Overmatching Superalloy Consumable Inco-weld® 686CPT® Broadens its Applications to Include Welding Super Austenitic and Super Duplex Stainless Steels

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Abstract

The concept of using a more highly alloyed welding product to weld corrosion resistant alloys is not new. Early examples are 317LMN and 904L being welded with INCONEL® FM 625 and INCONEL WE 112. There are more than five well-known pit and crevice-corrosion resisting nickel alloys that benefit from being welded with the superalloy INCO-WELD® 686CPT®. In addition, there is a greater number of super austenitic and super duplex stainless steels, that may be used to their maximum capabilities when welded with the overmatching fully austenitic, INCO-WELD 686CPT products.

Typical applications and performance criteria include the fabrication of flue gas desulfurisation (FGD) equipment where extreme pitting and crevice corrosion environments are generated by scrubbing high concentrations of sulfur and halogens from coal-fired boilers. These environments often include chloride concentrations beyond 100,000 ppm and pH levels of less than 1. Super austenitic and super duplex stainless steels are continuing to find wide acceptance in handling aggressive fluids in pulp and paper applications. Bleach plant piping and vessels are often specified in stainless steels that need much better welds than matching composition can supply.

It is no small task to meet the weld requirements of nickel superalloys and the stainless super austenitic and duplex alloys, but INCO-WELD 686CPT meets the challenge.

The INCO-WELD welding products 686CPT may be deposited by a variety of processes including SMAW, GMAW, GTAW, PAW and SAW. Surfacing can also be undertaken with the electroslag and submerged arc processes. In the case of welding super austenitic and super duplex stainless steels, careful adherence to tightly prescribed welding procedures can be performed easily with INCO-WELD FM 686CPT because it is fully austenitic and produces optimum corrosion-resistance at all cooling rates from a wide range of welding parameters.

1. Introduction

Corrosion resistant materials such as alloys 625 (UNS N06625) and C-276 (UNS N10276) have provided excellent corrosion resistance for equipment in the oil and gas, chemical, petrochemical, pollution control and similar industries. New nickel-chromium-molybdenum alloys (INCONEL Alloy 686, HASTELLOY® C-2000 and alloy 59) have been developed, which provide increased resistance to corrosion beyond the capability of both stainless steels and existing nickel based alloys. The use of these new alloys can provide a number of benefits to operators including improved reliability, increased product life cycle, lower maintenance and repair costs and reduced down time.

The chemical compositions of several nickel-chromium-molybdenum (Ni-Cr-Mo) alloys are detailed in Table 1. Substantial additions of the major alloying elements provide a high level of general corrosion resistance whilst the combination of chromium and molybdenum improves resistance to both pitting and crevice corrosion. Additions of tungsten also provide improved resistance to localized corrosion.

1.1 Localized Corrosion Resistance

One of the most commonly observed failure mechanisms in stainless steels and Ni-Cr-Mo alloys is pitting or crevice corrosion. These forms of corrosive attack are less predictable than general corrosion and may limit the performance of the material. An estimate of the relative pitting resistance of alloys can be made using the Pitting Resistance Equivalent Number (PREN) which is calculated using the chemical composition of the alloy. The calculated PREN values for a range of Ni-Cr-Mo alloys are shown in Table 1. The standard PREN calculation used for stainless steels cannot be used for nickel alloys, with the equation which most closely represents the performance of Ni-Cr-Mo alloys in various media being:

PREN = % Cr + 1.5 (%Mo + %W + %Nb)

It has been demonstrated that alloys with the highest PREN values have the highest critical pitting and critical crevice corrosion temperatures when evaluated using standard test methods (ASTM G48 acidified $FeCl_3$ solution). Corrosion tests undertaken with Ni-Cr-Mo alloys in flowing sea water and elevated temperature stagnant sea water have also shown a correlation between the PREN value and the depth of crevice attack [1].

2. Selection of Welding Filler Metal

The selection of consumables for welding high nickel alloys (Ni-Cr-Mo), super duplex stainless steels and super austenitic stainless steels requires consideration of both the mechanical properties and the corrosive environments to be experienced by the welded joint. As deposited weld metal has a dendritic structure with micro segregation of alloying elements through the structure. It has been shown that autogeneous welds completed in 316L and 317L plate have a reduced resistance to pitting corrosion in oxidizing acid chloride environments compared to the parent plate [2]. The decreased pitting resistance of the weld metal is due to micro segregation of alloying elements within the dendrites. Electron microprobe measurements of the chromium and molybdenum contents showed that the centers of the austenitic dendrite were depleted in chromium and especially molybdenum. In contrast, the interdendritic regions which were the last to solidify, were enriched in molybdenum and chromium. Autogeneous welds in a 316L type stainless steel containing 2.8% Mo exhibited a variation in Mo content of between 1.8% and 5.7%. Preferential corrosion of the dendrite cores was observed in the regions which had suffered pitting attack.

