EVALUATION OF HOT CRACKING SUSCEPTIBILITY OF NICKEL-BASED ALLOYS BY THE PVR TEST

C. Fink, D. Keil and M. Zinke

ABSTRACT

Due to their good corrosion resistance in high-temperature and wet corrosive environments, nickel-based alloys are widely used as construction materials in the chemical industry, as well as in offshore applications and other energy and environmental technologies. Their outstanding corrosion performance, however, is often accompanied by a limited weldability due to a high hot cracking sensitivity. This paper presents a comparative overview of the hot cracking susceptibility of iron and nickel-based alloys type 1.4958 (alloy 800 H), 2.4663 (alloy 617), 2.4816 (alloy 600 H), 2.4856 (alloy 625) and 2.4605 (alloy 59). Hot cracking tests are performed by PVR test (deformation crack test), using GTA-welded externally loaded specimens to rank the hot cracking sensitivity of the base metals. In order to gain further knowledge regarding formation and propagation of the hot cracks, optical microscopy and EDX-analyses were performed. In addition to a ranking of materials and processes, interim results regarding the crack types and the metallurgical causes of cracking are discussed.

IIW-Thesaurus keywords: Fractography; Hot cracking; Nickel alloys; Weldability tests.

1 Introduction

Welding nickel-based alloys [1] and highly nickel-alloyed steels [2] is often regarded as problematic due to their sensitivity to hot cracking in the weld metal and the heat-affected zone (HAZ) of the base material. According to DIN EN ISO 5817:2007, cracks, whether hot or cold cracks, are therefore undesirable in arc welded joints, even at the lowest quality level, and generally represent the most dangerous weld imperfection in dynamically stressed components [3]. It is also almost impossible to detect micro cracks in weld seams using the established methods for non-destructive testing and they, thus, only become visible either as a result of their stress concentration after several years [2] or – more or less by chance – in the metallographic examination of work samples.

Due to their limited weldability, pertinent guidelines and standards exist for the welding of fully austenitic Ni-based alloys which, for example, limit the energy input per unit length or heat input and the interpass temperatures or stipulate the use of the string bead technique. However, despite complying with the specified energy input per unit length, hot cracks repeatedly appear in the weld seams of nickel-based alloys under certain structural conditions caused by the component, even as a result of established welding processes, such as the economical pulsed GMA welding. However, since their specific properties mean that there are often very few possible alternatives, knowledge about the hot cracking sensitivity of the materials to be joined, the resulting weld metal and the effect of the welding process on the material is essential.

DIN EN ISO 17641-1:2004 defines hot cracks as *"material separations occurring at high temperatures along the grain boundaries (dendrite boundaries), when the level of strain and the strain rate exceed a certain level."* In addition to the definition provided in the standard, the specialist literature also describes hot cracks as brittle separations in the weld metal and the base metal HAZ which may occur in the solidification range during and following welding [4-7].

When analysing hot cracking, a distinction is made between the origin and type. German Research Association on Welding and Allied Processes (DVS) technical bulletin 1004-1:1996 differentiates between the following three types: solidification cracks (SC), liquation cracks (LC) and ductility-dip cracks (DDC). Hemsworth *et al.* [8] also classify the three types of hot cracks into two main types which occur at different temperature ranges (Figure 1). Type 1 cracks cover segregation cracking and refer to the type of cracking where intergranular liquid films are present. This includes solidification cracks and liquation cracks. Type 2 covers ductility-dip cracking, where grain boundaries are free from liquid films.

