FLUX CORED WIRE FOR DUPLEX STAINLESS STEELS

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Abstract

Because of their superior mechanical and corrosion resistant properties over conventional austenitic stainless steels, duplex stainless steels have been increasingly used in many industry areas, especially in the offshore, petrochemical and shipbuilding industries. In the fabrication of duplex structures, compared with shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) processes, the application of flux cored wires (FCW) has been limited, although this process has a great potential for a significant improvement in productivity. This is mainly attributed to a lack of suitable wires that are capable of offering all-positional operability, particularly for the positions of ASME 5G/6G fixed pipework. Development work of an all-positional rutile flux cored wire for duplex steels has recently been carried out which resulted in the formulation and manufacturing technologies for the wire being well established. The design of the wire successfully achieved a combination of satisfactory operability, especially for difficult welding positions, radiographically sound weld metal and adequate impact toughness at sub-zero temperatures. In this paper, the design philosophy of the wire and its welding performance with a special emphasis on the positional capability are introduced. The weld metal properties together with the results from procedure testing and practical considerations are also presented.

Key Words

FCW, Duplex, Positional Weldability, Toughness, Productivity

1. INTRODUCTION

In recent years, the application of duplex stainless steels has increased rapidly in various industry areas, particularly in the offshore, petrochemical and shipbuilding industries [1-4]. This is mainly attributed to their alloy design which consists of 22-24%Cr with about 5%Ni, up to 4%Mo and a controlled addition of nitrogen. These produce a well balanced ferritic/austenitic duplex microstructure, and hence a unique combination of high tensile strength, enhanced corrosion resistance and good toughness at sub-zero temperatures (e.g. -50°C).

The welding industry has been keeping up with the pace of parent material developments. Welding technologies for duplex steels are now well established and various types of welding consumables, such as SMAW electrodes, solid wires for GTAW, gas metal arc welding (GMAW), submerged arc welding (SAW) processes and some flux cored wires are readily available for the fabrication industry.

In the fabrication industry, although submerged arc welding and gas metal arc welding with solid wires and, to a much lesser extent, flux cored wires are employed, the most commonly used processes for welding duplex stainless steels have been GTAW and SMAW, particularly for thicker-section pipe which cannot be rotated, or large vessels where the use of positioners is impractical. However, because of their relatively low deposition rate, GTAW and SMAW processes can prove to be time-consuming and hence less economic. This disadvantage has raised an increasing concern among industries which are always keen to cut costs and remain competitive. Improved welding productivity has become a major driving force and this has led to welding consumables manufacturers developing consumable which can offer higher productivity while maintaining weld consistency and joint quality.

GMAW with a flux cored wire, as a semi-automatic continuous wire process offers a higher deposition capability than GTAW, SMAW and solid wire GMAW processes and therefore has the potential for a significant improvement in productivity. Figure 1 compares the deposition rates of different processes and shows a significant advantage of FCW. Until very recently, however, the application of FCW in welding duplex stainless steels has remained limited, although some progress in this area has been made and reported [5, 6]. The main reason for this is that there are very few flux cored wires available in the market which are suitable for positional welding. Moreover, of the wires that are claimed to be all-positional, many are actually only suitable for some ‘easier’ positions like ASME 3F/3G and small angled inclined welding and cannot satisfactorily cope with the more stringent operability demanded by ASME 5G/6G fixed pipework. This has been confirmed by the procedure tests carried out by many offshore fabricators. These flux cored wires, strictly speaking, should only be categorized as ‘semi’ positional. Therefore, sourcing wires with ‘real’ positional welding capability has become a major challenge to the duplex fabricators who are seeking to take advantage of the increased productivity achievable by using FCW.

This paper presents the successful development of an all-positional duplex flux cored wire which resulted in SUPERCORE 2205P that meets the exacting demands of the offshore industry and stringent requirements of pressure vessel codes. The design philosophy of this wire and its welding operability with a special emphasis on the positional capability are introduced. The weld metal properties and microstructure together with the results of procedure testing and practical considerations are also presented.

2. DESIGN REQUIREMENTS

The major challenge facing the development of this type of flux cored wire was optimising the formulation design to achieve 'user friendly' operability with all-positional capability (including fixed 5G/6G pipework), conformance to the relevant national standards (e.g. AWS) with an appropriate weld metal microstructure and sub-zero temperature impact properties. To achieve these, the following were considered to be the key aspects.