In high nickel alloy weld deposits Mo and Nb and sometimes Cr are enriched at the dendrite boundaries in the interdendritic regions [3, 4]. During solidification of the weld metal these elements become enriched in the liquid phase. This segregation within the dendritic structure results in reduced corrosion resistance compared to the homogeneous alloy. Additionally, there is an enhanced risk of intermetallic phase precipitation due to the local enrichment of Mo, Cr and Nb in the interdendritic regions. Work undertaken with Ni-Cr-Mo alloy filler metals, that have additions of tungsten, has shown that tungsten is enriched in the core of the dendrite and is depleted in the interdenritic regions [4, 5]. As both molybdenum and tungsten provide increased resistance to localised corrosion the difference in segregation behaviour of tungsten acts to support that of molybdenum.

2.1 Over Alloyed Filler Metals

The concept of using an “over alloyed” filler metal has been developed in order to counteract the effects of segregation across the dendritic structure. The selection of an appropriate filler metal, which is over alloyed compared to the base metal, ensures that the concentrations of the major alloying elements across the segregated dentritic regions are sufficient to provide superior corrosion resistance to that of the base material. When such an approach to the selection of welding consumables is used it has been shown that the critical pitting temperature of the weld metal exceeds that of the base material [5]. In order to produce welds, in high alloy stainless steels, which exhibit corrosion resistance superior to that of the stainless steel base material it has proved necessary to select nickel alloy filler metals based on the Ni-Cr-Mo chemistry. Welds completed in 904L and 254SMo stainless steel using 625 and C-276 (Ni-Cr-Mo) alloy filler metals have been shown to exhibit pitting performance superior to that of the stainless steel base material [6].

The use of over-matching nickel alloy filler metals has also been employed for the welding of corrosion resistant nickel alloys used in the construction of flue gas desulphurisation (FGD) plant [7]. Pitting and crevice corrosion testing of both alloys and weld deposits has been undertaken in an oxidising chloride solution (11.9% H_2SO_4+1.3%HCl+1%$FeCl_3$+1%$CuCl_2$ for 72 hours at 103°C). It has been found that the composition of this solution is similar to the environment experienced in some areas of FGD plant [5]. Welds made in a number of alloy base materials including C-2000, alloy 59, C-22 and C-276 with matching filler metals have been found to pit severely whilst welds made with the overmatching filler metal INCO-WELD 686CPT (AWS A5.14 ERNiCrMo-14) showed no attack. The 686CPT alloy filler metal is based on the Ni-20%Cr-16%Mo chemistry with an addition of 4% W. In nickel alloys tungsten acts in a similar manner to that of molybdenum in providing resistance to pitting and crevice corrosion. Welds made in the same materials but with the over matching alloy 686CPT filler metal were found to be resistant to attack (Figure 1). Optimum pitting resistance is obtained when the over alloyed filler metal 686CPT is employed to complete the welds.

In a hot bypass duct in FGD plant in the Seminole Electric System severe corrosion of welds in C-276 base material completed with C-276 filler metal was observed [8]. The weld were repaired using the 686CPT alloy filler metal in order to provide an over alloyed weld deposit compared to the base material. Replacement welds made with the over matched 686CPT filler metal showed no corrosion whilst the C-276 plate corroded. The over alloyed 686CPT filler metal has been successfully used for joining C-276 plate in other FGD plant [9].

On the basis of the results of comparative pitting and crevice corrosion performance of a number of nickel alloy filler metals a Pitting Resistance Equivalent Number (PREN) has been proposed to predict the relative performance of the alloys [9].

PREN = %Cr-0.8%Cu+1.5 (%Mo + %W)

This formula provides equal weighting to the beneficial effects of molybdenum and tungsten in providing resistance to localized corrosive attack. The comparative resistance of weld deposits to attack in oxidizing chloride environments is reflected by this formula.

3. Welding of Super Austenitic Stainless Steels

The super austenitic range of stainless steels containing 6-7% Mo have a high resistance to pitting and crevice corrosion due to the high molybdenum and nitrogen contents (Table 2). The addition of nitrogen improves both the mechanical properties and pitting resistance of these alloys. The super austenitic stainless steels exhibit higher PREN values (PREN = %Cr + 3.3 (%Mo) + 16 (%N)) than the duplex grades of stainless steel. The super austenitic steels are used in environments where aqueous corrosion by chloride (and other halides) is a concern (e.g. sea water, paper and pulp bleaching, flue gas desulphurisation plant etc). However, super austenitic stainless steels can exhibit susceptibility to chloride ion stress corrosion cracking in hot chloride solutions. However, these steels offer resistance to crevice corrosion in sea water at elevated temperatures. Alloy 27-7Mo (UNS No. S31277) offers corrosion resistance superior to that of the 6%Mo super austenitic steels (UNS N08926, S31254) and in some instances has corrosion resistance approaching that of nickel based alloys such as 625 and C-276 [10].

The 6% Mo super austenitic stainless steels are welded with high nickel alloy welding consumables of the Ni-Cr-Mo type (eg. 625, 622 and 686CPT). Welds completed in 6%Mo super austenitic steels with 625 type consumables have been found to exhibit pitting in ASTM G48A tests at 40-50°C, compared to the base material, which exhibits pitting at 55-60°C [11]. Autogeneous welds in these steels show a loss in corrosion performance due to the effects of segregation in the as deposited weld metal. When welding super austenitic stainless steel it is not necessary to impose the same heat input controls as are applied to duplex stainless steels as there is no requirement to obtain the ferrite-austenite balance needed in duplex stainless steels for mechanical properties and corrosion behaviour.