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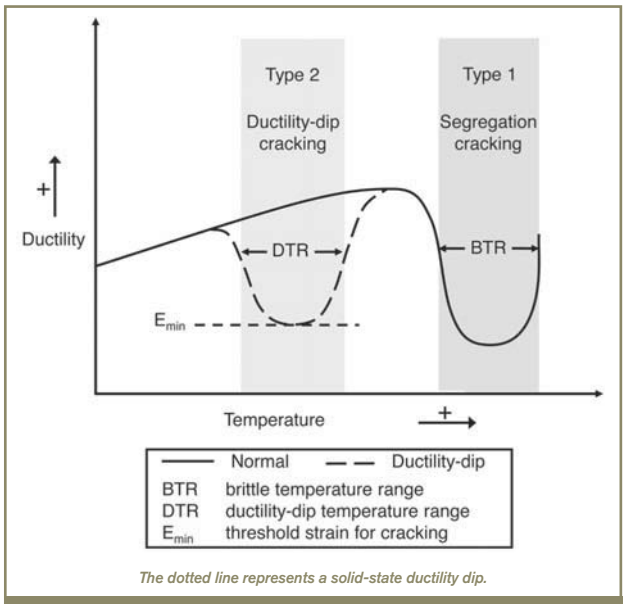


Figure 1 – Schematic illustration of ductility as a function of temperature [9, 10]

Solidification cracks (SC) form in the weld metal during the terminal stages of solidification when a liquid film is distributed along solidification grain boundaries and interdendritic regions and the shrinkage strains across these boundaries cannot be accommodated [11]. They generally stretch up to the surface of the weld metal and are often recognizable using a magnifying glass, or sometimes even the naked eye (centreline cracks, crater cracks). It is therefore possible to use non-destructive testing methods such as dye penetrant testing (PT).

Liquation cracks (LC) occur in the heat-affected zone (HAZ) of the base metal during the heating and cooling cycles of the welding process. Liquation cracks may also form in the weld metal of reheated multipass welds due to the repeated thermal effects of subsequent beads. Liquation cracking in the HAZ is often adjacent to the fusion line and to some extent runs over the fusion boundary into the weld pool. The appearance of liquation cracks is always associated with the occurrence of liquid phases, which provide weak paths for grain boundary separation under the welding stresses. There are various reasons why such phases occur. They may form as a result of, among other reasons, segregation of alloying elements, low-melting eutectics or constitutional liquation due to precipitation at grain boundaries [12].

Ductility-dip cracks (DDC) are a solid-state phenomenon, which forms during welding by a precipitous drop in ductility as a result of high temperatures in primary weld metal, base metal HAZ or reheated weld metal away from the fusion line. These intergranular separations solidify immediately after welding occurs. However, the grain boundaries of this type of crack do not fuse. Ductility-dip cracks tend to be a particular form of hot cracking, although there is a wide terminology for ductility-dip cracking in the welding literature [11]. Mechanistically DDC are very different to solidification and liquation cracks [13-15]. Ductility-dip cracking occurs following grain boundary sliding (GBS) around the recrystallization temperature [16]. Larger grain materials tend to be more susceptible to ductility-dip cracking than fine grain materials [17], which suggests that weld metals and cast alloys are more susceptible than wrought alloys. According to DVS technical bulletin 1004-1:1996, ductility-dip cracks may also be classed separately from reheat cracks, which only occur due to relaxation as a result of post-weld heat treatment. The Hemsworth *et al.* [8] definition of ductility-dip cracking however is not specific enough and still includes such forms of cracking like reheat cracking, stress-relief cracking and strain-age cracking [11].

The specialist literature contains a great deal on the phenomenology of hot crack formation although it is mainly based on simplified models, due to the extreme complexity of the phenomenon. Details on the mechanisms of hot cracking are not provided here but may be found in the literature, e.g. [4, 11].

2 Materials

The object of this article is a comparative investigation of the hot cracking resistance of industrially relevant iron and nickel-based alloys, based on the PVR test. The chemical composition of the test materials is listed in Table 1. The investigated materials are austenitic, highly nickel-alloyed metals often used as construction materials in high-temperature or wet corrosion procedures in the chemical processing industry.

