Corrosion resistant cored wires for the oil and gas industry

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Summary

Today there is a clear trend towards the use of corrosion resistant cored wires in the oil & gas industry. Within this industry bismuth free wires are increasingly required for applications at both high and low temperatures. We give here examples of recent applications where a new generation of Bi-free wires is used for welding and cladding. This includes most of the austenitic stainless steel compositions that are used for heat- and corrosion-resisting applications. Recent applications also include cored wires for submerged arc welding, particularly grades 308H, 347 and 347H.
Nickel based wires of the NiCr, NiCrFe, NiCrMo and NiCu types are also increasingly used, Practical examples illustrate their use.

Introduction

For joining or cladding stainless steels and most nickel base alloys (corrosion resistant alloys – CRA), there is a vast choice of possible welding processes. Each of these processes involves specific filler metal forms and sizes as well as dedicated chemical compositions [1]. The weld metal must satisfy the usual requirements of corrosion resistant constructions: it should be smooth, clean and free of cracks, porosity, spatter or slag. At all levels of dilution, the weld metal composition must at least match that of the base material. The weld microstructure should be appropriate, sound and as stable as that of the base material at all temperatures experienced during service life.
The following types of welding consumables for CRA exist (numbers refer to the welding process according to EN ISO 4063):

- Covered welding electrodes (SMAW / 111)
- Bare welding wires shielded with an inert (131) or slightly oxidizing (135) gas in MIG-MAG (GMAW)
- Bare welding wires for plasma arc welding (PAW / 151)
- Bare wires with a flux for submerged arc welding (SAW / 121)
- Bare (141) or flux cored (143) rods for GTAW with an inert gas
- Flux cored wires for open arc welding (FCAW-S / 114)
- Flux cored wires for welding with an active gas (FCAW-G / 136)
- Metal cored wires for welding with an active (138) or inert gas (133)
- Cored wires for submerged arc welding with a neutral flux (125)

Stainless steels and nickel alloys are used for corrosion resisting applications involving heat and corrosion resistance (Figure 1) The most widely used stainless steels are the low-carbon types for corrosion resistance at ambient or moderate temperatures e.g. 304L, 347L, 316L, 317L, 904L, or those containing controlled higher carbon levels for elevated temperature properties e.g. 321, 347, 310, 253MA. Alloys based on nickel and iron in approximately the same proportions may be considered either as stainless steels or as nickel-base alloys.

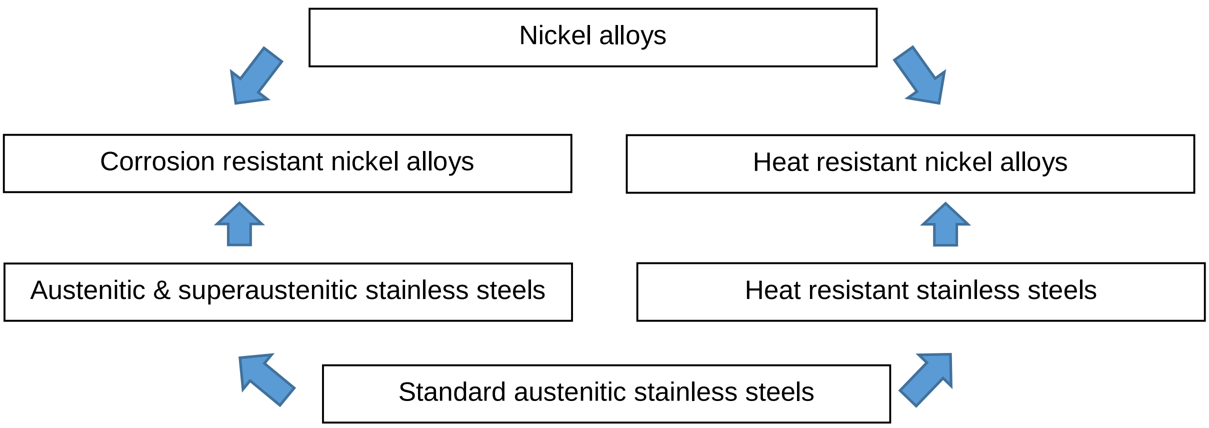

Figure 1: relation between stainless steels and nickel base alloys (after J.C.M. Farrar) [2].

