue with hot roll bonding is the temperatures used during rolling. The rolling temperature, and the time spent at this temperature, is notorious for sensitizing many different types of stainless steel or nickel alloys. While the stabilized grades of stainless steel used in this service are much less susceptible than some metals, it is a common concern of hot roll bond to degrade the materials in an unrecoverable way during bonding.

FIGURE 2: WELD OVERLAY WITH MULTIPLE PASSES IN AN ATTEMPT TO MEET CHEMISTRY REQUIREMENTS.



Weld overlay is a fusion deposition of corrosion resistant alloy onto a steel or alloy steel substrate. Usually, weld overlay is done in place, after the pressure vessel has been through many of the fabrication steps, but not always. There are many fusion techniques that qualify as 'weld overlay' and are used for depositing the corrosion resistant alloy onto the steel, but all involve melting the entirety of the cladding metal and some part of the base metal. The result is dilution of the two materials. It is frequently required that two or three passes of weld overlay are deposited depending on the technique (Figure 2). In many cases, dilution concerns necessitate the use of 'butter passes' and over alloying in an attempt to overcome the issues of dilution (Davis). Most weld overlay quality is measured with an analysis of the resulting chemistry, and the depth of that chemistry from the process surface. It is not unusual that a large degree of dilution is considered acceptable in the final product, and the effective thickness (the thickness where the chemistry is considered 'good enough', even if diluted to some degree) is typically less than the thickness of the clad material deposited by either hot roll bonding or explosion welding. There are also issues with the corrosion resistant alloy being laid as a cast structure as compared to a wrought structure. In addition, the inspectability of weld overlay is significantly hindered by a rough finished surface. Despite some of its challenges, weld overlay is the best method for cladding forged rings, used frequently in very heavy wall construction. It also is required to complete the joints between clad plates produced by other methods. The net effect is that while weld overlay is not ideal, it is a necessary process to understand and control if one is designing equipment for hot, high pressure, corrosive hydrogen environments.

FIGURE 3: EXPLOSION WELDED CLAD MATERIAL, DEMONSTRATING FULL THICKNESS CHEMISTRY.



Explosion welding is another alternative for making clad metal for hydrogen applications. Explosion welding has established itself over a 50 year history of the technology, as a high quality, reliable cladding technique for a variety of metals and service environments. There are a number of explosion cladded metal providers around the world. It is important to note, the specialized technique required for explosion welding and the capability of the clad material producer, are not always equally matched. Like roll bond and weld overlay, explosion welding has notable characteristics. Explosion welding is typically characterized by a wavy bond interface and an unaltered corrosion resistance of the cladding layer (Figure 3). Within these waves, small pockets of oxide or melted materials may become trapped. It is intuitive to consider these to be possible initiation points for hydrogen disbond – just like oxides left with roll bonded clad metal. The difference is the very high shear strength that can be achieved by certain explosion welding companies (Blakely). The tenacious nature of the bond resists the most aggressive hydrogen charging scenarios and all but the most aggressive cooling rates. The performance of explosion welded clad material as it relates to hydrogen disbonding is on par with fusion welded overlay deposits, but is superior in terms of inspectability and corrosion resistance.

REVIEW OF TEST DATA AND PUBLISHED PAPERS

BANKER AND CAYARD

In 1994, John Banker and Michael Cayard published an evaluation of stainless steel explosion clad to chrome molybdenum steel for high temperature, high pressure hydrogen service (Banker). The paper focused on the use of specimens that had intentional areas of disbond to observe if those areas would grow. The paper also explored two different specimen configurations; a rectangular block with 5 of the 6 faces left as open paths for hydrogen exit upon cooling and a cylindrical puck with weld overlay on the cylinder sides to more closely simulate the restricted exit paths available to hydrogen in a complete vessel.

The process conditions explored in the paper are best described as 'typical'. While the paper recommended as a finding that testing under more severe service conditions might be advisable, the tests that were run were expected to cover the process conditions typically seen in industry at the time. Specific details on charging conditions and cooling rates can be found in the publication.

The result of the study was conclusive. The explosion welded clad material performed without any issues. The sample that had been prepared without disbond did not demonstrate any disbond after testing and the sample with an intentionally unbonded area did not see the areas grow. Additionally, the specimen design explored by the paper with a cylindrical geometry became the industry standard and is now referenced in the G146-01 standard itself. This cylindrical geometry is represented by a qualification cladding on one flat surface, and weld overlay around the side of the cylinder, with the alloy steel left exposed on the bottom.

PRESSOUYRE ET. AL.

In 1981, The Metallurgical Society of AIME published the proceedings of their third international conference on the effects of Hydrogen on Behavior of Metals conference. One of the papers discussed the behavior of cladded steels in hydrogen (Pressouyre). The paper focused on multiple different cladding options including hot roll bond, hot roll bond with a nickel interlayer, weld overlay cladding, explosion welding and explosion welding followed by subsequent hot rolling.

The testing in this paper was not according to the ASTM G146-01 practice, but still explored the charging and cooling of clad samples in an attempt to cause hydrogen induced disbonding in clad materials. Significant testing was undertaken to evaluate each cladding type.

The results of this evaluation were clear; "When exposed to hydrogen gas…the interface offering the highest resistance is that of explosion cladding".

IIW SPONSORED TESTING

In 2007, The International Institute of Welding sponsored a study, with the primary work done by The Welding Institute (Gittos). Like the Pressouyre paper, this testing was not according to ASTM G146-01, but still evaluated the propensity of certain clad systems to disbond in hydrogen environments. Multiple weld overlay cladding techniques were analyzed. The authors used chrome molybdenum backing steel with different weld overlay compositions and techniques.

