

Duplex Stainless Steel For Flowlines Past, Present and Future

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Memorie

Experience with duplex stainless steel flowlines dates back to 1975 with sustained growth so that there is now more than 845 km now in service, approximately 400 km (48%) offshore. Some early use was made of a 18-19% chromium content duplex (UNS S31500), but the majority of the pipelines are constructed in standard 22%Cr grade (UNS S31803) with a small but significant use of superduplex (25%Cr) grades (various UNS numbers). The distribution of usage in terms of length of pipe laid is 18.5%Cr (0.5%), 22%Cr (86.5%) and 25%Cr (13%) grades. The pipe diameters which have been applied are both in the range 4"-36". This paper summarises details of applications of some of these flowlines along with experience in their fabrication, installation and operation. It highlights good practice for optimum welding of duplex stainless steel flowlines, hydrotesting and commissioning procedures and considerations regarding their coating and cathodic protection.

In the last 3 years about 380km of duplex stainless steel flowlines have been installed. In the coming 3 year period less duplex flowline is expected to be installed, principally because of competition from other corrosion resistant flowline material options including the newly emerging martensitic stainless steels.

1. INTRODUCTION

In general terms, produced fluids are typically wet, corrosive, gas or multiphase fluids, which need to be transported in a pipe to a treatment plant for drying. The flowline is the pipe which carries the well fluids from the wellhead to the treatment plant. Flowlines may be fairly short lengths of piping if the wellheads are closely associated with the plant (for example wellheads on platforms) or they may be many kilometres long where wellheads are remote from the gas treatment facilities. In some cases several wellheads may be joined together at a manifold to gather the production and then a larger pipe, termed a gathering line, leads to the treatment plant. This paper is concerned with the use of duplex stainless steels for these flowlines and gathering lines. The fundamental interest in duplex stainless steels for flowlines is because of their resistance to CO₂-corrosion. They were identified as materials which could be used to replace carbon steels where the carbon steel would corrode too quickly or where the implementation of a corrosion inhibitor programme was impractical or found to be too expensive over the full duration of a project (1). In the 1970s and early 1980s the benefit of reducing the operating costs was often used to justify the expense of using duplex stainless steels (i.e. a life cycle cost view was taken). Furthermore, the use

of duplex stainless steels reduced the demand for manpower to operate, monitor and inspect a carbon steel system as they were identified to have much greater reliability in service.

Whilst there are many proprietary grades of duplex stainless steels, rather a small selection has been applied in the past for flowlines. The first alloy to be used for a pipeline application was the Sandvik Alloy 3RE60 (UNS S31500) which was used in 1975 in The Netherlands. The composition of this alloy is indicated in Table 1 along with typical compositions of the other main grades of duplex stainless steel which have been used for flowline service.

From the late 1970s onwards all the duplex stainless steel flowlines which were installed were 22Cr duplex stainless steel up until 1992 when some super duplex (25%Cr) grade flowlines were installed.

The shift from the 3RE60 grade material to the 22Cr duplex stainless steel can be readily understood as the latter material has a much more stable microstructure, reforming a balanced austenite - ferrite microstructure in the heat affected zone after welding. (The early 3RE60 grade tended to have a very high ferrite content in the heat affected zone with associated lower toughness properties).

Whilst there are many preparatory grades of the 22Cr type these have been unified over the years into one chemical composition, covered by the UNS designation, UNS S31803.

Table 1 - Chemical Composition of Duplex Stainless Steels Used in Flowlines.

Tab. 1 - Composizione chimica degli acciai inossidabili duplex utilizzati nelle flowlines.