In order to determine the suitability of high nickel alloy (Ni-Cr-Mo) filler metal for welding super austenitic steel the mechanical properties and corrosion behaviour of weld deposits have been assessed. Welds were completed in super austenitic stainless steel using the TIG process in accordance with the procedure detailed below

Weld preparation:
Single V 60° included angle
Base Material:
12.7 mm thickness
Position:
Vertical up

Fill Current:	180 A
Fill Voltage:	14 V, DC –
Fill Speed:	115 mm/min (4.5"/min)
Fill Heat Input:	1.3 kJ/mm (33kJ/inch)

Welds in 25-6 Mo plate (UNS N08926) were completed using 622 and 625 filler metals whilst welds in 27-7 Mo plate (UNS S31277) were completed using 686CPT filler metal. A macro section from one of these single sided welds is shown in Figure 2 and the compositions of the filler metals are listed in Table 4.

The tensile properties of the welds were determined from both weld metal tensile and cross weld tensile specimens. The Charpy V-notch impact toughness of the weld deposits was evaluated at -50°C using specimens located at the weld center line. Pitting corrosion testing of the weld metal was undertaken using the acidified $FeCl_3$ solution in ASTM G48 for 24 hours.

The weld metal yield and tensile strengths (Table 5) for the Ni-Cr-Mo alloy filler metals were 520-527MPa (75.4-76.4ksi) and 797-802MPa (115.6-116.3ksi) respectively. These strength values exceed the specified minimum values for the grades of super austenitic steels. All the cross weld tensile specimens exhibited ductile fracture in the base plate away from the weld (Table 6). For all three nickel alloy filler metals the weld metal toughness values at -50°C (-58F) exceeded 70J (52ft.lbs). The impact toughness performance of 622 and 686CPT was similar with impact toughness values at -50°C (-58F) lying in the range 72-88J (53-65ft.lbs). The toughness of the 625 weld deposit was higher with 100-104J (74-77ft.lbs) being achieved at -50°C (-58F).

Pitting corrosion testing of the welds completed in 25-6Mo plate (UNS N08926) showed that no pitting was observed at a temperature of +50°C with both 622 and 686CPT filler metals (Figure 3). However, at +60°C pitting occurred in the HAZ at the weld root location. For the weld completed in 27-7Mo plate (UNS S31277) with 686CPT filler metal no pitting was observed at +60°C. At a temperature of +70°C pitting was observed to occur in the HAZ at the root of the weld. There was no pitting in the weld deposit in either the cap or root locations at +70°C, however there was some evidence of slight corrosive attack in the cap of the weld. The high alloyed Ni-Cr-Mo weld deposits (625, 622 and 686CPT) were found to exhibit superior pitting corrosion resistance to that of the HAZ of the base material. In all instances pitting was found to occur preferentially in the HAZ at the root of the weld.

The 686CPT filler metal has been used successfully in a production environment for welding 4.5%Mo and 6%Mo super austenitic stainless steels. During welding procedure qualification good levels of impact toughness have been recorded at temperatures down to -196°C and tensile properties exceeding the specified minimum values have been achieved. Pitting corrosion tests in accordance with ASTM G48A for 24 hours showed no evidence of pitting with weight loss values of <3glm² being recorded.

4. Welding of Duplex Stainless Steels

Duplex and super duplex stainless steels provide good resistance to stress corrosion cracking together with higher strength levels compared to both standard austenitic and super austenitic stainless steels (Table 3). These steels are characterized by a microstructure containing both ferrite and austenite. Duplex stainless steels are sensitive to variation in chemical composition, which will influence the microstructure and phase balance in the weld region. Super duplex stainless steels are characterized as containing higher levels of Ni, Cr, Mo and N compared to standard duplex stainless steels. Some super duplex stainless steels are also alloyed with tungsten (Table 2).

The amount of ferrite and austenite in the weld deposit and HAZ depends on the cooling rate during welding with high cooling rates resulting in higher levels of ferrite when welding is undertaken with duplex stainless steel filler metals. Nitrogen acts to aid the reformation of austenite in the weld region [12] by promoting austenite reformation at higher temperatures. Nitrogen also improves the corrosion resistance, especially of the austenite phase. Practically, heat inputs in the range of 0.5-1.5kJ/mm for super duplex, and 0.5–2.0kJ/mm for standard duplex stainless steels are employed in conjunction with maximum interpass temperatures of 100°C and 150°C respectively dependent upon wall thickness. Interpass temperature is often restricted on thin wall super duplex materials to prevent the precipitation of third phase intermetallics. Welding consumables for duplex stainless steels are similar in composition to that of the base material but with higher levels of nickel to ensure an appropriate phase balance (30-60% ferrite) in the deposited weld metal.

Many fabrication specifications in the oil and gas industry require ASTM G48A pitting corrosion testing of the deposited weld metal to be undertaken at +25˚C and +40˚C for duplex and super duplex stainless steels respectively. In many instances super duplex filler metal is used for welding standard duplex stainless steels. The use of such an over alloyed filler metal (super duplex stainless steel) in these circumstances produces weld deposits with enhanced pitting corrosion resistance compared to standard duplex stainless steel weld deposits.