2.1. Specified deposit composition ranges and microstructure control

The basic weld metal composition of the flux cored wire should match that of the standard 22%Cr duplex stainless steels. Due to the special nature of the welding thermal cycle, the deposit composition was required to overmatch the nickel content of the parent material in order to achieve a similar dual-phase microstructure balance, namely 30-50% ferrite. At present, there is only one relevant national standard-AWS A5.22 E2209T0-X [7][1]. The compositional requirements of this specification are listed in Table 1.

2.2. Operability consideration

As indicated above, the most important feature for an all-positional rutile flux cored wire is its operating characteristics, especially for pipework fabrication in the offshore industry. In order to perform satisfactorily, in what is generally considered to be the most difficult situation, i.e. the 5 to 7 o'clock position on a fixed 5G pipe, the wire must operate in the spray transfer mode, with a stable spatter free arc at low voltages.

Apart from the positional capability, the weldability of the wire in other positions was also considered important, since this would allow a single wire to be used for fabrication work that involves both positional welding and work in the flat position.

2.3. Slag removal and weld profile

Slag detachment is one of the essential features for judging the quality of a flux cored wire. An easy and self-releasing slag can not only provide a neat cosmetic bead appearance, but more importantly minimise the need for post-weld dressing and so lead to improved productivity. Avoidance of entrapped slag and the potentially adverse effects on weld radiographic quality is also considered to be important. With the rapid development of flux cored wire design in recent years, many of the latest FCWs for austenitic stainless steels demonstrate excellent slag removal and set a standard and a level of expectation from the users which any new wire has to achieve.

2.4. Mechanical and corrosion properties requirements

The tensile strength of duplex stainless steel weld metals are not normally a concern, they will comfortably exceed the requirements of matching base materials. The impact properties, on the other hand, have considerable importance in applications requiring adequate toughness at sub-zero temperatures (down to as low as -50°C), such as offshore structures and land-based oil and gas systems. Most offshore specifications will have a minimum Charpy impact requirement, normally at -46°C or -50°C. For example,

NORSOK M601 [8]:	27 Joules at -46°C
Shell ES124 [9]:	41 Joules average and 27J minimum individual value at -50°C
Shell ES106 [10]:	40 Joules average and 30 Joules minimum individual value at designed temperature.

Pressure vessels codes also lay down requirements for the use of duplex stainless steel consumables, although, in terms of specified temperatures, they are normally higher than those for the offshore structures.

Another key property of duplex steels is pitting corrosion resistance. This is controlled by alloy content and indicated by the Pitting Resistance Equivalent Number (PREN), based on the following commonly used empirical equation,

$$PREN = Cr + 3.3Mo + 16N$$

Naturally, welding consumables are required to match the PREN of the parent materials. The PREN of duplex weld metals are normally controlled within a range of 34-38.

2.5. Wire feedability

It is well known that the operability of a flux cored wire is critically dependent upon the wire feedability. The required operability of a wire cannot be achieved unless the wire can be fed through the system smoothly and consistently. For this reason, it is essential that the wire is manufactured, lubricated and tested to guarantee consistent, satisfactory feedability.

3. THE FCW DEVELOPMENT AND PRACTICAL TESING

With the above requirements in mind, the newly developed wire, Supercore 2205P, was systematically tested and modified until it reached its current design, which successfully achieved the optimum combination of all-positional operability and properties.

The wire was designed to be used with a shielding gas mixture of Ar-20%CO_2 (with or without 2%O_2). The evaluation included two major aspects, i.e. laboratory examinations of operability, radiographic and mechanical inspections; and formal procedure qualification testing. The operability evaluation was carried out using a variety of welding positions, including ASME 1F/G, 2F/G, 3F/G, 4G, 5G and 6G. The procedure qualification testing was carried out by Kvaerner Oil & Gas with a butt weld in a fixed 6G pipe.

3.1. Weld metal composition and microstructure

In order to insure optimum and consistent ferrite-austenite balance and hence consistent mechanical and corrosion properties, the deposit analysis of the Supercore 2205P wire was controlled to far tighter limits than the AWS specification (as shown by Table 1).

The all-weld metal of Supercore 2205P showed a typical duplex microstructure with a ferrite content of 30-50FN (the ferrite content of the weld metal was measured using a Feritscope calibrated with IIW secondary standards). Figure 2 illustrates the microstructure of the capping bead from a fixed 6G pipe butt joint completed using Supercore 2205P in the procedure testing. This particular weld had a ferrite content of 50FN.

