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Alloy UNS N08827: a New and Advanced Version of Alloy UNS N08825 with Better Corrosion and Hot Cracking Resistance

Julia Botinha
VDM Metals International GmbH
Kleffstrasse 23
58762 Altena, Germany

Martin Wolf
VDM Metals International GmbH
Kleffstrasse 23
58762 Altena, Germany

Bodo Gehrmann
VDM Metals International GmbH
Kleffstrasse 23
58762 Altena, Germany

Helena Alves
VDM Metals International GmbH
Kleffstrasse 23
58762 Altena, Germany

ABSTRACT

Alloy UNS[(1)] N08827, herein called Alloy 825 CTP, is a nickel-iron-chromium alloy with additions of molybdenum and copper. It was recently designed as a further development of the standard Alloy 825 (UNS N08825) for applications in the chemical process industry as well as in the oil and gas industry, where resistance to pitting and crevice corrosion in chloride environments is required.

Because of its high nickel content, alloy 825 CTP shows an outstanding resistance to stress corrosion cracking in aqueous and acidic chloride-containing solutions. Furthermore, as showed by previous tests, its increased molybdenum content of around 6% leads to an increased critical pitting temperature in comparison to standard alloy 825.

In combination with the ameliorated corrosion resistance of Alloy 825 CTP, in particular the absence of titanium in its chemical composition promotes a reduction of its susceptibility to hot cracking during fusion welding. The improvement of weldability is shown in the present study theoretically, through themodynamical modeling of the solidification process and confirmed hereafter experimentally, through Modified Varestraint Transvarestraint (MVT) hot cracking tests.

Plasma arc welding (PAW) trials simulating component weldments were additionally carried out to test the weldability of Alloy 825 CTP under nearly practical conditions. These weldments were evaluated by metallographic examinations and corrosion tests like ASTM[(2)] G28 A and ASTM G48 A, C and D.

Key words: Nickel Alloys, Alloy UNS N08825, Alloy UNS N08827, Alloy 825 CTP, Crevice corrosion, Pitting corrosion, weldability

(1) Unified Numbering System
(2) American Soscciety for Testing and Materials (ASTM), West Conshohocken, Pennsylvania, US

INTRODUCTION

The standard alloy UNS N08825 is a titanium-stabilized fully austenitic nickel-iron-chromium alloy with additions of copper and molybdenum[1]. This combination of elements grant to the alloy resistance to corrosion under both oxidizing and reducing conditions, what leads to a great variety of applications in the chemical industry, oil and gas producing and processing, maritime applications among others. Nevertheless, alloy UNS N08825 has only a limited resistance to chloride-induced localized corrosion, which is a common corrosion type in the oil and gas industry.[2]

In order to improve resistance to chloride-induced localized corrosion, the chemical composition of Alloy UNS N08827 (herein called Alloy 825 CTP) has been optimized by increasing the molybdenum content from around 3 wt.-% in the alloy UNS N08825 to around 6 wt.-% in the alloy 825 CTP. By increasing the molybdenum content, the PREN (Pitting Resistance Equivalent Number), given by formula (1), is increased from 33 to 42, giving the first indication of improved corrosion resistance. The improved corrosion resistance was confirmed experimentally by an increase of the Critical Pitting Temperature (CPT) from 30 °C (86 °F)[2] in alloy UNS N08825 to around 55 °C (131 °F)[3-5] in Alloy 825 CTP.

$$\text{PREN} = \%\,Cr + 3.3 \times \%\,Mo + 16 \times \%\,N \quad (1)$$

Additionally, Alloy UNS N08825 is well known to be highly prone to hot cracking during welding, which can occur in the Heat Affected Zone (HAZ) or in the weld metal itself, representing an intergranular mode of failure.

In order to evaluate the hot cracking susceptibility of a material, the solidification temperature range (solidus-liquidus difference value, ΔT) is usually used as a first assessment. Higher ΔT leads to residual liquid phase distributed along grain boundaries and interdendritic regions, leading to a loss of grain boundary ductility during cooling shrinkage and, consequently, hot cracking can take place.[6,7] Experimentally, the hot cracking susceptibility can be evaluated by means of Modified Varestraint-Transverestraint (MVT) Tests. MVT tests are used as an “universal” weldability test, designed to permit independent control of the welding parameters and mechanical loading, which allows the evaluation and comparison of materials by number of hot cracks and hot crack length on welded samples.

