Causes of hydrogen embrittlement in the case of drawn-arc stud welding

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Keywords

Hydrogen content, hydrogen embrittlement, drawn-arc stud welding, ceramic ring, fracture position

1. Procedure

A determination of hydrogen content is based on hot extraction method using a Rosemount device of the SLV Duisburg (Figure 1) at a temperature of 1040°C. The induction furnace was charged with specimens consisting of approx. 50% base material and approx. 25 - 30 % stud material. The balance of 20 to 25 % is weld metal which is formed by the arc and is to be regarded as a mixture of stud and plate material.

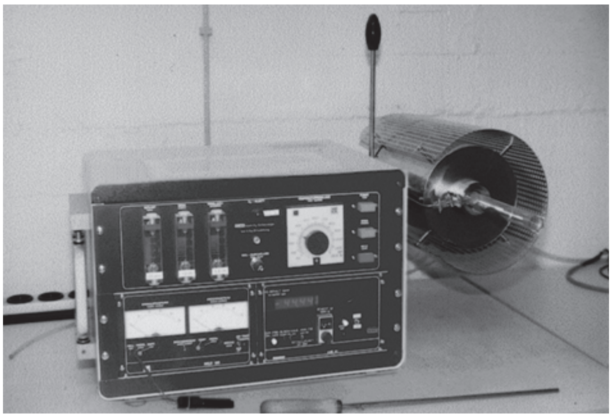


Figure 1. Rosemount device of SLV Duisburg for hydrogen determination according to the method of hot extraction at 1040°C. Using nitrogen as a carrier gas, in the induction furnace escaping hydrogen is fed into a thermal conductivity measurement cell under high temperature.

The investigated welding variants mainly refer to ceramic rings with different contents of humidity. This humidity was adjusted in a water bath, a climatic chamber and in an annealing furnace and/or a defined combination of furnace and climatic chamber to simulate various weather conditions. Reference welds were carried out with ceramic rings which were in delivery condition after storage in a cellar. In addition, plate materials S235, S355 and P460 are combined with stud materials S235, X5CrNi18 10, 19MnB4 and 8MnSi7. Then hydrogen contents are determined, depending on surface preparation: metallic bright, scaled, oil wetted and water wetted. Also a pre- and post-weld heat treatment of the materials is an interesting topic to be investigated.

After mechanical tests like bending and tensile tests, further investigations were carried out to determine fracture behavior using a SEM and to determine fracture position.

After knowledge of influencing factors, measures may be taken to avoid hydrogen embrittlement at drawn-arc stud welded joints.

2. Influence of a ceramic ring on hydrogen content of weld specimen

No significant influence of atmospheric fluctuations could be identified in a range of welding work at approx. 20°C using humid ceramic rings which were exposed to up to 94 % rel. humidity for 1, 2 or 4 days.

There is a graphic presentation of H_2 contents based on average value and dispersion around the mean of each welding variant with various ceramic ring preparations (stud diameter 22 mm). The results from cryogenic and non-cryogenic storage are summarized as individual values and do not significantly differ from each other. Mean values of individual rows are at an average of approx. 1 ppm hydrogen content, whereas a variant 'ceramic ring climate 40' deviates downwards with a H_2 content of 0,66 ppm, the variant 'ceramic ring climate 70' deviates upwards with a H_2 content of 1.33 ppm. A relevant influence of ceramic ring preparation cannot be identified.

The low influence of the ceramic ring can be taken from a comparison of stud welds with annealed ceramic rings (1050°C, 1 h) which were taken out of the furnace at approx. 150°C immediately before welding. Indeed there is a minor reduction of H_2 content at some test series. With other test series, the H_2 content increases when welding with annealed ceramic rings.