3.2. Operability and positional capability

The general design philosophy of the formulation was to provide the wire with a strong but smooth arc drive and a supportive slag, so that spray transfer with a easy control of weld pool can be achieved at the most difficult welding positions, such as 5-7 o'clock with a 5G pipe.

Supercore 2205P satisfactorily accomplished the required features through its specially designed flux system. The flux has the combined attributes of allowing a stable, spatter free spray transfer to be maintained at the low voltage/current needed for optimum positional welding, namely 22-24volts/140-160amps, and a fast-freezing slag for good weld pool support and control. The wire also demonstrated an excellent, self releasing slag which produced a uniform weld bead profile and a radiographically sound weld deposit.

Based on the results of the systematic evaluation over a wide range of operating conditions, an operability tolerance box was established, as shown by Figure 3.

3.3. Mechanical properties

The Charpy impact toughness of all-deposit metal and weld joint of Supercore 2205P wire was tested at sub-zero temperatures down to -50°C. Using a shielding gas of 78%Ar+20%CO_2+2%O_2 (80/20), the test pieces were prepared at different welding positions, including fixed pipe (6G), vertical-up (3G) and flat (1G). The results are shown in Figure 4. The deposits of the wire demonstrated consistent impact properties in both all-weld plates and pipe joints, irrespective of welding position. The toughness values comfortably meet the above mentioned requirements for both offshore structures and pressure vessels. The average and minimum impact properties found in tests at -50°C are as follows:

	All-weld	All-weld	Pipe joint
	Flat/downhand (1G)	Vertical-up (3G)	6G
CVN @-50°C:	49J avg. (46J min)	48J avg. (44min)	51J avg. (45J min)

For applications which are likely to be subject to sour service conditions then the material requirements of NACE MR0175 are normally imposed. The NACE standard defines maximum hardness levels that are acceptable to ensure resistance to sulphide stress corrosion cracking (SSCC); for UNS S31803 this is 36HRc maximum.

Using a 10kg load, the Vickers hardness of Supercore 2205P weld metals was assessed. The results showed the hardness to be in the range of 250-300Hv. Using the ASTM E140 Hv-HRc correlation (for carbon steels) [11], 300Hv correlates to 30HRc; using the more recent TWI (The Welding Institute) Hv-HRc correlation [1] 300Hv is equivalent to only 25HRc. These indicate that the typical hardness values of Supercore 2205P deposits fall well below the 36HRc maximum.

3.4. Corrosion properties

In order to ensure a satisfactory corrosion resistant property, the PREN of Supercore 2205P was controlled within the range of 34-38, typically being >35. To evaluate the corrosion resistant property of Supercore 2205P deposits, a pitting corrosion test of as-welded metal was carried out in $FeCl_3$ media (G48A procedure). During the test, the capping runs were subjected to the testing media. The results showed that the Supercore 2205P weld can reliably meet G48A corrosion test requirements up to at least +22.5°C.

In general, the most critical area for corrosion on a single-sided weld is the root because the weld metal and heat affected zone (HAZ) in this area are subjected to reheating from subsequent welding thermal cycles. FCW would not normally be expected to be used for single-sided root runs so would not be subjected to these conditions. If, however, FCW were to be exposed to process media, it would be in the as-deposited conditions, i.e. the capping runs.

3.5. Feedability Test

Using an automatic welding rig, the feedability of Supercore 2205P wire was tested. The test duration was controlled to be ~15-20 minutes continuous welding, which was considered to be representative of semi-automatic welding. Figure 5 shows a typical feeding trace of the wire during welding. This trace qualitatively illustrates the level of friction between the wire and liner, which gives indication of the degree of difficulties of feeding the wire through the welding hose cable during welding. Supercore 2205P demonstrated very smooth and stable feedability. This, in turn, partially contributed to its satisfactory operability.

3.6. Procedure testing results

The procedure qualification testing was carried out with a standard 2205 type duplex pipe of 168.3mm OD × 18.26mm thickness. The details of the joint geometry and weld run sequence are illustrated in Figure 6. After two root passes of GTAW, the butt joint was completed using 12 passes of Supercore 2205P filler. Non destructive examination which included 100% radiography and 100% dye penetrant inspection was carried out. The Charpy impact toughness at -50°C, side bend properties and pitting corrosion resistance at +22.5°C of the weld joint were assessed.