The elements titanium and niobium are usually added to alloys to stabilize the carbon and to prevent the precipitation of chromium carbides at the grain boundaries that may cause intergranular corrosion. On the other side, in the welding point of view, it is known that titanium has a potent influence on the material’s weldability,[7] but limited information regarding this aspect of titanium is available in the literature.

Shankar et al. verified a general high titanium enrichment along cracks and interdendritic regions of Ti-Stabilized austenitic stainless steels weldments. According to him, higher titanium contents result in increased segregation to the grain boundaries, what lead to the formation of more detrimental secondary phases in these regions that may later contribute to the formation of cracks.

Additionally, titanium and other partitioning elements are known to enrich the grain and subgrain boundaries during solidification. These elements, when partitioned to the boundaries area act to significantly depress the effective solidification temperature range at these sites.[8]

Another flaw of titanium as an alloying element is its unpredictable oxidation behavior during arc welding, which may lead to a depletion of interstitial titanium – thus reducing its stabilizing effect - in conjunction with the occurrence of titanium oxides in the weld metal.

Since the recently developed Alloy 825 CTP can achieve very low carbon contents through advanced secondary metallurgical production processes, titanium addition is not required with the purpose of controlling the corrosion susceptibility of the material by the precipitation of titanium carbides as described above. In this context, the production of a titanium-free material with good intergranular corrosion resistance is possible.

EXPERIMENTAL PROCEDURE

Material

Heats A, B and C are plate material from Alloy 825 CTP with 5 mm (0.08-in) and 16 mm (0.25-in) thickness. These heats were melted by an open melting process followed by continuous casting. After hot rolling, the plates were annealed in atmospheric industrial furnace. Heat D is plate material from Alloy UNS N08825 used in this study as a reference for standard material properties. **Table 1** shows the main chemical composition of all heats. Note that titanium is not intentionally added to Alloy 825 CTP.

Table 1
Main chemical composition of heats A, B and C of Alloy 825 CTP and heat D of Alloy UNS N08825 in wt.%

Heat	Alloy	Cr	Ni	Fe (balance)	Cu	Mo	Ti
A	Alloy 825 CTP	22.59	39.28	28.59	2.1	5.66	0.07
B	Alloy 825 CTP	22.28	39.19	29.02	2.05	5.88	0.06
C	Alloy 825 CTP	22.31	39.19	29.32	1.95	5.66	0.07
D	UNS N08825	22.53	38.37	31.48	1.86	3.27	0.81

Mechanical Testing / Metallography

Tensile testing and microstructural inspection were carried out to verify the material properties.

Microstructure

Microstructural investigations were performed on mechanically polished and chemically etched specimens. For etching, a pickling solution containing 100 mL H_2O, 100 mL HCl, and 10 mL HNO_3 was used. Evaluation of the microstructure was performed using light optical microscopy techniques. The grain sizes were measured according to DIN(3)/ISO 643-2013[9].

Tensile Testing

Tensile testing was conducted according to DIN/ISO 6892-1[10] at room temperature. Smooth specimens in the transversal direction were machined and tested at room temperature, 175 °C (347 °F), and 205 °C (401 °F).

Corrosion testing

The corrosion testing program was established to meet the requirements of NACE(4) MR0175 / ISO(5)15156-3[11] for qualification of Corrosion Resistant Alloys (CRAs) for H_2S-service, taking Sulfide

(3) German Institut for Standardization (DIN) e. V., Am DIN-Platz, Burggrafenstraße 6 10787 Berlin, Germany
(4) National Association of Corrosion Engineers (NACE) International, 15835 Park Ten Place, Houston, TX 77084
(5) International Organization for Standardization (ISO), 7 ch. De la Voie-Creuse, Case Postale 56, Geneva, Switzerland

Stress Cracking (SSC), Galvanically Induced Hydrogen Stress Cracking (GHSC) and Stress Corrosion Cracking (SCC) into account. All corrosion testing on solution annealed material according to the requirements of NACE MR0175 / ISO 15156-3 for qualification of CRAs was performed at the Salzgitter Mannesmann Research Institute. Corrosion testing of welded material was carried out at the laboratories of VDM Metals GmbH.