Nickel alloy filler metals have been used in some applications to complete welds between duplex stainless steels and other alloy materials (eg. Cr-Mo steels, nickel based alloys etc.). The use of a fully austenitic high nickel Ni-Cr-Mo alloy filler metal for welding duplex and super duplex stainless steels provides potential advantages in terms of welding procedural approach and improved pitting corrosion resistance compared to the use of super duplex stainless steel filler metals. The use of a fully austenitic nickel alloy weld deposit removes the requirement which exists with duplex stainless steel filler metals to produce welds with balanced quantities of austenite and ferrite.

The variation in weld metal

mechanical properties for INCONEL FM 686CPT with heat input has been determined by depositing all weld metal test plates with the TIG welding process in the flat position. The variation in 0.2% proof strength and tensile strength with heat input is shown in Fig.4 which shows that 0.2% proof strength levels in excess of the 550 MPa specified for super duplex stainless steels are achieved in the weld deposit at a heat input of less than 1.5kJ/mm. The impact toughness of welds completed with 686CPT filler metal shows little variation with heat input with values in excess of 95J and 65J being achieved at -50˚C and -196˚C respectively (Figure 5).

These mechanical property results for the 686CPT wire, combined with the pitting corrosion performance of this alloy, clearly demonstrate its suitability for welding both standard and super duplex grades of stainless steel. To ensure that the weld metal strength and other mechanical properties exceed the minimum requirements for super duplex stainless steels appropriate control of welding parameters will be required.

5. Conclusions

The selection of a welding consumable must be based on anticipated service requirements and specified weld metal mechanical property requirements. The as deposited weld metal microstructure, exhibits some variation in chemical composition of the main alloying elements due to the effects of segregation during solidification. The selection of an over alloyed welding consumable compensates for these segregation effects. There are many applications where highly alloyed Ni-Cr-Mo filler metals, including 686CPT filler metal, provide enhanced resistance to pitting and crevice corrosion compared to the base material being welded. Examples of the applications for these alloys include:

Welding of C-276 material in flue gas desulphurisation (FGD) plant using 686CPT filler metal provides welds with enhanced corrosion resistance compared to the base material.
Welding of super austenitic stainless steels with Ni-Cr-Mo filler metals (625, 622 and 686CPT) enables welds to be produced with enhanced critical pitting temperatures and superior performance to that of the base steel. The use of these nickel alloy filler metals enables weld metal mechanical properties specified for these super austenitic steels to be readily achieved.
Nickel alloy filler metals provide enhanced pitting and corrosion resistance compared to that obtained by duplex and super duplex stainless steel filler metals.
For welding duplex and super duplex stainless steels the deposition of a fully austenitic weld deposit removes the requirement to produce welds with balanced quantities of ferrite and austenite.

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Tables

Alloy	UNS Number	Ni	Cr	Fe	Mo	W	Nb	Cu	Total Cr+Mo+W	PREN*
686	N06686	Bal	20.5	<1.0	16.3	3.9	-	-	40.8	50.8
C-2000	N06200	Bal	22.5	1.0	16.5	-	-	1.5	40.5	47.3
59	N06059	Bal	23.0	<1.5	16.0	-	-	-	39.0	47.0
622	N06022	Bal	20.5	2.5	14.2	3.2	-	-	37.9	46.6
C-22	N06022	Bal	21.4	4.0	13.4	3.1	-	-	37.9	46.2
C-276	N10276	Bal	15.5	5.5	16.0	4.0	-	-	35.5	45.5
625	N06625	Bal	21.5	3.0	9.0	-	3.5	-	30.5	40.3
C-4	N06455	Bal	16.0	2.0	16.0	-	-	-	32.0	40.0
G	N06007	Bal	22.0	20.0	6.5	0.6	-	2.0	29.1	32.7

**PREN = %Cr+1.5%(Mo+W+Nb)*

Table 1: Chemical composition of a range of Ni-Cr-Mo alloys

	UNS Number	Ni	Cr	Mo	N	Cu	W	PREN
27-7Mo	S31277	27	22	7.2	0.34	0.9	-	51.2
25-6Mo	N08926	25	20	6.5	0.20	0.9	-	44.7
254SMo	S31254	18	20	6.1	0.20	0.7	-	41.5
Super Duplex	S32750	7.0	25	4.0	0.27	-	-	42.5
Super Duplex	S32760	7.5	25	3.8	0.25	-	-	41.5
Standard Duplex	S31803	5.5	22	3.1	0.17	-	0.7	35.0

PREN = %Cr + 3.3(%Mo) + 16 (%N).

Table 2: Duplex and super austenitic stainless steel compositions.

Material	UNS Number	0.2% Proof Strength (MPa)	Tensile Strength (MPa)	Elogation (%)
27-7Mo	S31277	>360	>770	>40
25-6 Mo	N08926	>295	>650	>42
Super Duplex	S32750	>550	>800	>25
Super Duplex	S32760	>550	750-895	>25
Standard Duplex	S31803	>450	>620	>25

Table 3: Duplex and super duplex austenitic stainless steel mechanical property requirements.

Alloy	AWS A5.14	Ni	Cr	Fe	Mo	W	Nb	Total Cr+Mo+W	PREN*
686	ERNiCrMo-14	59.5	20.1	0.10	16.1	3.9	-	40.1	50.1
622	ERNiCrMo-10	57.3	22.2	2.33	14.2	3.4		39.8	48.6
625	ERNiCrMo-3	Bal	22.1	0.61	9.0	-	3.5	31.1	40.9

**PREN = %Cr-0.8%Cu+1.5(%Mo+%W)*

Table 4. Chemical composition of TIG welding wires.