The macro-image of the joint is shown in Figure 7. Satisfactory results were achieved with all the scheduled tests. The absorbed impact energy of the weld cap was very consistent with 55J average and 56, 55, 54J individual values. Figure 8 plots out the transverse hardness distribution of the weldment across the capping area.

The procedure test also confirmed the productivity advantages of applying flux cored wire. In the test, after the GTAW rooting, 22 minutes arc time of FCW was required to complete the pipe joint. This is about a third of the arc time needed if the SMAW process were used for a joint with the same dimension, and only about one quarter of the time required by GTAW.

4. PRACTICAL CONSIDERATIONS

According to the results of the comprehensive evaluations of Supercore 2205P, some practical considerations have proved to be important when using flux cored wire for fixed duplex pipework (5G/6G) or for positional welding of large duplex tanks and vessels.

4.1. Minimum material thickness and pipe diameter

For plate, flux cored wire can be used on any thickness from about 6mm upwards for fillet welds but for butt welds 10mm is a more practical minimum. When welding pipe, the use of flux cored wire should be considered if the pipe dimensions are above the following guidelines:

15mm wall thickness
6" diameter
e.g. 6" NB Schedule 160

4.2. Joint preparation

The joint preparation should be selected on the basis that it must be wide enough to allow access for the welding gun, but the volume of joint kept to a minimum to allow maximum productivity. Typical joint preparations are shown in Table 2.

4.3. Root welding

Flux cored wire is normally not designed for depositing root runs, and in most cases, even the second pass should be deposited using the GTAW process. As indicated earlier, the root is normally the most critical region from a corrosion viewpoint, so the procedural control for the root and second ‘cold pass’ should be very tight. A relatively wide root gap (about 4mm) will ensure sufficient filler being added to the root to produce as large a weld bead as practicable. The second pass (or ‘cold pass’) should be deposited using a heat input of about 60-75% of the root run, to minimise the risk of overheating the root run.

4.4. Welding parameters

Supercore 2205P was designed to be used with a gas mixture of Ar-20%CO_2 (with or without 2%O_2) and the gas flow rate should be controlled in the range of 20-25l/min. The wire stickout length should be maintained at 15-20mm. For 5G/6G pipe, it may be necessary to reduce the stickout length to about 10mm in the 5 to 7 o’clock position to maintain optimum weld pool control.

Welding gun manipulation is also important to achieve an optimum FCW weld bead, particularly during positional welding. For example, in the ASME 3F/3G position, the gun should be angled down from the perpendicular by about 10-20°, while in a 5G/6G pipe joint, the gun angle should normally be kept at about 80-90°, as shown by Figure 9.

5. CONCLUSIONS

An all-positional rutile flux cored wire for standard duplex stainless steels, Supercore 2205P, has been developed. The wire demonstrates excellent positional welding capability. It offers an important and high productivity option for welding duplex stainless steels, especially for constructions involving difficult welding positions, such as fixed pipe work in the offshore industry.

Supercore 2205P operates in a spray transfer mode with a very stable, spatter-free arc and has easy slag removal producing an excellent uniform weld bead profile. The weld deposits achieve satisfactory and consistent mechanical properties, particularly impact toughness at sub-zero temperatures, which meet all current specification requirements for offshore structures and pressure vessels. The weld metal of Supercore 2205P also shows good pitting resistance in procedure testing. In terms of productivity, the flux cored wire demonstrates a significant improvement over the SMAW and GTAW processes. For completing a 6" diameter 18mm wall thickness pipe in the 5G/6G position, Supercore 2205P would save about two thirds of the arc time over the SMAW or three quarters over GTAW process.

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[9] Shell U.K. Limited, Welding and Inspection of Process and Utility Pipework, Doc. No.: ES/124 Part 1, Rev. 1, 1993.

[10] Shell U.K. Limited, Welding of Steel Pipelines on Land and Offshore, Part 2: Duplex and Super Duplex Stainless Steels, Doc. No. ES/106, Rev. 0, 1997.

[11] American Society for Testing and Materials, ASTM Satndard E140-95, Standard Hardness Conversions tables for Metals. ASTM Vol. 0301, 1996.