All test materials have a fully-austenitic structure. Alloy 625 is in a soft annealed state, while all the other test materials are solution annealed. Alloy 600 H and alloy 800 H

Table 1 – Chemical composition of base metals (test certificates) [wt. %]

Alloy	Mat. no.	Ni	Cr	Fe	C	Mn	Si	Mo	Co	Al	Ti	P	S	Cu	Other
800H	1.4958	30.40	20.50	Bal.	0.07	0.70	0.46	-	0.10	0.28	0.32	0.010	0.002	0.06	Nb: 0.01
617	2.4663	Bal.	22.19	1.20	0.06	0.05	0.13	8.66	11.6	1.02	0.43	0.002	< 0.002	0.11	B: 0.002
600H	2.4816	Bal.	16.40	8.20	0.07	0.21	0.33	-	0.10	0.20	0.30	0.008	0.002	0.02	B: 0.002
625	2.4856	Bal.	21.33	4.47	0.021	0.09	0.21	8.62	0.09	0.14	0.20	0.005	0.010	0.02	Nb: 3.32 Ta: 0.01
59	2.4605	Bal.	22.60	0.60	0.003	0.19	0.03	15.50	0.02	0.27		0.006	0.003	0.01	-

Table 2 – Grain size of base metals (ASTM E 112)

	Alloy 800H	Alloy 617	Alloy 600H	Alloy 625	Alloy 59
ASTM grain size number G	2.4	5.0	1.8	4.5	4.3

have a significantly coarser grain than the other base metals (Table 2). The extremely heterogeneous grain size of alloy 617 is also noticeable which is characterized by a particularly fine-grained structure in the areas around segregated carbide stringers and a significantly coarser grain structure in carbide-free areas.

3 Experimental

Hot cracking susceptibility is quantified using appropriate test methods, as classified and described in ISO/TR 17641-3:2004 and the national DVS technical bulletin 1004:1996. In addition, numerous other test procedures (well over 200) have been developed to study and quantify hot cracking susceptibility [18]. Hot cracking test procedures fall into two major groups; those with self-restrained specimens and those with externally loaded specimens. The PVR test (deformation crack test) belongs to the latter group and along with the MVT test (Modified Varestraint Transvarestraint test) and the hot tensile test, is one of the three externally loaded test methods listed in the ISO standard.

The PVR test is a highly significant, quantitative test method developed according to the hot cracking theory of Prokhorov [19] for determining the hot cracking resistance of filler metals [20]. In the PVR test, a flat tensile test is carried out simultaneously with a welding process at a linearly increasing speed with a maximum tension speed of v_{max} (Figure 2). The point on the PVR specimen where the initial hot crack occurs corresponds to the critical tension speed v_{cr}. This correlates directly with the critical deformation rate [%/°C] mentioned in the hot cracking theory of Prokhorov [19] and can therefore be used as a criterion for assessing hot cracking resistance.

The critical tension speed is calculated by the following equation:

$$v_{cr} = \frac{a * L_{1stHC}}{v_w}$$

where

v_{cr} = critical tension speed (cross-head speed),

a = acceleration of cross-head,

$L_{1st\,HC}$ = position of the first hot crack,

v_w = welding speed.

The PVR test may be used to test specimens of the base metal, the pure weld metal or weldments (joint welds, as well as deposition welds). The hot cracking test allows a variation of welding processes (GTA, GMA, MMA), the filler metal, the welding consumables (shielding gas, electrode coverings) and the welding parameters. The welds are produced as bead-on-plate welds or as deposit runs at constant, controlled welding conditions. The determined critical tension speed v_{cr} therefore quantifies the respective hot cracking susceptibility in relation to the assessed type of hot crack caused by a particular welding procedure on the test specimen. Variations in the welding process therefore determine the extent of testing. The advantages of the inspection process include the low test complexity, the excellent reproducibility of the test results and the good differentiation between the three types of hot cracking: solidification cracks (SC), liquation cracks (LC) and ductility-dip cracks (DDC). According to Farrar [21] the PVR test is currently a method which, in terms of reproducing quantitative results, is the most appropriate for meeting the requirements of future international standardization of hot cracking tests.