| UNS No. Rev.1993 | C % | Cr % | Ni % | Mo % | N % | Mn % | Others % |
|---------------------|-------|-----------|---------|---------|-----------|-----------|-------------------------|
| S31500 (3RE60*) | 0.030 | 18.5 | 5.0 | 2.7 | 0.07 | 1.5 | 1.75Si |
| S31803 (22Cr) | 0.030 | 21.0-23.0 | 4.5-6.5 | 2.5-3.5 | 0.08-0.20 | 2.00 max. | |
| S32750 (SAF2507*) | 0.030 | 24.0-26.0 | 6.0-8.0 | 3.0-5.0 | 0.24-0.32 | 1.20 max. | |
| S32760 (Zeron 100*) | 0.030 | 24.0-26.0 | 6.0-8.0 | 3.0-4.0 | 0.20-0.30 | 1.0 max. | Cu 0.5-1.0 W 0.5-1.0 |
| S39274 (DP3W*) | 0.030 | 24.0-26.0 | 6.0-8.0 | 2.5-3.5 | 0.24-0.32 | 1.0 max. | Cu 0.2-0.8 W 1.5-2.5 |

*3RE60 and SAF2507 trademarks of AB Sandvik Steel, Zeron 100 trademark of Weir Materilas Ltd., DP3W trademark of Sumitomo Metal Industry Ltd

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The grades of superduplex stainless steel which have been applied are UNS S32750, UNS S32760 and UNS S39274. The improved corrosion properties and superior mechanical strength of the superduplex grades has been utilised for certain flowlines carrying higher pressure or more aggressive fluids.

2. PAST CONSUMPTION OF DUPLEX STAINLESS STEEL

The authors have carried out a detailed survey and analysis of the market for corrosion resistant alloy flowlines including the use of duplex stainless steels (2). Experience with duplex stainless steel flowlines dates back to 1975 with more than 845km now in service, approximately 400km (48%) being installed offshore. Particularly substantial use of duplex stainless steel flowlines was made in 1996 and 1997. The trend in past demand for duplex stainless steel is readily visualised by considering five year time periods as this smooths out inaccuracies in defining precise project timings. Figure 1 shows a sustained growth in the use of duplex stainless steel over more than 20 years.

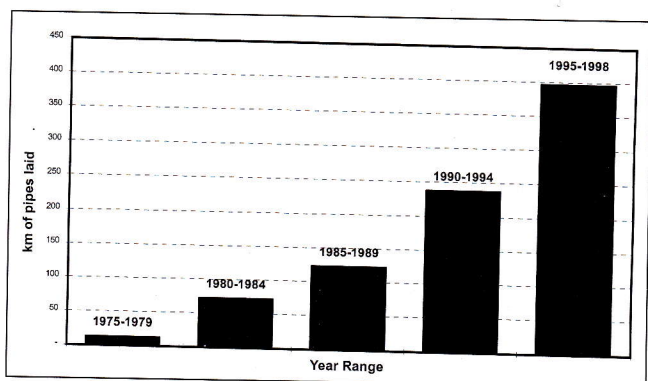


Fig. 1 – Length of duplex stainless steel pipelines laid in time periods since 1975.

Fig. 1 – Estensione delle pipeline in acciaio inossidabile duplex in periodi di tempo dal 1975.

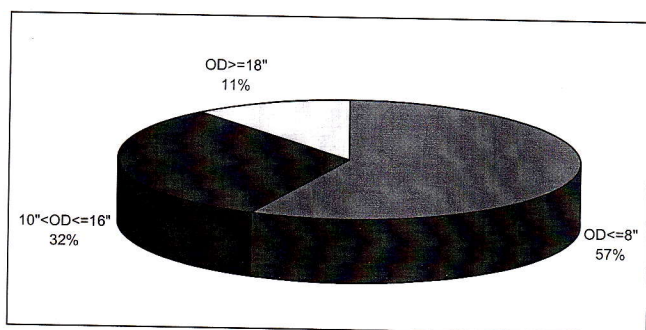


Fig. 2 – The distribution of past use of duplex stainless steel flowlines as a function of diameter.

Fig. 2 – Distribuzione dell'impiego di acciaio inossidabile nelle flowlines in funzione del diametro.

As stated in the introduction, early use was made of an 18-19% chromium content duplex (UNS S31500), but the majority of the pipelines are constructed in standard 22Cr grade (UNS S31803) with a small but significant use of superduplex (25Cr) grades (various UNS numbers). The distribution of usage in terms of length of pipe laid is 18.5Cr (0.5%), 22Cr (86.5%) and 25Cr (13%) grades.