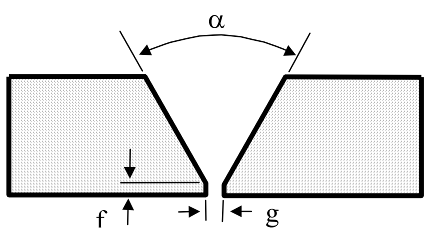
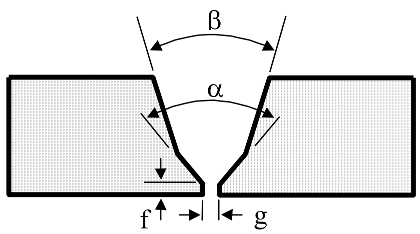
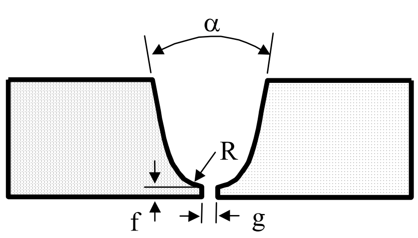
Notes:
1. The AWS specification only recognises a duplex flux cored wire for use in the 1G/2F positions and this is classified as **T0**. All other classification details are relevant to an all-positional wire.

Table 1. Chemical composition ranges of specification and Supercore 2205P

	AWS A5.22 and ASME SFA-5.22	Supercore 2205P (Range)	Supercore 2205P (Typical)
C	0.04[1]	0.04	0.03
Mn	0.5-2.0	0.5-2.0	0.9
Si	1.0	0.5-0.9	0.7
S	0.03	0.02	0.009
P	0.04	0.03	0.025
Cr	21.0-24.0	21.5-23.5	22.8
Ni	7.5-10.0	8.5-10.0	8.8
Mo	2.5-4.0	2.8-4.0	3.4
N	0.08-0.20	0.10-2.0	0.12
Cu	0.5	0.5	0.1
PREN[2]	-	34-38	>35

1: Single values in the specification and composition range are maximum values;
2: PREN = Cr + 3.3Mo + 16N

Table 2. Joint preparations

	Wall Thickness (mm)	**Included angle (°) α**	**Included angle (°) β**	**Root gap g (mm)**	**Root face f (mm)**
	2 – 3	70 – 90	-	2 – 3	0.5 – 1.5
	> 4	70 – 80	-	2 – 4	0.5 – 1.5
	> 20	70 – 80	15 – 20	2 – 4	0.5 – 1.5
	> 20	15 – 30	Radius R (mm) 4 – 6	2 – 4	0.5 – 1.5