To achieve a quantitative and comparative statement on the hot cracking resistance of the investigated highly nickel-alloyed base metals, the PVR test was performed using the fully-mechanized GTA welding process without any filler metal (bead-on-plate welds). Due to the sheet thicknesses of the test materials, the PVR specimens had a uniform thickness of 5 mm. This deviates from the standard PVR specimen measurements specified in the aforementioned standard (thickness: 10 mm). Recent investigations on high manganese steels confirmed the applicability of the PVR test, even on thin sheet metals (thickness: 1.5 mm) [22]. The selected welding and test parameters have been specifically developed for the nickel-based materials. They are listed in Table 3 and remained constant for all test materials. A minimum of three PVR specimens was examined for each test material. The hot cracking resistance criterion used in the PVR test is the critical tension speed v_{cr} which is determined at the point at which the first hot crack occurs. The initial macro or micro crack on the PVR specimens was determined in both macroscopically using dye penetrant testing (PT) and microscopically using a stereo microscope

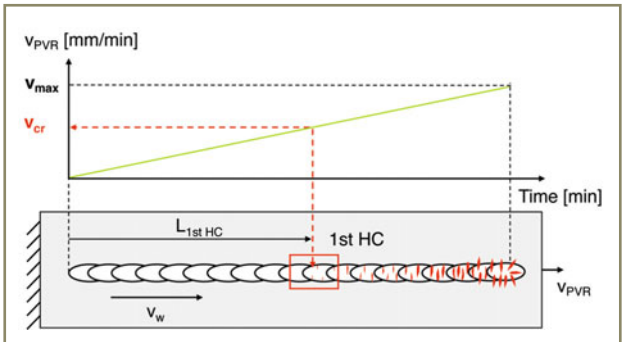


Figure 2 – PVR test – schematic illustration

Table 3 – Welding and test parameters for PVR test of base metals (GTA bead-on-plate welds)

I [A]	U [V]	v_w [cm/min]	E [kJ/cm]	v_{max} [mm/min]
180	12	20	6.5	45

at 25x magnification. Surface sections of selected PVR specimens were prepared to confirm the results of the tests conducted on the stereo microscope with respect to the type and position of the initial hot cracks.

4 Results and discussion

The results of the hot cracking investigations of the base metals in the PVR test using GTA bead-on-plate welds are presented in Figure 3. The type of initial hot crack is listed in addition to the critical tension speed v_{cr}. The greater the determined critical tension speed, the greater the resistance of the examined test materials to the occurrence of hot cracks. In a comparison of the base metals used in the PVR test, alloy 59 exhibited the greatest resistance to hot cracks, whereas alloy 600 H is characterized by the highest tendency towards hot cracking.

The individual test materials differ widely in the type of initial hot crack to occur in the PVR test (Figure 3). The first crack to occur in alloy 59 was always a liquation crack (LC) in the base metal HAZ adjacent to the fusion line. The alloy 625 PVR specimen on the other hand exhibited both solidification cracks (SC) in the fusion zone and liquation cracks near the fusion line, as initial hot cracks. Alloy 800 H only exhibited weld solidification cracking, as first type of cracking. The first cracking to occur in the PVR specimens of alloy 617 and alloy 600 H was ductility-dip cracking (DDC) in the base metal HAZ. While alloy 617 also exhibited liquation cracks near the fusion line, as initial hot cracks in addition to the ductility-dip cracks, only HAZ ductility-dip cracking was ever recorded as the first cracking occurring in alloy 600 H. Figure 4 illustrates solidification cracking in the fusion zone of the GTA bead-on-plate weld of alloy 800 H and the first liquation cracks in alloy 617, alloy 625 and alloy 59, which occurred in the partially melted zone adjacent to the fusion line.