Pitting and crevice corrosion

Corrosion test according to ASTM G48[12] Method C was carried out to determine the critical pitting temperature (CTP) in acidified ferric chloride solution. ASTM G48 Method D was used to assess the critical crevice temperature (CCT) in the same solution.

Sulfide Stress Cracking (SSC) Resistance

SSC testing according to NACE TM0177[13] Method A was performed at 24 °C ± 3 °C (75 °F ± 5 °F) on triplicate smooth round specimens with a gauge diameter of 6.35 mm (0.25 inch) and a gauge length of 25.4 mm (1 inch). The testing was carried out in Solution A saturated with 100 kPa (14.5 psi) H_2S, resulting in an initial pH of 2.7; the final pH was measured and was less than 4.0. Stress level of 90 % AYS was applied by deflection of the proof ring. Test duration was 720 h (30 d).

Galvanically Induced Hydrogen Stress Cracking (GHSC) Resistance

GHSC testing was performed in accordance with the previously conditions for SSC testing. In addition, the tested specimens were electrically coupled by platinum wire to carbon steel, which was fully immersed in the test solution.

Stress Corrosion Cracking (SCC) Resistance

SCC testing was performed according to NACE TM0177 Method C (C-ring test). The material was tested under Level VI and Level VII test conditions as specified by NACE MR0175 / ISO 15156-3, Table E.1. SCC testing was conducted on triplicate C-ring specimens at 100 % of AYS at the test temperature. Four C-ring specimens were machined from each heat with an outer diameter (OD) of 40 mm (1.57 inch). For each set of four specimens, one C-ring was strain gauged to determine the necessary deflection corresponding to 100 % AYS at test temperature. The determined data was then used to deflect the tested triplicate set of specimens. SCC testing was carried out in autoclaves made of corrosion resistant material. After placing the specimens in the vessel, the test solution was added, so that all specimens were completely immersed in the liquid phase. Temperature was daily monitored. Separate specimens were used for 3 months testing at Level VI and 1 month testing at Level VII. After exposure to the corrosive environment, C-ring specimens were rinsed with distilled water and photographed. Examination for evidence of cracking was performed visually at 10x magnification.

Hot Cracking Susceptibility

Solidification Temperature Range

With the use of the software JMatPro[(6)], using the NiSuperalloy data base, solidus and liquidus temperatures at different cooling rates were calculated in order to get the solidification intervals with the aim of having a first assessment of the hot cracking susceptibility of Alloy 825 CTP. The same calculations were carried out for standard compositions of alloys UNS N08825 and UNS N06625, well known alloys in the market and literature, in terms of comparison.

[(6)] Trade name. Java-based Materials Properties.

MVT Tests

MVT tests were used to allow the evaluation of the hot cracking susceptibility of Alloy 825 CTP in comparison to samples of alloy UNS N08825. Samples were welded with an energy input per unit length of 7.5 kJ/cm and 14.5 kJ/cm and bending strains of 1%, 2 % and 4%.

The influence of the differences in the chemical composition of both tested heats C (Alloy 825 CTP) and D (UNS N08825) were evaluated according to ISO/TR 17641-3:2005[14]. After welding, the welded samples were analyzed in a stereo microscope according to ISO/TR 17641-3:2005 and the cracks were counted and measured to their lengths.

The results were then plotted in a total-crack-length versus strain diagram, where the materials are grouped into sectors that define their hot cracking tendency, as “vulnerable to crack”, “increasing tendency to cracking” and “hot cracking safe”.
The MVT tests were performed at the BAM[(7)].

Welding Trials

Plasma Arc Welding

For the assessment of the joint weldability and the corrosion resistance of weld joints, plasma arc weldings (PAW) were carried out using 5 mm (2-in) plates of Alloy 825 CTP with ground surface finish. As shielding -, plasma - and backing gas, pure argon (purity > 99.996%) was chosen. The PAW was used as autogenous process, which means that no filler material was added. Potential heat tints were removed with a stainless steel brush after welding. The welded plates were used for metallographic examinations and furthermore subjected to different corrosion tests in the as-weld condition as well as simulated PWHT condition.