The majority of the demand has been for pipes of 8" diameter or less, typical of flowlines from wellheads to production facilities. Some large diameter pipe in the range from 12" to 36" has been used for gathering lines from wellhead ma-

nifolds to treatment plants. This is clearly shown in Figure 2, showing the past use of small, medium and large diameter pipes.

3. PAST EXPERIENCE WITH DUPLEX STAINLESS STEEL FLOWLINES

In surveying the last 25 years experience with duplex stainless steels it is reasonable to state that the field experience has been very good. No flowline has failed because of internal corrosion problems during production. Selection of good quality starting material with correct microstructure and attention to optimised welding practice are necessary to ensure that the finished pipe meets all requirements for mechanical and corrosion properties.

Nevertheless, the application of duplex stainless steels has not been problem-free. Difficulties which have arisen with this class of materials have tended to be in ensuring that the weld region has optimum corrosion resistance in seawater, both in the weld deposit and in the surrounding heat affected zone, particularly in the presence of any heat-tint on the surface. In some cases the presence of high levels of ferrite in the microstructure, particularly in combination with high hydrogen charging from incorrectly designed cathodic protection systems has given rise to cracking, but such occurrences have been very rare.

A review of some of the experience given below is intended to aid future users of duplex stainless steels to avoid such problems.

3.1 Corrosion When In Contact With Water

There have been a number of cases where duplex stainless steel flowlines have failed because of exposure to oxygenated chloride-ion-containing water, either internally, for example, being brought into service, or on the external surface.

In the early applications of duplex stainless steels there was a tendency to regard them as the "answer to all corrosion problems" and there was a lack of recognition of their limitations with respect to pitting and crevice corrosion. An extreme example of this is the case of a 6" diameter 22Cr duplex stainless steel flowline which was installed offshore in warm seawater by Brunei Shell Petroleum in 1981. The flowline was not externally protected in any way either by coating or cathodic protection. It suffered severe pitting corrosion both externally and also internally as it had been filled with untreated seawater for hydrotesting.

Subsequent to this failure a much clearer understanding was reached of the tendency for pitting of this material. Good practice established the need to provide suitable external protection in seawater utilising coatings and cathodic protection and to hydrotest duplex stainless steel lines with water with chemical treatment to remove oxygen (so stopping the initiation of pitting and crevice corrosion) and biocide additions (to prevent microbiologically induced corrosion).

A comparable problem was experienced in the case of a 22Cr duplex stainless steel pipeline which was laid in the early 1980s in the Netherlands. The welds in this case were made using the shielded arc welding (SMAW) technique with basic electrodes. The finished welds had the typical features of SMAW welds with the oxidation of the heat affected zone causing blackening of the surface and the weld bead itself having an adherent flux layer. The line was laid on land and hydrotested using the most readily available water source which was canal water without any chemical treatment. After hydrotesting the canal water was left in the line for a period of some months before being flushed out. That length of pipe was subsequently attached to a longer length of flowline and the complete flowline hydrotested as

a single entity. The section of the line which had been originally hydrotested was then found to be leaking at many of the girth welds. Severe crevice corrosion had initiated at the flux coated welds and oxidised heat tinted zones where the surface condition reduced resistance to corrosion locally. This experience highlighted the fact that attention should also be paid to the ambient temperature and to minimising the duration of hydrotesting as well as to the water quality since the corrosion resistance of 22Cr duplex stainless steels in chloride-containing waters is not good, particularly where there are local spots of reduced corrosion resistance such as at welds.

The risks of crevice corrosion are highest around welds with surface flux or high temperature oxidised scales present. Optimum welding techniques can therefore be adopted to give as clean an internal surface as possible to help reduce the crevice corrosion cracking risk. In general this has meant that the SMAW technique is not applied except for flowlines where it is possible to clean away the flux on the inside surface (e.g. short flowlines or on plot piping). Gas shielded processes such as gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) with an inert internal backing shield are much preferred since they have much reduced heat affected zone oxidation and discoloration and no surface flux. Quality guidelines have been published which indicate allowed levels of discoloration which may be tolerated in the heat tinted area of welds (3). Optical examination of the internal surface of welds is a practical option using internal video inspection techniques.