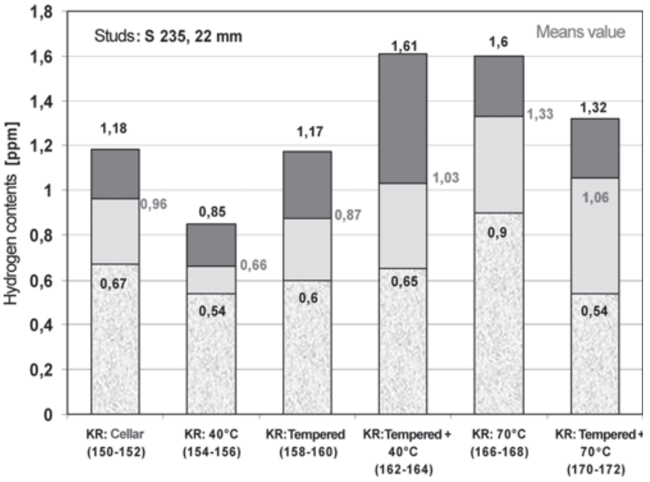
A noticeable increase of hydrogen content to values above 2 ppm up to the end of measurement scale could only be found in the case of storage the ceramic rings in water for several hours. In the case of a ceramic ring which was stored in water for 24 h, welding results were very faulty. In practice, such welds can easily be detected in combination with bending tests due to a heavily jagged collar.

The initial point of this project - a supposed high influence of the ceramic ring to a possibly hydrogen induced embrittlement tendency of drawn-arc stud welds - could not be proved based on the stud welds using prepared ceramic rings in a defined way in a climatic chamber.

3. Correlation between hydrogen contents of base materials and completed drawn-arc stud welds

To find out the influence of stud and plate materials, at first H_2 contents are determined prior to welding. In this way one can carry out tailored test series at various hydrogen containing materials. Base materials showed hydrogen levels of approx. 1 ppm (S235) and approx. 3.5 ppm (X5CrNi18 10).

Specimen with a layer of scale on plate surface showed an increased hydrogen level of 1.8 ppm, compared with sand blasted plates (1.2 ppm). A correlation between previously determined nominal hydrogen contents of materials and welded specimens proved to be contradictorily at some test series. E. g. weld specimens with a low hydrogen content at plate and stud (0.6 ppm) provided - as welded specimens - a hydrogen content of 2.7 ppm. The results became more plausible with a determination of H_2 contents which was hot-extracted with pieces of plates cut at the plate side (specimens were made smaller, original plate thickness 12 mm). It turned out that H_2 real values at the welding area deviate significantly from nominal values determined with the same sample plate previously, however, they correspond sufficiently with the contents of the specimen.

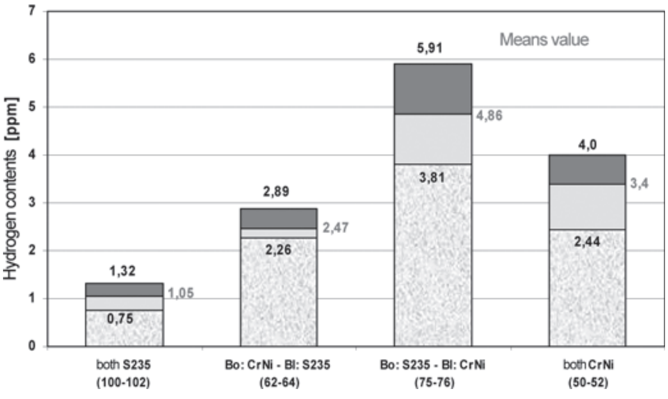


Conditions 40°C at 90% rel. humidity, 70°C at 75% rel. humidity, Annealing temperature 1050°C of the ceramic ring.

Figure 2. Influence of a graded preparation of ceramic rings compared with cellar storage and annealed ceramic ring (KR) to S235 of same kind material. Studs Ř 22 mm, set values (BMH30i): Current 1760 A, welding time 740 ms, lift 4,0 mm, projection 5,0 mm.

As a comparison, H_2 contents are displayed in Figure 3: material combinations 1) materials of the same kind S235, 2) stud CrNi - plate S235, 3) stud S235 - plate CrNi and 4) both CrNi for a stud diameter of 16 mm and cellar stored ceramic rings. Same kind CrNi stud welds have a H_2 content of 3.4 ppm, i. e. this value is three times higher than same kind S235 joints. Even higher H_2 contents presents the joint mild steel-CrNi plate with an average value of 4.86 ppm. In this case one must explain that the specimen proportions which are formed of base material of the stud (approx. 25 %), base material of the plate (approx. 50 %) and of weld metal (approx. 25 %) could only be estimated roughly. At some specimens with a flatter collar, the stud was cut for extraction hard above the welding zone. However, it is a matter of fact that the plate influence dominates the executed hydrogen determination.