Corrosion resistant alloy (CRA) cored wires

Cored arc welding wires are one category of welding filler materials used to assemble or clad stainless steels. Welding performance, weld metal corrosion resistance and mechanical properties depend on the specific cored wire type and the details of its formulation. Strip, core ingredients and production processes all exert a strong influence. Productivity and quality of cored wires depend on a balance of alloying additions, slag formers and modifiers, gas formers, denitriders and deoxidisers all of whose effects are intimately linked. Flux cored arc welding wires consist of a seamed tube and a filling of metallic and nonmetallic powders (Figure 2). For a given alloy, it is possible to design several different types of flux-cored wires to suit specific applications. The starting point is the choice of strip: usually the more highly alloyed, the better. Metallic powders are added to the core to achieve the desired chemical analysis. Nonmetallic powders (usually minerals) form a protective slag over the weld metal and influence the characteristics of the welding arc. Each type has advantages and disadvantages: there is no one type that outperforms all the others under all conditions. A range of stainless steel or nickel base cored wires usually consists of five product types [3, 4, 5, 6, 7, 8].

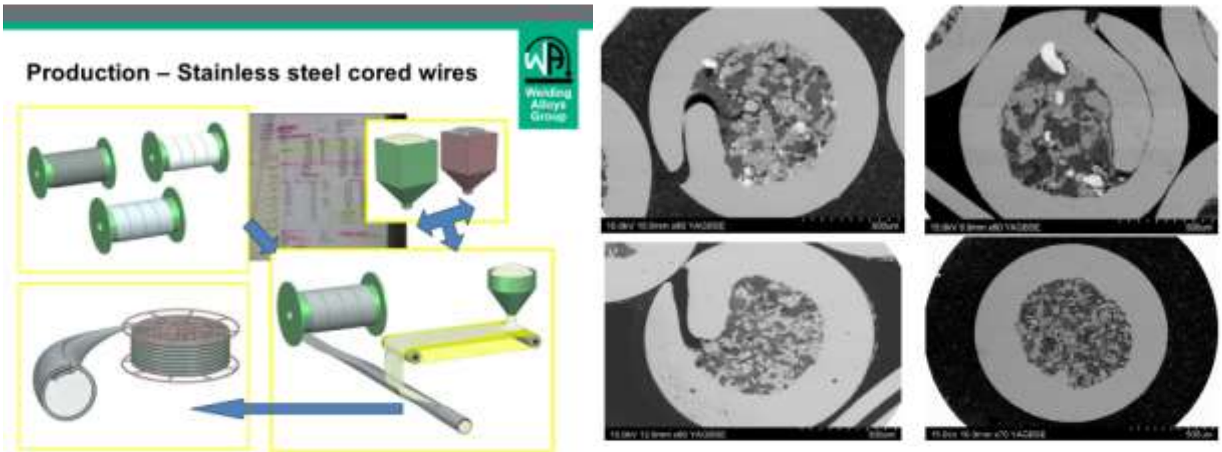

Figure 2: left side; production route – right side; typical modern seam configurations for 1.2 mm wire

1. **Open arc (self-shielded).** WA TRI S (FCAW-S). These wires do not need an external protective

gas. Their filling contains gas-forming compounds and other materials which help purify the weld pool. Metal transfer is of the globular type. Self-shielding with a slag system alone is not as effective as shielding with a combination of a slag system and an external shielding gas. For this reason, deposits made by open arc welding usually have a higher nitrogen content, which lowers the ferrite content in the weld metal. To compensate for this, self-shielded wires have different Cr/Ni ratios from their gas shielded counterparts. Nitrogen interference explains why no duplex stainless steel open arc wires are produced.

Self-shielded stainless steel wires are of interest for cladding and repair work, and small diameter wires are also used for assembly work when the use of an external gas protection is impractical or uneconomic.

Figure 3 illustrates open arc cladding with TRI S 309L-O, E309LT0-3 wire.