Inevitably the SMAW technique has to be used in some pipelines and is also often used for repair welds so prevention of crevice corrosion at welds during hydrotesting also requires attention to the hydrotesting procedure and, particularly, the quality of the water used. If correctly treated water is used for hydrotesting then CRAs can be exposed to this controlled environment for long periods without initiating corrosion. So, in cases where a long period of commissioning is necessary it would generally be safer to keep a line filled with treated hydrotest water than, perhaps, to attempt to empty and dry a line, where there is always the risk of leaving puddles of water which slowly evaporate, concentrating an oxygenated, chloride-ion containing solution at low points along the length.

Besides the commissioning period, any damage to a duplex stainless steel pipeline during service which allows seawater to enter the line (for example, anchor damage) requires immediate action to remove the water to avoid any possible risk of pitting attack.

The use of duplex stainless steels also requires attention to the steps which are taken for commissioning of pipe including storage of the pipe in the field prior to welding where pipe should be racked at an angle to allow any water to drain out of the pipe.

There is also a need for care in avoiding the concentration of a salt solution on the external surface of pipe which is operating at high temperature as this might induce external chloride stress corrosion cracking under worst case conditions.

3.2 Embrittlement

Early problems experienced in fabricating duplex stainless steel pipe, flowlines and piping systems highlighted the risk of hydrogen cracking in welds with excessively high ferrite contents and the risk of embrittlement in welds made with too high heat input because of precipitation of sigma phase or '475°C embrittlement'.

In one case cracks were found in longitudinal welds in pipe which were found to have been 'dressed' with a GTAW torch, without using filler metal, in order to improve the weld surface appearance. The effect had been to introduce a rapid cooling cycle with the metal transforming to high tempera-

ture ferrite and then being quenched so that it did not reform a balanced duplex microstructure. The affected zones had ferrite contents in excess of 70% and suffered from delayed (hydrogen) cracking which was fortunately detected when X-raying a girth weld. Control of the ferrite content is critical with duplex stainless steels and requires careful control of the heat cycle and the use of welding processes with filler metal addition. This early welding experience was widely disseminated (4) and rapidly became incorporated in standard good practice.

3.3 Cathodic Protection

Hydrogen cracking of duplex stainless steels has also risen in certain specific cases because of the influence of cathodic protection. It seems that in cases where cathodic protection has resulted in hydrogen cracking there have also been other negative factors which have contributed to the failure. This also explains why the vast majority of duplex flowlines, which are also cathodically protected, have not failed as it may be assumed that they do not have the other negative aspects affecting their performance.

The Marathon Central Brae project, completed in 1989 was Marathon's first sub-sea development. Two 7km 6" diameter x 12.7mm wall thickness 22Cr duplex stainless steel flowlines were installed by reeling. The pipes were subjected to a rigorous evaluation with respect to their resistance to the internal corrosion conditions, the effect of the strain induced by reeling on the corrosion properties and the influence of applied cathodic protection (5). Other aspects investigated at length were insulation material performance and trenching and rock dumping requirements necessary to prevent upheaval buckling when the pipe was hot.

The cathodic protection (CP) investigation using slow strain rate tests (1.3x10⁻⁶S⁻¹) and constant load tests showed that the pipe potential had to be maintained between -450mV and -800mV vs. Ag/AgCl. Duplex steel samples tested at -850mV fractured in a partially brittle manner with secondary cracking along the whole length of the specimen. The CP design required only 4 aluminium alloy bracelet anodes because of the good insulating coating (12mm of solid polyurethane and 33mm of micro-cellular polyurethane) which had only a 1% breakdown value assumed. Schottky barrier diodes were placed in series with the connection to the pipe.

Bearing in mind the installation date of 1989 the care taken in the design of the pipe coating, cathodic protection and prevention of in-service thermal straining is remarkable. The in-service performance of these lines has been very good.

Other pipelines have been installed internationally with apparently less concern applied regarding these design issues and in the vast majority of cases there have been no problems. Where failures have occurred there have tended to be other factors, which have contributed to the failure.