Base Alloy	Filler Metal	0.2% Proof Strength (MPa)	Tensile Strength (Mpa)	Elongation (%)	Charpy V-Notch (J@ - 50°C)
27-7 Mo	686CPT	527	802	26.5	72-86
25-6 Mo	622	520	797	39.0	76-88
25-6 Mo	625	N/D	N/D	N/D	100-104

N/D – Not determined.

Table 5: Mechanical Properties of Welds completed in Super Austenitic Stainless Steel

Base Alloy	Filler Metal	0.2% Proof Strength (Mpa)	Tensile Strength (Mpa)	Location of Fracture
27-7 Mo	686CPT	423	811	Ductile fracture in 27-7Mo plate
		406	811	Ductile fracture in 27-7Mo plate
25-6 Mo	622	386	787	Ductile fracture in 25-6Mo plate
		388	776	Ductile fracture in 25-6Mo plate
25-6 Mo	625	420	776	Ductile fracture in 25-6Mo plate
		403	784	Ductile fracture in 25-6Mo plate

Table 6: Cross Weld Tensile Data for Welds in Super Austenitic Stainless Steels.

Base Alloy	Filler Metal	Pitting Corrosion	Weight Loss
27-7 Mo	686CPT	No visible pitting at +60° Pitting in HAZ at weld root at +70°C	1.05 glm² -
25-6 Mo	622	No pitting at +50°C Pitting in HAZ at weld root at +60°C	0.16glm² -
25-6Mo	625	No pitting at +50°C Pitting in HAZ at weld root at +60²C	0.51glm² -

ASTM G48C for 24 hours

Table 7: Pitting corrosion behaviour of super austenitic stainless steel welds.

Figures

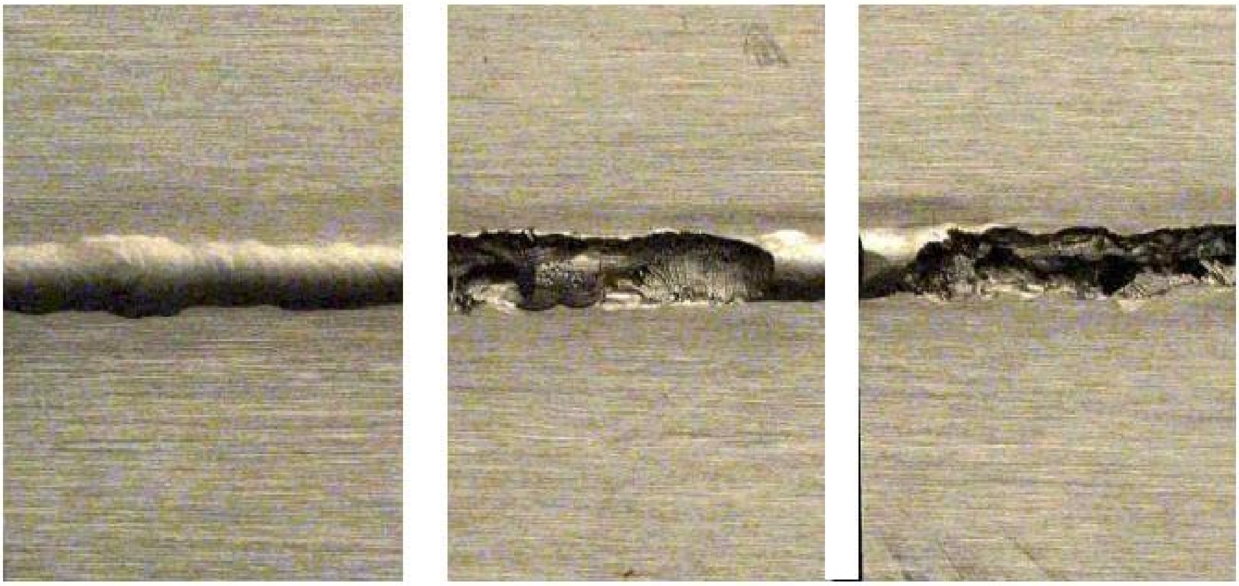

Figure 1a: INCONEL 622 welded with INCONEL 622 filler metal (pitting resistance of various base metal and weld metal combinations).