2. **Metal cored**. WA TUBE S / WA STELLOY (GMAW or SAW): contain metal powders only in the core, and are therefore slag-free. This design allows the widest range of compositions, because there are no space-filling minerals in the core. CRA metal cored wires are usually welded using

argon shielding or argon + 0 - 5% CO_2 gas mixtures with or without helium. They may also be welded using flux protection, usually with larger wire diameters. The penetration shape is favorable and the deposit usually has good mechanical properties. The usable welding parameter window is similar to that of solid wire, but larger. Metal cored wire for GMAW demands a high level of welder skill, particularly when working away from the horizontal position.

3. **Flat position gas shielded rutile.** WA TETRA S (FCAW-G): contains a mix of minerals, preponderantly rutile and other oxides, designed for maximum welding performance and "welder appeal". It is welded using argon + 15 - 25% CO_2 mixtures or pure CO_2. This product type gives the best weld bead appearance of all, and needs only minimal post-weld finishing (brushing, grinding, machining). However, it is only suitable for use in the horizontal and near-horizontal positions, and the mechanical properties of the weld deposit (particularly the toughness) are not as good as those of solid or metal cored wires because the minerals add oxygen to the weld pool. This element usually acts as a parasite in steels.
4. **Flat position gas shielded basic**. WA TETRA SB / WA GAMMA (FCAW-G): contains a "basic" flux mix, composed largely of fluoride minerals. It is welded using argon + 15 - 25% CO_2 mixtures. The fluorides have a purifying action on the weld metal and reduce the oxygen content considerably. As a result, this wire type gives the toughest and most ductile weld metal of all. However, its welding behavior is not as good as that of the rutile types, the appearance of the weld deposit is less pleasing, and it can only be used in horizontal and near-horizontal positions.

Figure 4 shows a PB-2F fillet weld on AISI 310. The characteristic convex shape of the basic flux cored wire fillet favours a reduced tendency to hot cracking.

5. **All position gas shielded**. WA TETRA V / WA GAMMA V (FCAW-G): Whereas most stainless steel welding and cladding is performed in the downhand or flat position, there still is a significant requirement for positional welding. This presents an interesting challenge for the wire manufacturer. In both flat and positional welds, the slag is required to support the molten metal and maintain the perfect edge blend at the toe of the bead with good penetration but freedom from undercut. All-position wires are closely related to flat and horizontal gas shielded rutile cored wires, but the particular physical properties of the slag - viscosity, surface tension, melting range etc. - are different for the two types. They contain a similar mineral mix, but the proportion of rutile is increased in all-position wires in order to raise the freezing point of the slag. This allows the wire to be welded in any position, even overhead. The properties of the weld deposit are practically identical to those of the flat position wire but its appearance is not quite as pleasing when welded in the flat and horizontal positions. Interestingly, its impact toughness is slightly higher.

CRA wires and bismuth

CRA cored wires have existed for almost fifty years and have really taken off in the last twenty-five. The present state of evolution of CRA cored wires is captured in the current EN ISO 17633 / 12153 and AWS A5.22 and A5.34 standards. These standards include almost as many filler metal compositions as their counterparts for coated electrodes or solid wires. Interesting advances and innovations have been made in all alloy classes; not only the well-known martensitic, ferritic, austenitic and duplex stainless steels, but also special types for dissimilar welding. These standards include compositions designed for high temperature service and offer the possibility of classifying proprietary compositions. CRA cored wires are commonly chosen nowadays for cladding and joining. They are used in applications involving corrosion resistance and/or service at elevated or cryogenic temperatures, applications that are far beyond the scope of low alloy steels.

In the early 1990s, premature creep failures were reported in high service temperature applications in power plants. Since then, research has shown that segregation of bismuth (added to rutile-based cored wires to improve slag detachment) at the grain boundaries at high temperatures results in reduced ductility at temperatures above 650ºC and inter-granular cracks at temperatures above 700ºC [9, 10,11,12.]. Current bismuth levels recorded in weld metal produced by CRA wires sourced worldwide range from 150 to 400 ppm (0.015 to 0.040% by weight). Consequently, bismuth-free FCAW wires are required for applications involving high service temperatures or where a post weld heat treatment (PWHT) above 600ºC is specified. To resist high-temperature degradation under these conditions, weld metal must contain less than 20 ppm (0.002 %) bismuth.