In one example a pipeline failed on initial pressuring up after a shutdown whilst still cold. This 6" diameter, 14mm wall thickness 22Cr duplex stainless steel pipe had been in service at 100°C for four years. It was cathodically protected in the range -900 to -950mV.

The pipe was in the solution annealed condition with a normal microstructure (52% ferrite) and it met specification requirements for mechanical properties. The pipeline had experienced high thermal strains and because of a large number of on-off cycles the line had experienced it had steadily crept some distance across the seabed.

Cracking occurred at a fillet weld where an anode doubler plate was attached to the pipe wall causing some local stiffening. Finite element analysis estimated that the local tensile and bending stresses at this point were about 450MPa. In addition there would be unknown stresses arising from resi-

dual welding stresses and also thermal stresses from the difference in temperature across the pipe wall at start up plus the local stress concentration from the fillet weld. It is estimated that there was 2-3% strain at the location where cracks initiated.

The original epoxy phenolic coating of the pipe had blistered off large areas of the pipe due to the rather high temperature. On the retrieved sample which had no coating remaining, hydrogen measurements made close to the surface of the pipe indicate approximately 29ml of hydrogen/100g metal. The bulk level of hydrogen was much lower at about 4ml/100g. Other parts of the pipe, which were coated with a good polypropylene layer and where the coating was still adhering had only 2ml hydrogen/100g.

Undoubtedly, a key aspect in causing the crack initiation is the local stress concentration at the fillet wells. Another anode doubler plate has been retrieved and inspected and another crack was found on that but this was away from the peak bending stresses and therefore this crack had not grown.

The implication of this experience is that thermal stresses should be minimised and coatings should be carefully selected for the required operating temperature. There is also the possibility of limiting the cathodic protection potentials in order to reduce hydrogen pick-up.

Another case history is a subsea manifold which was constructed from a 25Cr duplex stainless steel. The manifold had been in position on the seabed for approximately 6 months. It had not been put into service and therefore the temperature was approximately ambient (about 4°C). The structure, which apparently, was not originally coated, was protected with aluminium anodes at about -12000 to -1060mV.

Pressure testing at this stage indicated that there were cracks on two ROV hubs. These were heavy section forgings, the surface of which had been machined back to produce the lands onto which out-coming pipes were welded. The forging process caused a noticeable grain orientation effect. The grain size was fairly large but the material had a good phase balance and was free of microstructural problems. The cracks were found to have initiated away from the attachment welds and HAZ. The precise location of the cracks was shown to be at the position of maximum stress concentration at the connection of the pipes to the hub.

The cause of the cracks is felt to be a combination of the effect of hydrogen uptake into the material from the applied cathodic protection plus local plastic strain due to the stress concentration. Laboratory simulation of the failure has been possible where specimens were strained to over 3.5%. The microstructure may have contributed to the failure in making cracking easier than might have been the case in an optimum equiaxed microstructure.

Prevention of cracking at other hubs in the field was carried out by preventing hydrogen entry through application of a heavy epoxy coating and by making individual stress analyses to decide which hubs were acceptable for service.

Again, the correct use of coatings and possible limitation of the cathodic protection current would minimise hydrogen entry whilst optimisation of the design to reduce stresses might reduce the risk of crack initiation. Thus no one factor can be identified as the single cause of the failure.

4. THE FUTURE DEMAND FOR DUPLEX STAINLESS STEEL FLOWLINES

Considering the future demand for duplex stainless steels it is anticipated that there will still be quite a number of duplex stainless steel flowlines installed over the coming 5 years but the installed quantity will probably reduce quite signifi-

cantly compared to the past 5 years. The principal reason for this change is the emergence of the so-called 'weldable' martensitic stainless steels which are being evaluated by many companies as potential flowline materials. Installations of these new materials have been made onshore by Shell in Nigeria and in the Netherlands and offshore by Statoil. The term 'weldable' means that these are steels which have a composition which gives a relatively soft martensite in the heat affected zone with reasonable as-welded hardness and toughness.