The findings of inhomogenus hydrogen distribution inside a plate are proved by additional measurements and also measurements of stud materials. This is why the complexity of this hydrogen investigation reaches the next level. Of special interest are the second joining partners, the CrNi studs whose H_2 contents were in the range between 1 and 6 ppm within the same material lot. Welds with alloyed studs made of CrNi steel show higher hydrogen contents than welds made of mild steel.

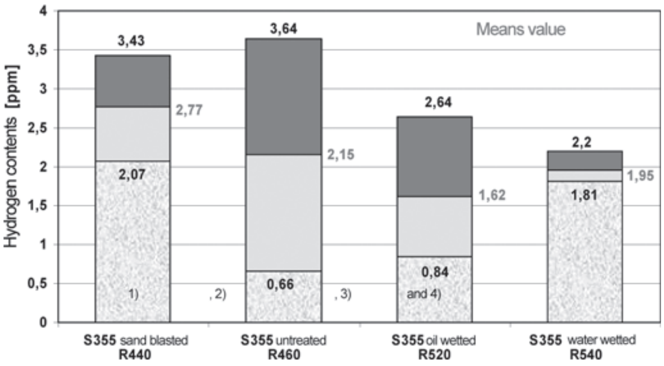


Big influence of CrNi steel becomes clear compared with S235.

Figure 3. Comparison of H_2 contents of different material combinations. Studs: Ř16 mm. Set values (BMH30i): Current 1230 A, welding time 550 ms with studs S235 and 480 ms at CrNi steel X5CrNi18 10, lift 3,0 mm, projection 4,0 mm. Specimen ageing and transport: cryogenic at -196°C in liquid nitrogen

4. Influence of plate surface

The present assumption regarding a main influencing factor 'base material' is supported by variations of plate surfaces. Figure 4 displays hydrogen contents of drawn-arc stud welds with studs of 16 mm diameter which were welded onto plates (S355) using the following surface variants 1) sand blasted, 2) untreated with scale, 3) oil wetted and 4) water wetted using a ceramic ring which was stored in a cellar. This test leads to the remarkable observation that welds on a metallic bright plate show the highest average H_2 value of 2.77 ppm. Welds on scaled plates show the widest scatter range. The procedural advantage which was recognized by



Sand blasting the plate proved to be unfavorable compared to other variants. Noticeably is the constancy of H_2 content at water wetted plate.

Figure 4. Influence of plate surfaces related to H_2 content at mild steel plate S355 with cellar stored ceramic rings. Studs: Ř 16 mm, S235. Set values (BMH30i): current 1230 A, welding time 550 ms, lift 3,0 mm, projection 4,0 mm, specimen ageing and transport: cryogenic at - 196°C in liquid nitrogen

former projects [2] when welding water and/or oil wetted plate surfaces also shows no negative effect on H_2 results in this case. It's just the opposite: In the case of water wetting as well as oil wetting, hydrogen will be provided to the arc. Nevertheless the arc manages to completely evaporate liquids on the surface at a certain extent. During the welding process, the formed chemical-physical reaction products can escape as metal vapor into the environment. Also the scale layer is not a problem to the arc in a welding period longer than 500 ms: surface contamination is eliminated by metal vapor emissions.

A H_2 content of the welding specimen is basically defined by individual H_2 contents around the welding area.

5. Bearing behaviour of investigated material combinations

Using stud materials S235, X5CrNi18 10 and 8MnSi7, generally heavy-duty drawn-arc stud welds can be produced meeting comprehensive quality requirements to DIN EN ISO 14555 /1/ regarding bending tests, figure 5, tensile tests and penetration shape. Only the material 19MnB4 as a material with the highest strength of approx. 850 MPa of this selection, showed bending angles of only 45° other materials achieved 60° as required. In tensile tests, fracture position is often located in the stud. Superficially, fracture occurred in the welding zone in some cases. Table 1 contains a survey on relevant test results and values of hydrogen contents of comparable welding specimens. As a result, there is no significant correlation between H_2 content of weld metal and fracture strength.