Besides the type of initial hot cracking, all further types of crack on the PVR specimens were determined. Figure 5 shows the critical tension speed v_{cr} for all types of hot crack to occur in the PVR specimens of the different base metals.

With respect to the occurrence of liquation cracks in the PVR specimens, grain boundary melting was visible along the grain boundaries adjacent to the fusion line in the surface section of the test materials alloy 59, alloy 625 and alloy 617. In Figure 4 the local liquation of the grain boundaries in the partially-melted zone adjacent to the fusion line is clearly visible. The composition of these liquid grain boundary films was determined by electron probe microanalysis (EPMA) and energy dispersive X-ray-analysis (EDX). Results for alloy 625 indicate a significant enrichment of the alloying elements Nb, Si and Mo at the grain boundaries in the area near the fusion line, with a simultaneous depletion of Ni and Cr. For alloy 617 the examined liquid films along the grain boundaries were significantly high in Mo.

According to [11] HAZ liquation cracking in nickel-based alloys can occur by the segregation of solute and/or impurity elements to the grain boundaries. They can suppress the local melting temperature and form continuous liquid films along these boundaries. Liquation within the HAZ can also occur by constitutional liquation of carbides and intermetallic phases or by localized melting of residual eutectic constituents. [11] According to [23], precipitation-strengthened nickel-based alloys tend to form MC-type carbides and Laves phases which form in the weld pool during primary solidification and spread out along the grain boundaries as a liquid film. With regard to the solid-solution strengthened alloy 625, the literature [11] particularly mentions carbides in the form of NbC with respect to the formation of liquation cracking in the HAZ near the fusion line.

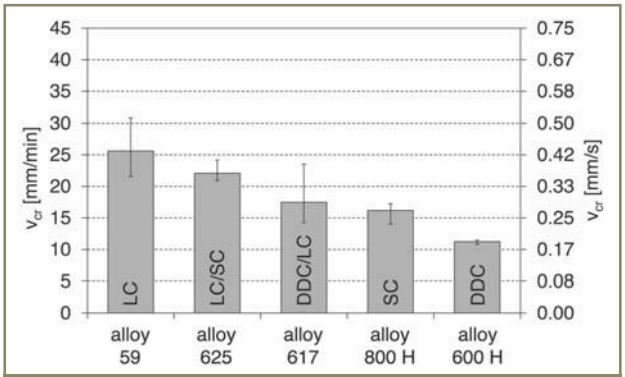


Figure 3 – Ranking of hot cracking resistance of base metals based on the PVR test (GTA bead-on-plate welds) and type of first hot crack