Metal cored and basic flux cored wires do not usually contain deliberate bismuth additions or other low-melting oxides such as those of lead and antimony. They are naturally bismuth-free.

High service temperature applications are mostly found in the power generation, chemical and petrochemical industries. Austenitic stainless steels and nickel base alloys are often used at temperatures between 500 and 950°C. Solution or stabilisation annealing of welded chemical process reaction vessels is very effective in avoiding relaxation cracking during service [13]. Figure 5 shows several CRA types for high temperature applications for which cored wires with matching compositions are available.

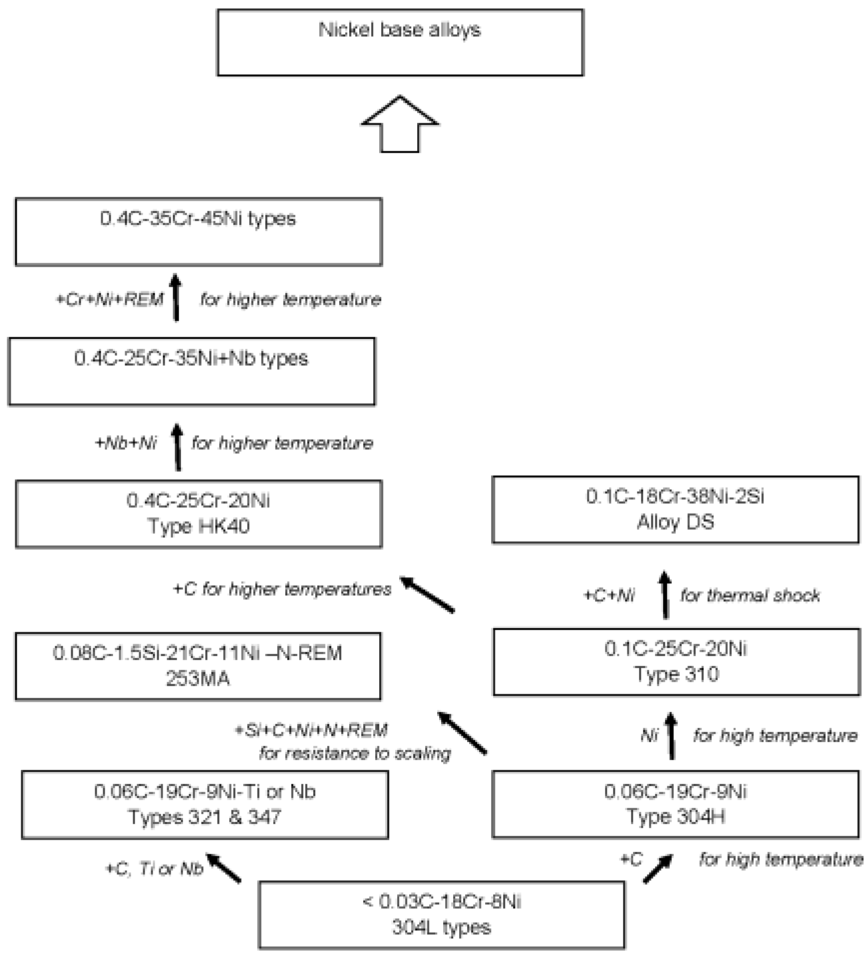

Figure 5: stainless steels designed for service at high temperature (from J.C.M. Farrar) [2].

Stainless steel cored wires with the “H” suffix must be bismuth-free to satisfy the current AWS A 5.22 and EN ISO 17633 standards. This element should be controlled in all stainless steel or nickel base cored wires intended for high-temperature service.