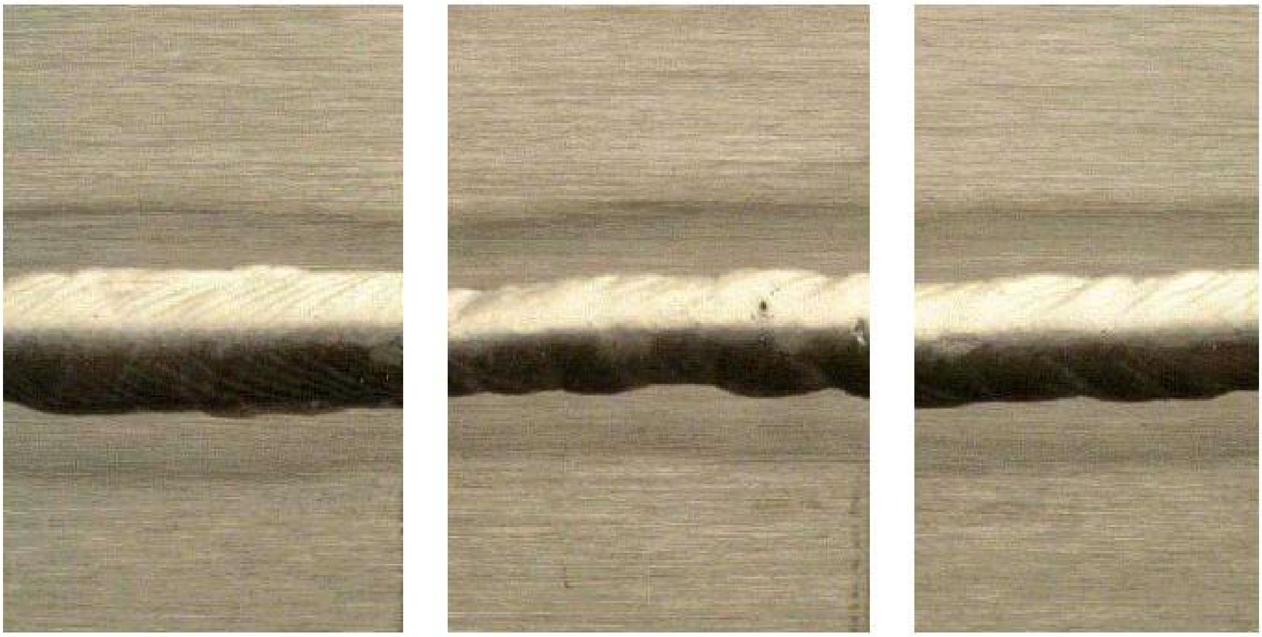

Figure 1b: INCONEL 622 welded with INCO-WELD 686CPT filler metal (pitting resistance of various base metal and weld metal combinations).

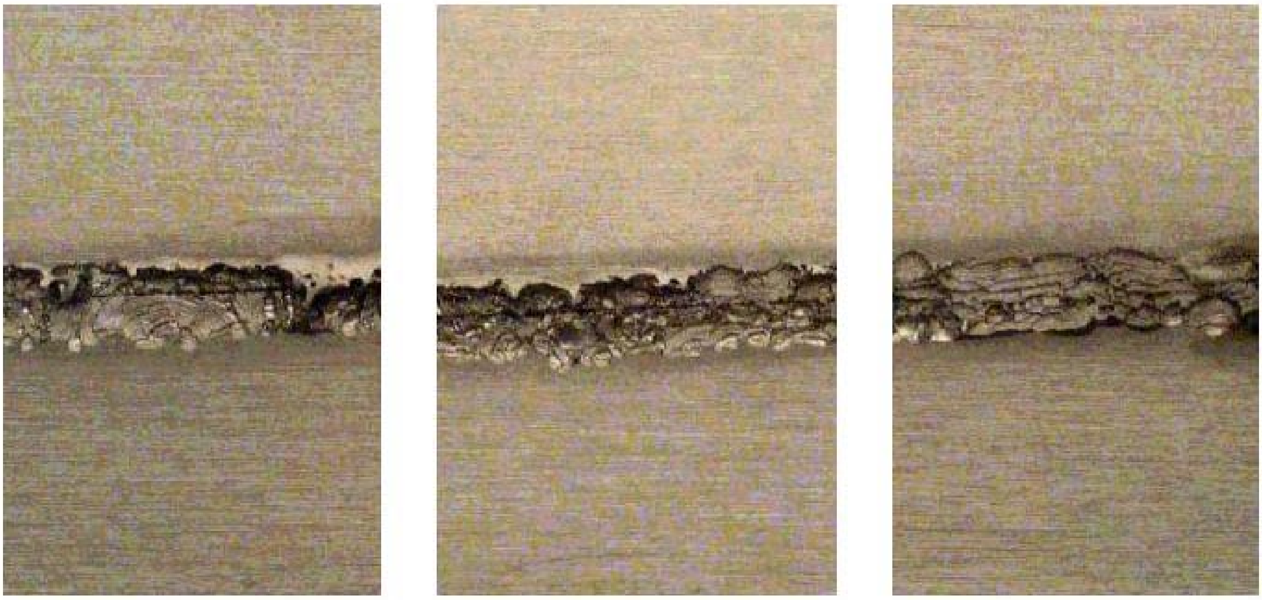

Figure 1c: INCONEL C-276 welded with INCO-WELD C-276 filler metal (pitting resistance of various base metal and weld metal combinations).