Some of the conclusions of the paper are instructive. Deposition process, consumable type, welding parameters, and heat treatment cycles seemed to have a great importance related to the results of the disbond testing. That being explained, the end result was that all of the overlay processes were susceptible to disbonding, and no weld overlay technique was immune from disbonding in conditions that could be characterized as less than the most demanding.

NOBELCLAD SPONSORED TESTING

Over many years, NobelClad has conducted G146-01 testing on explosion welded clad metal. Usually the parameters associated with the testing were defined by an engineering company or final equipment user who required their specific process conditions be validated.

In one case, testing was performed specifically to produce intentional disbonding of clad material. Extremely high cooling rates of 260°C/h were employed in an attempt to drive the explosion welded clad metal and backing steel apart. While it was expected that one cycle would cause a disbond between the metals, five individual charge and cooling cycles were required before disbonding was observed.

George Young published a paper in *HydroCarbon Engineering* in 2005 that reviewed the details of many previous disbond tests done by NobelClad (previously called Dynamic Materials Corporation) with explosion welded clad metal (Young).

Explosion welding has always performed exemplary in these trials.

PREVELANCE OF EXPLOSION WELDED CLAD METAL

NobelClad has reviewed previous clad material order information to observe the prevalence of explosion welded clad metal in high temperature, high pressure hydrogen service. While the exact end use is rarely known by a cladding company, process conditions can be broadly assumed when specific metals are involved. Projects requiring chrome - molybdenum base metal of a certain wall thickness, and clad with 321 or 347 stainless steel gives a good indication that high temperature, high pressure hydrogen is expected to be present. While the observed data only includes metal from one production facility, a review of fifteen years of data is demonstrative. The clad for approximately 75 pressure vessels of this type, plus a significant number of related HEX, have been produced over many years. The related wall thickness ranged up to 6 inches and vessel diameters measured up to 15 feet. Generally, the exact process conditions are unknown.

End users who have purchased finished equipment fabricated from explosion welded clad plates are a broad collection of international refining companies. The list of involved engineering companies is almost as long, demonstrating wide use and acceptance of explosion welded clad for this process environment. Most of the equipment has been in service for over a decade, with no known failures or issues related to the clad being reported. It is important to note that this is just the experience of one factory of one explosion welding company. The actual adoption of explosion welding in this service is very significant.

FUTURE WORK: DIRECT ATTACHED AND DISBOND

There is ongoing work in the field of hydrogen disbonding of clad materials. While many operating conditions have been explored and evaluated for the propensity of clad to disbond in high partial pressure of hydrogen environments, there are some areas where some evaluation is still required. NobelClad has developed a strong database of examples where clad material that meets certain qualification requirements can be deemed suitable for direct attachment of internals (Blakely). This work of directly attaching pressure vessel internals to the clad surface, coupled with hydrogen disbond testing to validate the strength of the bond, is an unexplored area. There is current work ongoing to examine samples in ASTM G146-01 type environments which have been exposed to direct attachment welding. The expectation is that there will be no change in the resistance to disbonding and no changes are expected with the tenacity of the bond between the clad and backing material. To ensure this is the case, through bond zone tensile specimens will be taken of the direct attach specimens after hydrogen disbond evaluations are completed. This paper will be updated with the results of that testing, as it becomes available.

CONCLUSION

This paper has reviewed the ASTM Standard Practice G146-01 and discussed a number of tests that have been conducted following the guidelines established in the practice. A select group of those tests are discussed here, including the testing that set the standard for the test specimen in the practice. The paper has also discussed some related tests that did not conform to G146-01, but yielded interesting conclusions.

Ultimately, a conclusion can be reached that explosion welded clad metal is a suitable and even preferred technique for producing clad plate for the most aggressive service environments.

RESOURCES

ASTM Standard G146-01, 2001, "Standard Practice for Evaluation of Disbonding of Bi-Metallic Stainless Alloy/Steel Plate for Use in High Pressure, High Temperature Refinery Hydrogen Service," ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/C0033-03, www.astm.org.

Banker, John G, and Michael S Cayard. "Evaluation of Stainless Steel Explosion Clad for High Temperature, High Pressure Hydrogen Service." Hydrogen in Metals Conference, Oct. 1994.

Blakely, M., and Pauly, S. "Design Considerations in Attaching Pressure Vessel Internals: Welding to the Pressure Boundary or Welding to the Clad?" European Symposium on Pressure Equipment. ESOPE 2016, 14 Sept. 2016, Paris, France, Palais Des Congrès.

Davis, J.R (ed.). "Stainless Steel Cladding and Weld Overlays." ASM Specialty Handbook: Stainless Steels, Materials Park, 1994, pp. 107–119.

Gittos, M F, et al. "Disbonding of Austenitic Stainless Steel Cladding Following High Temperature Hydrogen Service (February 2007)." TWI, TWI, Feb. 2007, www.twi-global.com/technical-knowledge/published-papers/disbonding-of-austenitic-stainless-steel-cladding-following-high-temperature-hydrogen-service-february-2007/.

Pressouyre, G. M, et al. "Behavior of Cladded Steels in Hydrogen." Metallurgical Society of AIME, Hydrogen Effects in Metals Proceedings of the Third International Conference on Effect of Hydrogen on Behavior of Materials, Moran, Wyoming, August 26-31, 1980, Edited by Irving Melvin Bernstein and Anthony W. Thompson, 1981, pp. 803–810.

Xie, Guangming, et al. "Interface Characteristic and Properties of Stainless Steel/HSLA Steel Clad Plate by Vacuum Rolling Cladding." Materials Transactions, vol. 52, no. 8, 2011, pp. 1709–1712., doi:10.2320/matertrans.m2011127.

Young, George A. "Explosion Clad Works for Reactors." Hydrocarbon Engineering, Mar. 2005, pp. 109–110.

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