Following welding parameters were applied:
Arc current = 220 A, arc voltage = 19.5 V, travel speed of the torch = 30 cm/min (11.8-in/min), plasma gas flow rate = 1 l/min, shielding gas flow rate = 20 l/min, working distance = 5 mm (0.2-in).

In order to assess the thermal stability of welded Alloy 825 CTP in the course of a critical heat treatment, welded samples of heat B were heat treated in atmospheric laboratory furnaces at 675 °C (1247 °F) for 8 hours of soaking time. The material was placed inside the furnace after the furnace reached the desired heat treatment temperature and the time started to be counted immediately. After 8 hours, the material was taken out of the furnace and left in air to cool. Details of sensitization heat treatment are summarized in **Table 2**.

Table 2
Heat treatment for sensitization of the tested materials (simulated PWHT)

Sensitization Temperature, °C (°F)	Holding time, h	Cooling media
675 (1247)	8	air

In order to check for the presence of hot cracking or precipitation of any detrimental phase as product of the welding process, optical metallography techniques were applied.

(7) Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87 12205 Berlin, Germany.

Corrosion Properties after Welding

In order to assess the corrosion resistance of the joint weld, and to be able to have them compared to the base material, samples of joint weld from heat B were tested for their pitting and crevice resistance. Testing was carried out according to ASTM G48 Method C to determine the critical pitting temperature (CTP), and according to ASTM G48 Method D, to determine the critical crevice temperature (CCT), both in acidified ferric chloride solution.

For all of the corrosion tests, two test repetitions were carried out.

RESULTS

Microstructure

Figure 1 shows the homogeneous microstructure of the three heats of Alloy 825 CTP, with average grain sizes within ASTM 5.5 and 6.5.

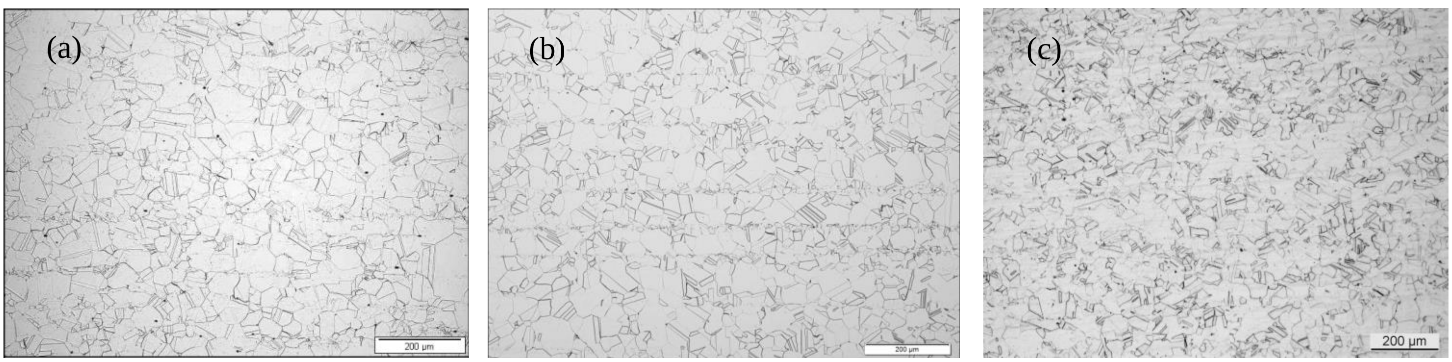

Figure 1: Microstructure of Alloy 825 CTP heat A (a), heat B (b) and heat C (c)

Mechanical testing

Tensile Testing

The tensile properties of heats A, B and C of Alloy 825 CTP are shown on **Table 3** and are the average of at least 3 tests. All the tensile properties are conforming to the requirements of ASTM B424-19[16] for UNS N08827 (Alloy 825 CTP), which are similar to the requirements for the UNS N08825.