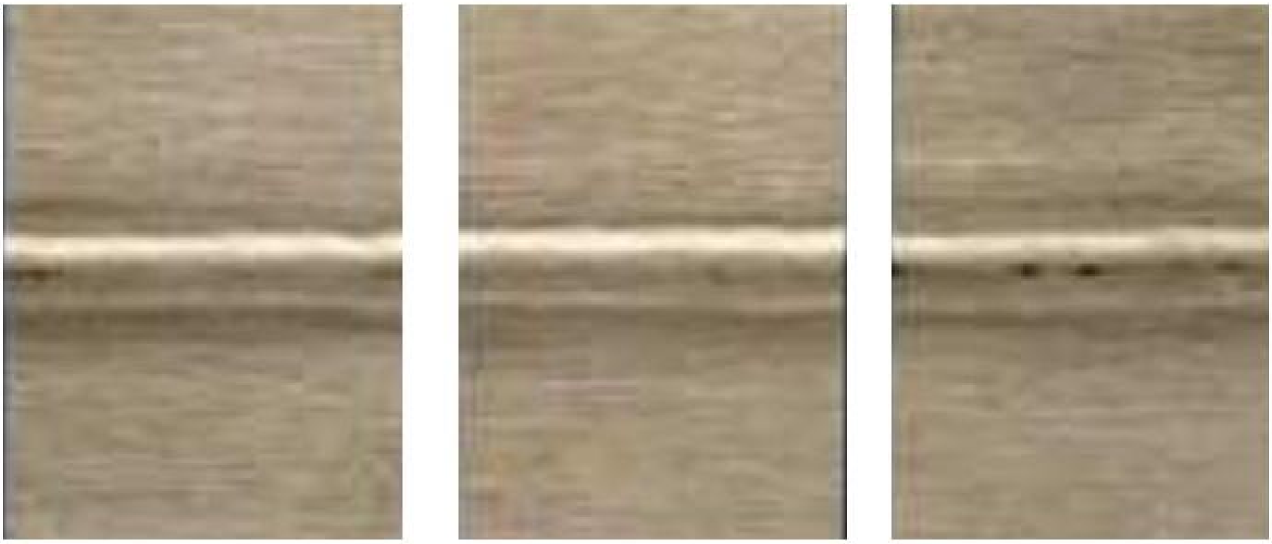

Figure 1d: INCONEL C-276 welded with INCO-WELD 686CPT filler metal (pitting resistance of various base metal and weld metal combinations).

Figure 2: Macro section from a TIG weld in super austenitic stainless steel.

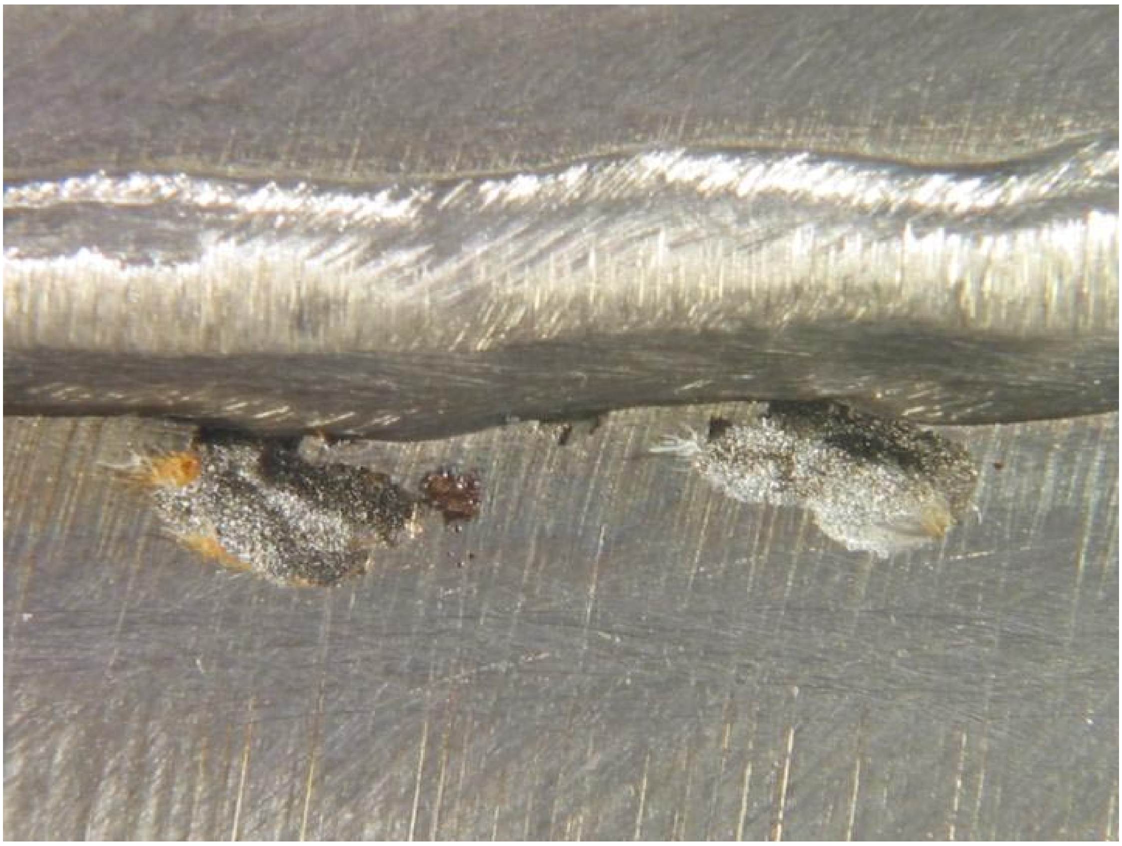

Figure 3a: Root of weld in 27-7Mo plate showing pitting in HAZ (G48C at +70˚C for 24hours) - Pitting resistance of welds in super austenitic steels.