Many engineering applications require both strength and corrosion resistance. Low alloy steels have the strength but not the corrosion resistance. Cladding makes it possible to combine both characteristics at a reasonable cost. However, post-weld heat treatments [14] are frequently applied to constructions clad with compositions such as 309(L), 309(L)Mo, 309LNb, 347, 316(L), 318, 308(L) or 317(L). The stress-relief temperature is chosen to suit the base material and is usually in the range 540°C to 700°C. In such cases, bismuth should be controlled even though the compositions used for cladding are not primarily designed for use at high temperature, especially in the case of undiluted buffer metal.

Sometimes a solution annealing heat treatment is needed after welding or repair, particularly to duplex and superduplex stainless steels [15]. Bismuth free cored wires should be specified in such cases.

Practical examples

Austenitic stainless steel cladding on low-alloy (CrMo) steel

347(H), 317(L), 316(L), 318 and 308(L) cored wires are often used to restore worn claddings or to clad areas that cannot be overlaid by electroslag or submerged arc strip cladding. Flux cored wires are an attractive solution when surfacing has to be done out of position: vertical up, horizontal-vertical or overhead. A further advantage of cored wires is the possibility of adapting the actual weld metal composition very closely to the application and the welding shop conditions. Dilution with flux cored wire is as predictable as with stick electrodes and the penetration shapes achieved allow virtually defect-free cladding to be obtained with good productivity. The quality of FCAW stainless steel welds is described in numerous papers. Some documents give detailed comparisons between common welding processes [16]. Flux cored arc welding certainly offers a good combination of quality and deposition rate which is translated into productivity.

Example of 347 all-weld metal – TETRA V 347L-G

Composition chimique du métal déposé hors dilution (%).
All weld metal batch chemical analysis (%).

C	Mn	Si	P	S	Cr	Ni	Mo
0,0327	1,57	0,60	0,0208	0,0020	19,16	10,89	0,067
Nb	Cu	N	Bi	Ferrite WRC 92		Ferrite FERITSCOPE	
0,398	0,067	0,0184	< 0,0005	5,5 FN		6.3 FN	

Example of cladding procedure record preparation – 316L cladding

Cladding type	316L
Consumables	TETRA S 309LMo-G 1.2 mm batch 10882 TETRA S 316L-G 1.2 mm batch 11004
Base metal	13CrMo45
Welding position	Flat position PA
Shielding gas	EN ISO 14175 – M21 – ArC – 18
Current type/polarity/pulse	DC+ not pulsed
Interpass temperature	≤ 150°C

First layer TETRA S 309LMo-G 1.2 mm BATCH 10882

Gun angle	trailing 6°
Wire feed speed	10m/min
Amperage	210 A
Voltage	30 V
Travel speed	50 cm/min
Electrical stick out	15 mm
Stepover distance	6 mm
Weld bead thickness	3 mm

First layer analysis and delta ferrite according to WRC 92

C	Mn	Si	Cr	Ni	Mo	Cu	Nb	N	Bi	FN WRC92
0.062	1.40	0.689	17.44	9.04	1.86	0.211	0.0273	0.0333	< 0.0005	6.4 FN

Second layer TETRA S 316L-G 1.2 mm BATCH 11004

Gun angle	trailing 6°
Wire feed speed	10m/min
Amperage	225 A
Voltage	30 V
Travel speed	50 cm/min
Electrical stick out	15 mm
Stepover distance	6 mm
Weld bead thickness	3 mm

Second layer analysis and delta ferrite according to WRC 92

C	Mn	Si	Cr	Ni	Mo	Cu	Nb	N	FN WRC92
0.0437	1.56	0.678	17.96	11.31	2.39	0.114	0.0321	0.0295	5.3 FN

Figure 6:
347 Bi-free cladding
TETRA V 309LNb-G + TETRA V 347L-G

Joining of austenitic steels for high temperature service

In principle, weld metal must not only match the composition but also the performance in service of the base metal. At elevated temperatures, the self-diffusion rate in the close-packed austenite is lower than in the more open ferrite. Therefore, the creep strength of chrome-nickel austenitic stainless steels and weld metals is greater than that of classical low-alloy creep-resisting ferritic steels.