Table 3
Tensile properties of heats A, B and C of Alloy 825 CTP

Heat	Yield strength		Tensile strength		Reduction of Area	Elongation
	MPa	ksi	MPa	ksi	%	%
A	320	46.4	667	96.7	80	50
B	303	43.9	680	98.6	75	48
C	316	45.8	672	97.5	77	49
ASTM B424	Min 241	Min 35	Min 586	Min 85	-	Min 30

Corrosion testing

Pitting and crevice corrosion

The CPT and CCT were determined by means of ASTM G48 test methods C and D on samples of Alloy 825 CTP (in solution annealed condition, annealed at 1010 °C, 1850 °F) coming from standard production route. These results are shown on **Table 4**. The high CPT and CCT values show an improvement in the chloride induced corrosion resistance driven by the augmentation of the molybdenum content to around 6 wt.-%. According to the literature[1], the CPT of UNS N08825 is 30 °C while the CCT is < 5 °C.

Table 4
Determined CPT and CCT on samples from heats A, B and C of Alloy 825 CTP in solution annealed condition

Material	CPT [°C]	CCT [°C]
Heat A	50	25
Heat B	55	15
Heat C	50	25
UNS N08825 (values from literature)	30	< 5

Sulfide Stress Cracking (SSC) Resistance

SSC resistance of Alloy 825 CTP was evaluated using uniaxial tensile tests according to NACE TM0177 Method A. No cracking or other defects were detected in any of the tested samples after a test duration of 30 days, so that all samples passed the tests.

Galvanically Induced Hydrogen Stress Cracking (GHSC) Resistance

GHSC testing was conducted using the same conditions and specimen geometry as for SSC testing, but with galvanic coupling to C-Steel. Because of the different potentials of the metals, a galvanic effect is established and may lead to accelerated cracking process of the tested CRA. However, after a test duration of 30 days, no cracking or any surface defects could be detected on the samples. All samples passed the tests.

Stress Corrosion Cracking (SCC) Resistance

SCC resistance was evaluated by using NACE TM0177 Method C. The tests were performed on C-ring specimens at environmental conditions corresponding to Level VI for 90 days and Level VII for 30 days. For each of the heats of Alloy 825 CTP, three C-Ring specimens were exposed to the test temperature after the application of a stress corresponding to 100 % of AYS. After test end, all tested specimens were cleaned and no evidence of cracks or other defects were observed.

All stress corrosion cracking test results are summarized on **Table 5**.

Table 5
Corrosion test environmental conditions for Alloy 825 CTP

Cracking mechanism	Specimen type	Specimens per heat	Duration / d	T / °C	H_2S /kPa	CO_2 / kPa	pH End	Cl^- / mg L^{-1}	S^0 / mg L^{-1}	Σ / % AYS	Galvanic coupling	Pass / Fail
SSC	*	3	30	24	100	-	2.8 / 2.9	Test solution A***	-	90	No	**P**
GHSC	*	3	30	24	100	-	3.6 / 4		-	90	Yes	**P**
SCC	**	3	90	175	3,500	3,500	-	139,000	-	100	No	**P**
	**	3	30	205	3,500	3,500	-	180,000	-	100	no	**P**

* acc. NACE TM0177 Method A (round bar tensile specimen)
** acc. NACE TM0177 Method C (C-ring specimen)
*** acc. NACE TM0177

Hot Cracking Susceptibility

Solidification Temperature Range

The calculated solidification intervals $\Delta(T_L - T_s)$ for different cooling rates were plotted in a diagram in order to get Alloy 825 CTP compared to alloys UNS N08825 and UNS N06625, since these both materials are well known in the literature and by the users. The curves are shown on the diagram of **Figure 2**.