On a cost basis martensitic stainless steels are somewhat cheaper than stainless steels (between 60 and 80% of the price of 22%Cr duplex stainless steel) and so there is quite some economic interest in these materials and they are being strongly evaluated and actively considered as replacements for duplex stainless steel where technically appropriate.

Nevertheless, they are not regarded at present as fully established materials for which all of the questions are answered regarding their response to welding, weld zone mechanical and corrosion properties and their response to cathodic protection. Despite these aspects which still require investigation the increasing interest in martensitic stainless steels is felt to be likely to have the most significant impact on the amount of duplex stainless steel which will be installed over the coming 5 years.

5. CONCLUSION

Duplex stainless steel flowlines have been widely applied in the oil and gas industry. They have served the industry well with very few field failures arising and no field failures occurring because of corrosion in the production environment. Problems arising during the early applications of some of these flowlines have been discussed and documented resulting in improved practice regarding their fabrication, installation and operation. Successful use of duplex stainless steel flowlines requires optimum welding, hydrotesting and commissioning procedures and careful consideration regarding their coating and cathodic protection.

Past experience may be applied such that projects can now go ahead with duplex stainless steel in full confidence and understanding of how to avoid any potential problems. More than 845km of duplex stainless steel is now in service with 400km being installed over the last 3 years showing a steady growth in demand over the past two decades.

Future demand for duplex stainless steel is anticipated to drop over the coming 3-5 year period because of competition from alternative flowline materials, particularly martensitic stainless steels.

REFERENCES

1. Smith L.M. and Celant M., Life Cycle Costing - Are Duplex Stainless Steels the Cost-Effective Choice? Paper KIX, Duplex '94, Glasgow, Scotland, 13-16th November 1994
2. Smith L.M. and Celant M., "Corrosion Resistant Flowlines - Market Analysis and Technical Trend", Confidential report to a group of sponsors, August 1998.
3. Smith L.M. and Klein M.R., "Acceptance Criteria for Oxidation of Stainless Steel Weldments", Stainless steel World Vol. 8, Issue 10, December 1996
4. Goenewoud K, "Application of Ferritic-Austenitic Stainless Steels in Oil and Gas Production", UK National Corrosion Conference 1982
5. Farrow R, "The Central Brae Pipelines", Offshore Pipeline Technology Conference, 8-9th February 1990.

**GLI ACCIAI INOSSIDABILI DUPLEX PER "FLOWLINES"
PASSATO PRESENTE E FUTURO**

Il primo impiego di acciai duplex nelle flowlines risale al 1975. Da allora ha mostrato una crescita sostenuta, tanto che ad oggi sono più di 845 km le flowlines in acciaio inossidabile duplex attualmente in servizio, di cui circa 400 km (il 48%) utilizzate negli impianti offshore.

Sebbene in alcune applicazioni iniziali veniva utilizzato un duplex con tenore di cromo del 18-19% (UNS S31500), la maggior parte delle flowlines sono costituiti dalle classi standard di acciai 22%Cr (UNS S31803) e da una piccola ma significativa porzione di superduplex (25%Cr).

La distribuzione dell'impiego in termini di lunghezza dei condotti installati è dello 0,5% per gli acciai duplex 18,5%Cr, del 86,5% per gli acciai duplex 22%Cr e 13% per

gli acciai duplex 25%Cr. Il diametro dei tubi impiegati riguarda tutta la gamma dai 4 ai 36 pollici.

La presente memoria passa in rassegna i dettagli applicativi di alcune di queste flowline unitamente alle esperienze per la loro fabbricazione, messa in opera e servizio.

Fa inoltre un riepilogo delle tecniche ottimali per la saldatura delle flowlines in duplex, dei metodi di prova (hydrotesting) e offre alcune considerazioni inerenti a metodi di ricopertura e protezione catodica.

Negli ultimi 3 anni sono stati installati circa 380 km di flowlines in acciaio inossidabile duplex.

Nei prossimi 3 anni è previsto un minore impiego di duplex, attribuibile in gran parte alla competizione con altri materiali per flowlines resistenti alla corrosione fra cui gli emergenti acciai inossidabili martensitici.