For the 300 series, weld metal with controlled ferrite must be selected (17, 18). Creep and high temperature cracking are retarded by the absence of low melting compounds and by the irregular austenitic microstructure containing ferrite islands, provided care is taken to avoid a continuous ferrite network which typically appears at delta ferrite levels above 10 – 15 FN. Cored wires, like stick electrodes, are an asset to the welding fabricator here because relatively small batches can be produced quickly that give the required weld metal composition under actual production conditions.

Figure 7 Horizontal fillet weld in AISI 304H using TETRA S 308H-G (E308HT0-4) – a typical application for stainless steel flux-cored wire with slow freezing slag

Figure 8
High pressure reboiler – Stainless steel 321
FCAW: TETRA V 347H-G
SAW: TUBE S347H-S + WAF 385
All cored wires are bismuth free
Courtesy WELDERS NV – Aalst Belgium

Figure 9
Static mixer, 304H steel
FCAW: TETRA S B308H-G
TETRA V 308H-G (bismuth free)
Courtesy WELDERS NV – Aalst Belgium

Figure 10.
Air nozzle materials 1.4828 – 1.4893
FCAW: TETRA V 309HT-G bismuth free

Many heat resisting steels such as those used in steam reformer furnaces for petrochemical plants are fully austenitic. They are derived from the standard AISI 310 (0.1C-25Cr-20Ni) with an increased carbon ranging from 0.3 to 0.5 %. These steels typically contain 20-35 % Cr and 25 - 50 % Ni, and other alloying elements such as Nb, Co or W. Such steels are welded with matching filler metal and some repair welding is carried out with nickel base consumables. Bismuth-free cored wires, mostly metal cored or basic flux cored, offer advantages in terms of quality, productivity and user friendliness.

Figure 11: 310S reactor under heat treatment
Cored wires: FCAW: TETRA S B 310-G
SAW: TUBE S 310-S + WAF 380
All consumables are bismuth free
Courtesy WELDERS NV – Aalst Belgium

(Super)duplex stainless steel

When a welded (super)duplex casting or welded exchanger head requires solution annealing at temperatures as high as 1150°C, it is safe to use bismuth free consumables. Cored wires are readily available with different slag systems.

Figure 12: Repair of casting defects on superduplex UNS S 32520
TETRA S D57L-G bismuth free

Nickel base alloys

Nickel base cored wires share many features with their stainless steel based cousins. The same types of wire are available: self-shielding, basic flux-cored, rutile flux-cored with fast freezing slag for positional welding, rutile flux-cored with slow freezing slag for neat welds in the flat or horizontal positions. Many of the core ingredients are common to both.

The first nickel base rutile type wires to appear proved very efficient in weld overlay applications and for constructing LNG tanks with NiCrMo compositions, where their positional welding capabilities (particularly vertical-up) were much appreciated. However, their limitations were demonstrated by failures of coke drum cladding repairs, dissimilar welds involving CrMo steels and repairs to heavy gauge carbon steels in cement production. SEM-EDS examination of failed welds revealed bismuth inclusions, unmolten metal alloying additions and non-metallic inclusions. New generations of rutile or rutile-basic cored wires are bismuth free. Many NiCrMo, NiCr(Fe) compositions and one NiCu (alloy 400) are currently available today. AWS A 5.34 [19] and particularly EN ISO 12153 [20] give a clear view of the standard types available.

Basic flux cored wires, either gas shielded or open arc, are still preferred for heavy repairs.

Figure 13: Crack repair with nickel base bismuth free wire GAMMA 182 (NiCrFe-3), as welded and after 30 months service life

Conclusions

Various processes are available for welding stainless steel with cored wire. For a comparable slag system, the quality achieved is generally the same as that of SMAW electrodes. As for productivity, it is at least as good as with solid wires with the additional advantages of versatility, ease of use, quality and compositional possibilities. Stainless steel cored wires are often a good choice for use in combination with other processes or when problems or performance limitations arise. With the availability of an exhaustive range of bismuth free types covering most corrosion resistant alloy grades, the scope of use is extended to applications at high temperature or for constructions undergoing post-weld heat treatment.

A homologous family of nickel base filler wires has been developed and is extending its range of application, now that some initial setbacks have been overcome.

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