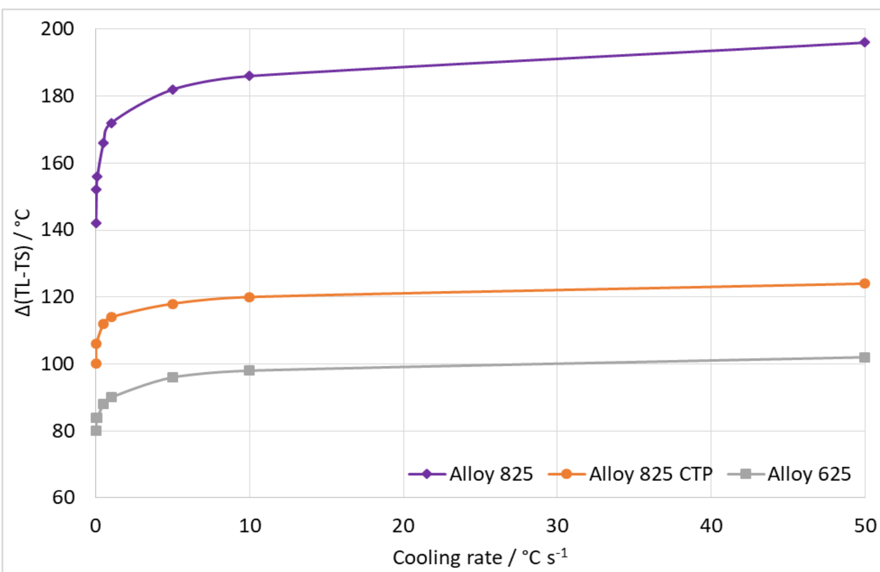

Figure 2: Calculated solidification intervals of Alloy 825 CTP (orange), UNS N08825 (purple) and UNS N06625 (grey)

The calculated solidification intervals of Alloy 825 CTP, when compared to the alloys UNS N08825 and N06625, give a first indication of good weldability of Alloy 825 CTP. The lower the solidification intervals, and therefore the difference between solidus and liquidus temperatures, the less the residual liquid phase present along grain boundaries and interdendritic regions during solidification. As the presence of liquid phase located in these regions and/or enrichment of detrimental phases on these regions can lead to a loss of grain boundary ductility during shrinkage, Alloy 825 CTP is expected to have better hot cracking resistance than UNS N08825. The curve of Alloy 825 CTP is much closer to the curve of UNS N06625, which is well known for its good resistance to hot cracking, making this nickel alloy one of the most used alloys for applications like weld overlaying.

<u>MVT Tests</u>

Samples of Heat C (Alloy 825 CTP) and heat D (UNS N08825) were investigated trough MVT tests to access their susceptibility to hot cracking. After welding, the total crack length of each sample was calculated and plotted on the diagram shown on **Figure 3**.

The results show that, as expected by the calculated solidification intervals, Alloy 825 CTP presents much less cracks after welding in comparison to UNS N08825. As it can be seen, the diagram of **Figure 3** can be divided in 3 sectors, each indicating a different behavior to hot cracking while/after welding: 1) hot crack safe, 2) increasing tendency to hot crack and 3) vulnerable to crack.

Alloy 825 CTP finds itself in the sector 1, which indicates that the material is hot crack safe, confirming the expectations given by the calculated solidification intervals, while UNS N08825 finds itself in sector 2, presenting increased tendency to crack.

These results confirm the theory of the depression of the solidus temperature by the segregation of titanium to the liquid phase, confirming that titanium may have a negative impact on the hot cracking susceptibility.