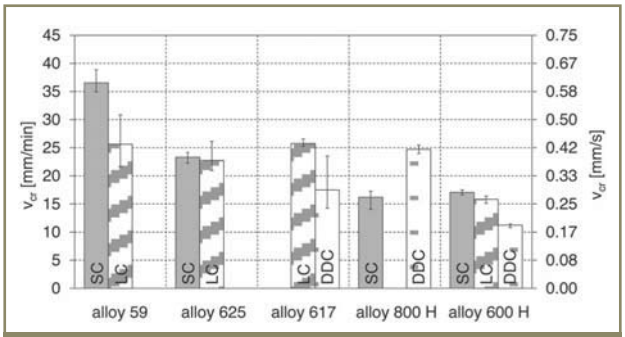
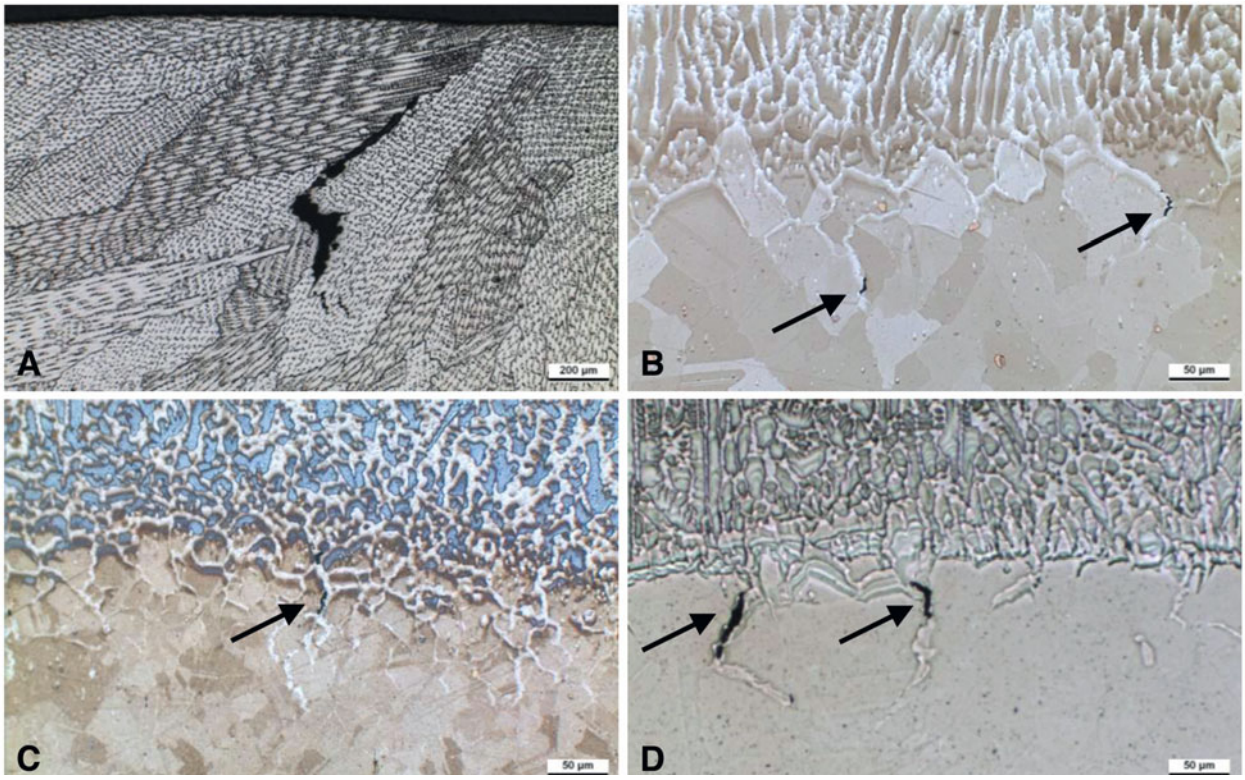


Figure 5 – Occurrence of all types of hot crack in the GTA-welded PVR specimens of the base metals



Note the difference in magnification.

Figure 4 – Solidification cracks in the fusion zone of alloy 800 H (A) and liquation cracks adjacent to the fusion line in alloy 617 (B), alloy 625 (C) and alloy 59 (D)