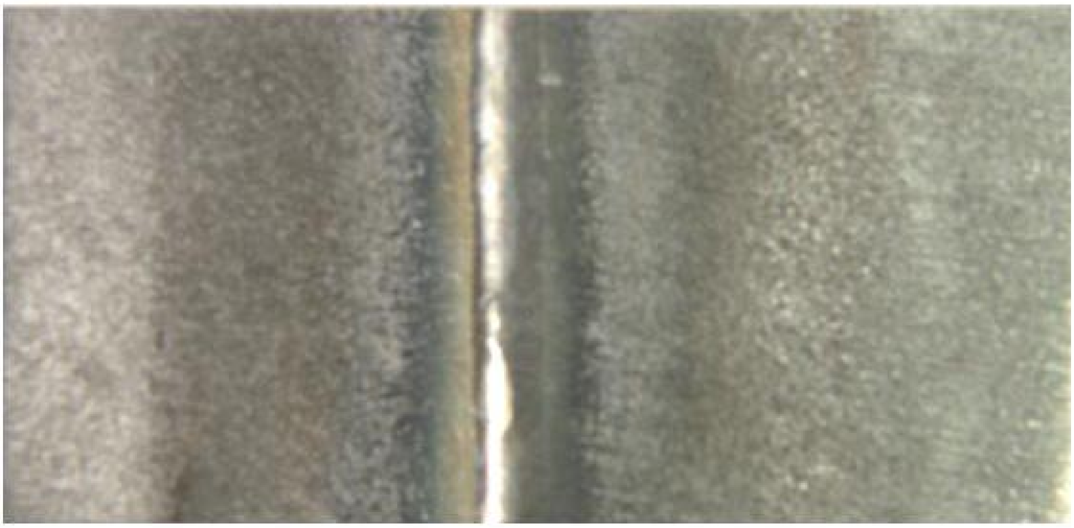

Figure 3b: Root of weld in 25-6Mo plate welded with 625 filler metal (G48A at +50˚C for 24 hours) - Pitting resistance of welds in super austenitic steels.

Heat Input (kJ/mm)	0.2% Proof Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
0,8	605	870	37,5
1,3	577	866	36,5

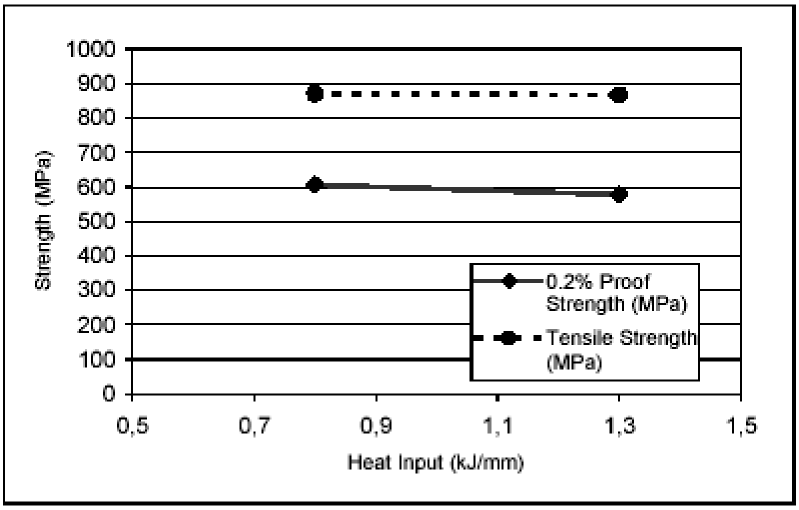

Figure 4: Variation in weld metal tensile properties for INCO-WELD 686CPT.

Heat Input (kJ/mm)	Impact Strength (-50°C)	Impact Strength (-196°C)
0,8	98	67
1,3	99	76

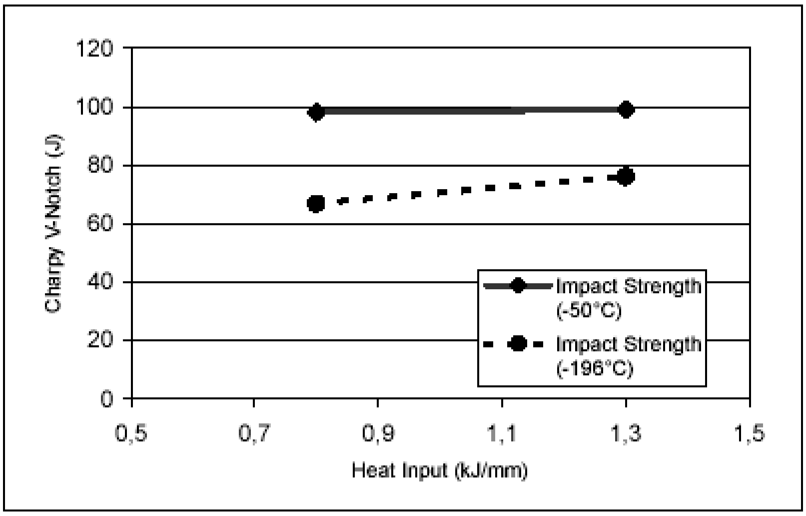

Figure 5: Variation in weld impact toughness properties for INCO-WELD 686CPT.