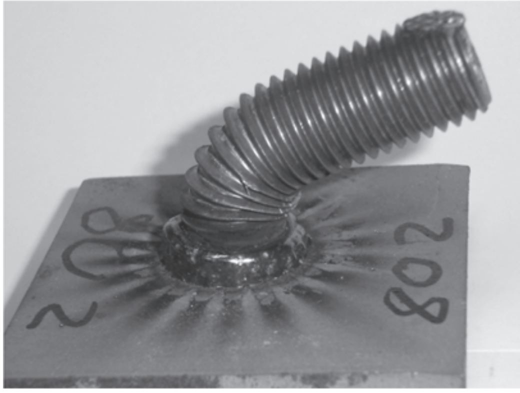


Figure 5. Bending test with M16 stud made of 8MnSi7, achieved bending angle: 60°. Set values (BMH30i): current 1230 A, welding time 450 ms, lift 2.5 mm, projection 3.5 mm

Table 1. Test results of drawn-arc stud welding at various material combinations as a survey. Stud: Ř 16 mm, ceramic ring: cellar storage, ageing for H_2: cryogenic

Material combination		Results				
Stud	Plate	Bending test	Tensile test [kN]	Fracture position	H_2 content Range [ppm]	H_2 content Mean value [ppm]
S235	S235	> 60°	65÷85	Plate		
S235	S355	> 60°	80÷100	Stud	1,20÷2,70	1,97
S235	P460	> 60°	100	Stud	0,75÷1,16	0,96
1.4301	S235	> 60°	110	Plate and WZ		
1.4301	S355	> 60°	100	Plate and WZ	1,78÷3,99	3,04
1.4301	P460	> 60°	90÷120	Plate and WZ	0,87÷0,88	0,88
19MnB4	S235	45°	100	Plate		
19MnB4	S355	45°	100÷110	WZ	0,94÷3,46	2,20
19MnB4	P460	45°	90÷35	Stud and WZ	0,60÷0,73	0,67
8MnSi7	S235	> 60°	120÷130	Stud		
8MnSi7	S355	> 60°	120÷130	Stud		
8MnSi7	P460	> 60°	100÷130	Stud	0,55÷1,54	1,05

Furthermore practice-relevant temporal effects of H_2 are investigated using tensile tests carried out with low-defect welds prompt after welding and after an ageing time of 8 weeks at room temperature. In this way, hydrogen has time enough to escape from the weld zone by diffusion. This time based behavior is determined using commonly used weld studs S235 and increasingly interesting weld studs made of 19MnB4. Results are shown in figure 6: fracture strength depending on stud material and ageing time for the variants tensile tests a) after 3 days and b) after 8 weeks after welding. In addition, the diagram contains further tensile tests results of welds with studs X5CrNi18 10 and 8MnSi7 from table 1. An influence of ageing time on achieved fracture forces due to a reduction of diffusible hydrogen content and consequently an influence on joint strength cannot be observed. In this way, the danger of unexpected failure of drawn-arc stud welds caused by hydrogen induced brittle fracture can be better assessed in practice.

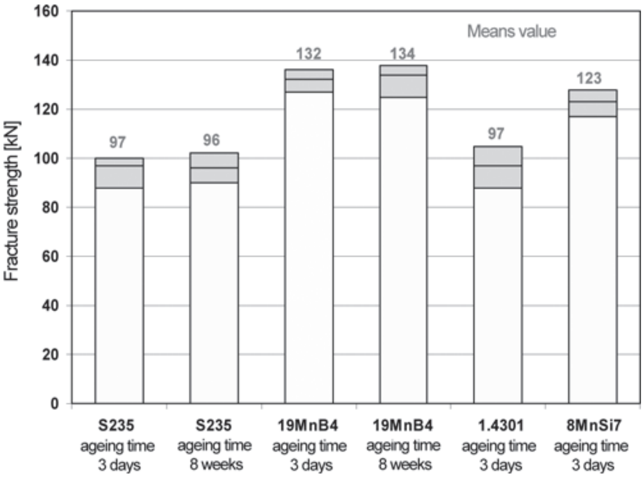
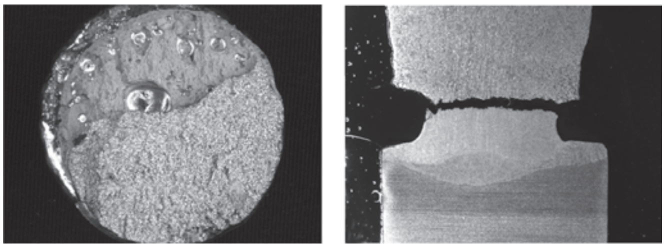


Figure 6. Fracture force depending on stud material with low-defect welds prompt after welding and after an ageing time of 8 weeks for studs S235 and 19MnB4. Studs: Ř 16 mm