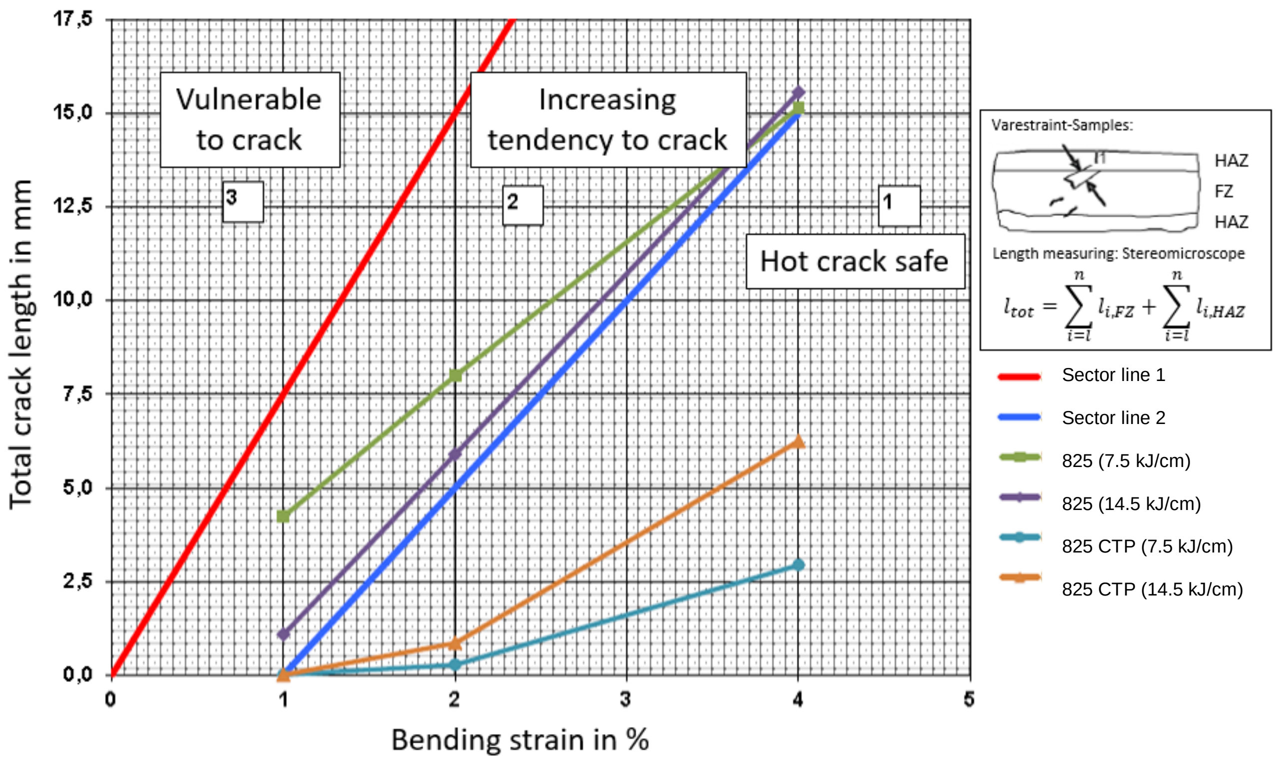

Figure 3: Influence of the bending strain in the total crack length of the investigated MVT samples of Alloy 825 CTP and UNS N08825

Joint Welding Trials

Plasma Arc Welding

The plasma arc weld (PAW) was carried out with common parameter setting. A metallography analysis of the weld joint was done using optical microscopy techniques and the cross-sectional view of the weld seam is shown on **Figure 4**. No nitrides, pores or cracks were found on the analyzed samples. Few to no precipitation in the grain boundaries and inside of the grains could be identified.

Figure 4: Transversal metallography view of weld seam

Corrosion Properties after Welding

The critical pitting and crevice corrosion temperatures determined through tests according to ASTM G48 Methods C and D are summarized on **Table 6**, where the average of two test repetitions is shown.

Table 6
Critical Pitting Temperature (CPT) and Critical Crevice Temperature (CCT) of welded joints of Alloy 825 CTP tested according to ASTM G48 Methods C and D

Heat	Condition	CPT [°C]	CCT [°C]
B	as welded	50	35
	welded + PWHT	50	30

The results show that Alloy 825 CTP weld joints do not present deteriorated corrosion resistance when compared to solution annealed non-welded material. Additionally, even after a sensitization heat treatment at 675 °C for 8 hours (PWHT), the material does not reduce its corrosion resistance, showing properties comparable to non-sensitized material.

CONCLUSIONS

These studies allowed the authors to take the following conclusions:

- Alloy 825 CTP with improved chemical composition has enhanced localized corrosion resistance compared to UNS N08825. Consequently, CPT and CCT obtained from corrosion tests were significantly higher.

- Advanced Alloy 825 CTP with higher Molybdenum content showed high resistance against environmental-assisted cracking (SSC, GHSC, SCC).

- Alloy 825 CTP presents weldability much better than UNS N08825 and is indicated for applications like welding overlays.

- Alloy 825 CTP weld joints do not present reduced corrosion resistance when compared to the base material. The CPT and CCT of welded joints and base material are similar.

- Weld joints of Alloy 825 CTP do not present sensitization behavior after being submitted to an intermediate temperature of 675 °C for 8 hours.

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