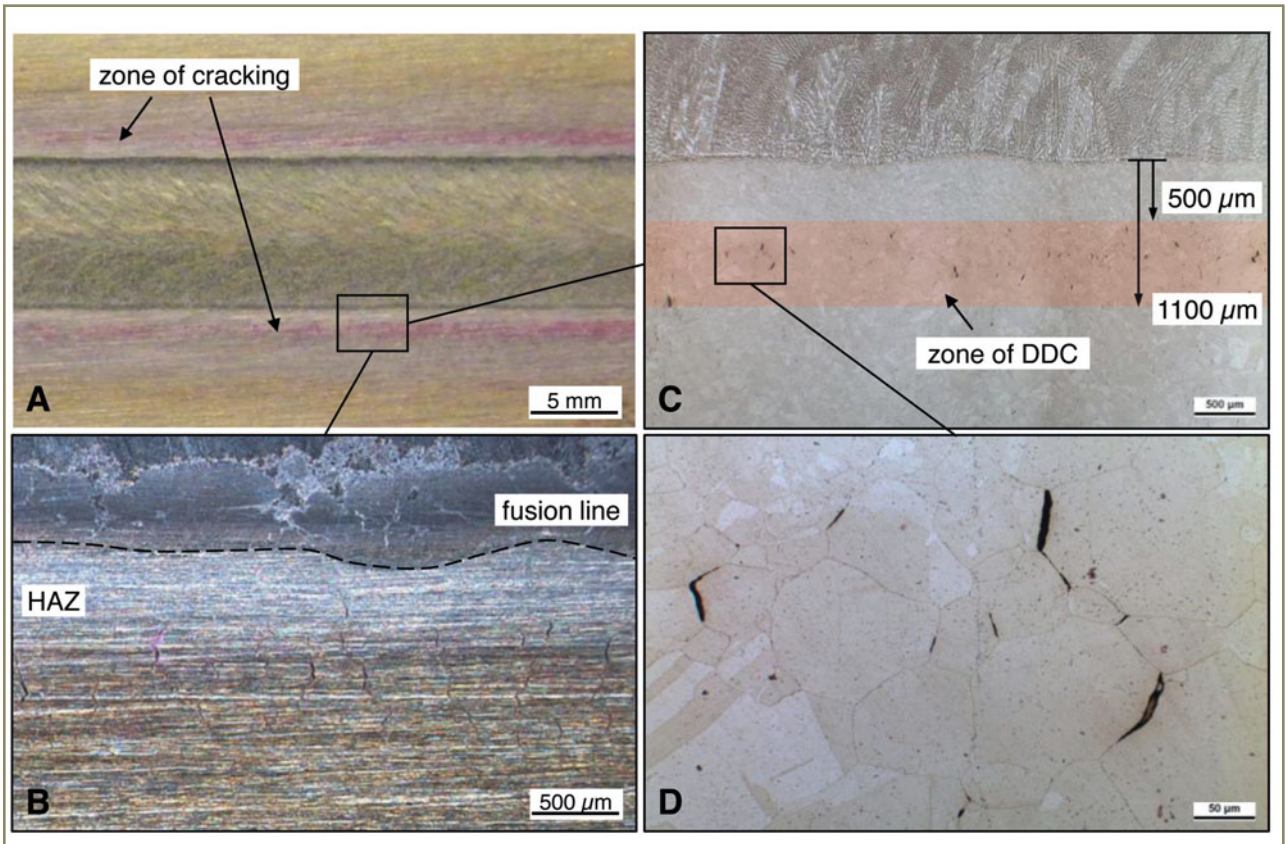


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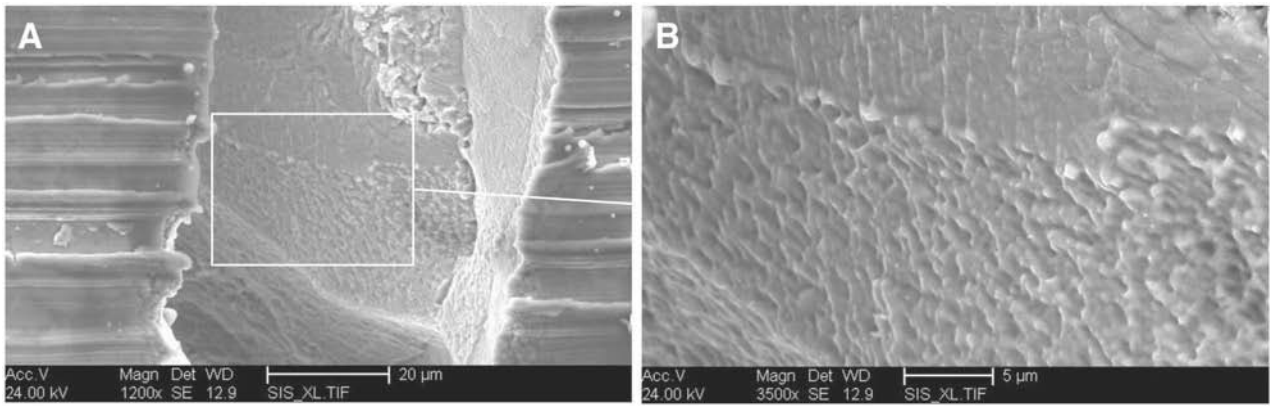
Figure 6 – HAZ ductility-dip cracking in alloy 617, dye penetrant testing (PT) (A), inset stereo micrograph (B) and photomicrographs (C) and (D).