6. Determination of fracture behavior

Based on SEM investigations, fracture faces were determined which are characterized by ductile fracture behavior (honeycomb fracture) as well as by brittle fracture behaviour. In many cases, a brittle fracture is characterized as transgranular hydrogen embrittlement and is marked by cleavage planes of different sizes [3, 4]. Normally both fracture types are to be found at a specimen with more or less ductile or brittle fracture areas. An example with separated fracture areas can be taken from figure 7a showing a brittle fracture area and a ductile fracture area of a weld with different materials, the stud was made of X5CrNi18 10. Evaluating the pores and cavities, one can find that the upper part of fracture area is located in the weld zone and/or at the transition to the weld zone. The lower part, separated from the upper part by a shear fracture edge, provides a homogenuous brittle fracture with fine glittering. This area corresponds with a fracture position in the plate or in the HAZ of the plate.


a) Upper area: Ductile fracture with pores in welding zone, lower area: brittle fracture.Stud X5CrNi18 10, plate: S235 sand blasted, brittle fracture amount 65%, fracture force: 118 kN

b) Fracture position in stud base material after notching H_2 content: 0,45 ppm, brittle fracture: 95 %. Stud S235, plate P460, both materials annealed (1050°C, 1 h) and sand blasted

Figure 7. Fracture behaviour and fracture position of various stud welded joints. Stud: Ř 16 mm, ceramic ring: cellar storage

A dependence of fracture type on hydrogen content of the weld specimens cannot be recognized. Consequently specimens show a brittle fracture behavior under both, high and low hydrogen contents of e. g. 0.6 ppm. A mostly ductile fracture behavior was achieved with specimens of low as well as with high hydrogen contents above 2 ppm.

7. Correlation between fracture behavior and fracture position

The uneven distribution of fracture types leads to an accurate determination of fracture locations using polished section investigations of composed stud and plate fragments. Fracture position in base material plate, HAZ plate, fusion zone, HAZ stud and base material stud are to be distinguished. This distinction can neither be carried out by bare eye using a stereo microscope nor by use of a SEM.

Results show a predominant brittle fracture behavior mostly at fracture positions out of the welded zone at the transition HAZ to stud base material or to plate. Fracture positions in the welded zone are mostly characterized by a ductile fracture behavior.

An example in figure 7b shows a notch fracture of a weld with a stud made of S235 whose fracture face is characterized by a homogenuously glittering notch. The share of brittle fracture is 95% with a fracture position at the transition of the obviously wide HAZ to stud base material, figure 7b. A low H_2 content of 0.45 ppm of this specimen results from use of annealed stud and plate (1050°C, approx. 1 h, Argon).

8. Summary

With this project a relatively low influence of ceramic rings on hydrogen content of drawn-arc stud welds was proved, provided a usual operation at atmospheric conditions. Only using long-term water exposed ceramic rings which picked-up high water quantities, weld quality was considerably affected in a negative way. Determined hydrogen contents between 0.5 and 4 ppm of stud weld specimens mainly correlate with initial H_2 contents of base materials as main influencing factor. Especially at CrNi steels, wide deviations of plates characterize the H_2 content of the welds. A significant correlation between hydrogen content and fracture strength under tensile stress cannot be recognized. In the case the fracture position is in the weld zone, the weld metal hardly shows indications of hydrogen embrittlement and predominantly shows ductile fracture behavior. In contrast, cleavage fractures with indications of transgranular hydrogen embrittlement were found with fracture position in base material and/or HAZ of stud and plate, even with low hydrogen contents of comparison specimens. During this short-time welding process, hydrogen can only be absorbed by weld metal at a relatively low extent. Humidity evaporating in the arc plasma, provided e. g. by a ceramic ring, scale layer or by water or oil wetted surface mainly escapes in welding vicinity.

Creep resistance of drawn-arc stud welds is guaranteed. In the framework of these investigations, tests with pre-tensioned drawn-arc stud welds with maximum recommended torque to DVS-Merkblatt 0904 /5/ did not show failures within 4 months. Bearing behavior of drawn-arc stud welds under static load is consequently safe. There is no need to expect hydrogen induced fractures in practice.

Even if further results cannot be implemented by users, they should observe the notes on quality assurance of Merkblatt DVS 0904 /5/ and DIN EN ISO 14555 /1/ carefully. A good weld execution compensates best the weld metal hydrogen concentrations found in the HAZ.

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