Note the difference in magnification

Figure 7 – SEM micrographs of the surface topography of ductility-dip crack in the HAZ of alloy 617

One characteristic of the test materials alloy 617, alloy 600 H and alloy 800 H was the occurrence of ductility-dip cracking (DDC) during the PVR test. Even in the dye penetrant testing (PT), the ductility-dip cracks in the HAZ of these alloys were visible as a type of "seam" alongside the fusion line of the GTA bead-on-plate welds, Figure 6 A. The inset stereo micrograph in Figure 6 B shows a higher magnification of the cracked region and reveals that cracking occurred at some distance from the fusion line. In surface sections of alloy 617, it was apparent that DDC only formed in a narrow band of the HAZ (approximately 600 µm), which has experienced lower peak temperatures than the area adjacent to the fusion line, where the liquation cracks in alloy 617 occurred, Figure 6 C. The DDC are short (their length corresponds approximately to their grain diameter) and have clearly defined, smooth edges following the outlines of the grain boundaries. The surface section of alloy 600 H presented a similar image. A cross-section of the alloy 600 H PVR specimen also showed that the DDC had a depth roughly equal to the diameter of a grain. The hot cracks described were identified as ductility-dip cracks by their characteristic lengths and typical properties. Additionally SEM-microscopy of the fracture surface topography of the cracks was performed. The ductility-dip cracks in the HAZ of alloy 617 exhibited a ductile intergranular fracture surface (Figure 7), likewise described in [24, 25]. This is therefore different from liquation cracks in terms of their fracture surface topography.

5 Conclusions

The hot cracking susceptibility of five different iron and nickel-based alloys was investigated by the PVR test. The following conclusions can be drawn from this work:

1. For the industrially relevant iron and nickel-based metals tested, it was possible to determine a ranking in relation to their hot cracking resistance in the PVR test. Alloy 59 exhibited the greatest resistance to hot cracks, whereas alloy 600 H is characterized by the highest tendency towards hot cracking in the PVR test.
2. The test materials differ widely in the type of initial hot crack to occur in the PVR test. The first cracks in alloy 59 were liquation cracks in the base metal HAZ adjacent to the fusion line, whereas alloy 800 H exhibited weld solidification cracking as first type of cracking. Alloy 625 exhibited both solidification and liquation cracks as initial hot cracks. The first cracking to occur in alloy 617 and alloy 600 H was ductility-dip cracking in the base metal HAZ.
3. With respect to the occurrence of liquation cracks in the PVR specimens of alloy 59, alloy 625 and alloy 617 grain boundary melting was visible. EPMA and EDX results for alloy 625 indicate a significant enrichment of Nb, Si and Mo at the grain boundaries with a simultaneous depletion of Ni and Cr. For alloy 617 the examined liquid films along the grain boundaries were significantly high in Mo.
4. Alloy 617, alloy 600 H and alloy 800 H exhibited ductility-dip cracking in the HAZ alongside the fusion line of the GTA bead on plate welds. SEM-microscopy of the DDC in alloy 617 showed typical fracture surface topography for this type of cracking.

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