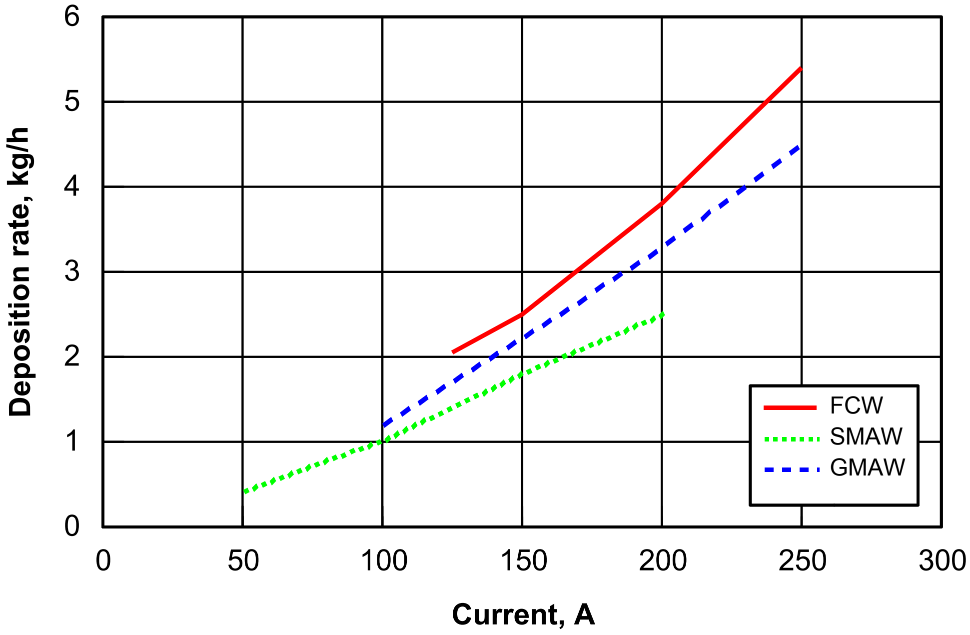


Figure 1. Deposition rate comparison of different welding processes

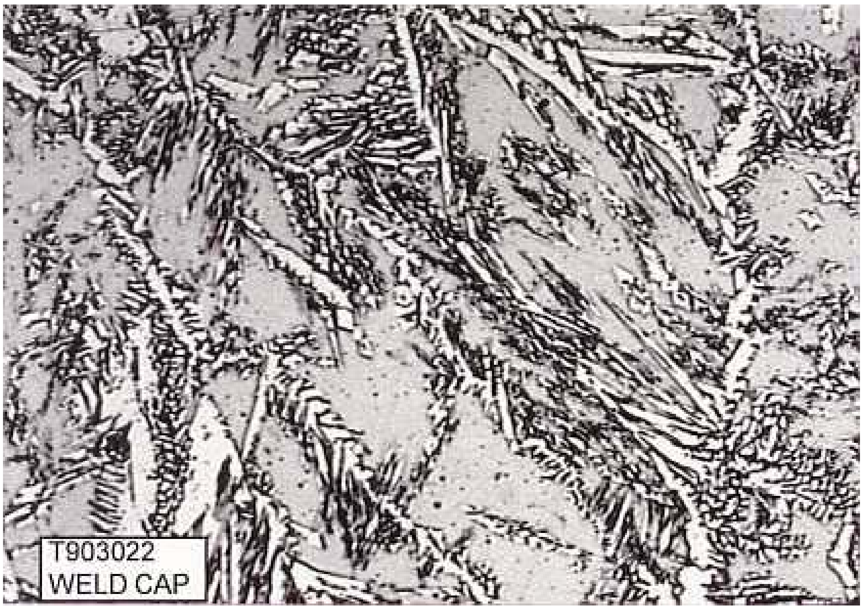


Figure 2. Typical microstructure of weld metal of Supercore 2205P, ×400

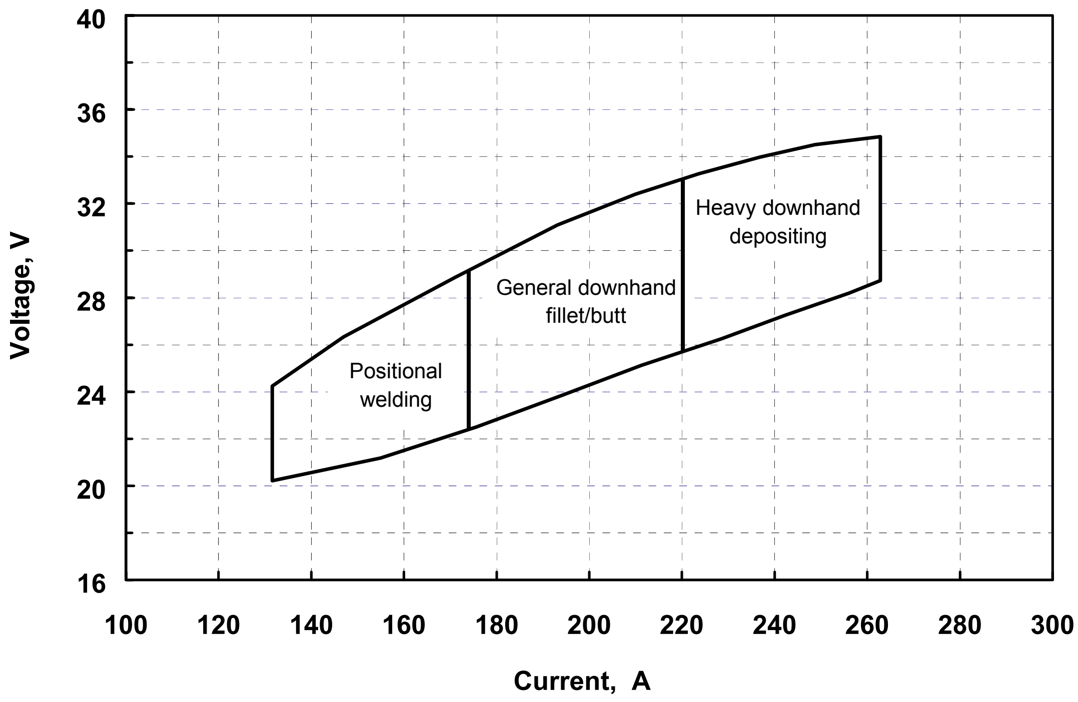


Figure 3. Operability tolerance box of Supercore 2205P

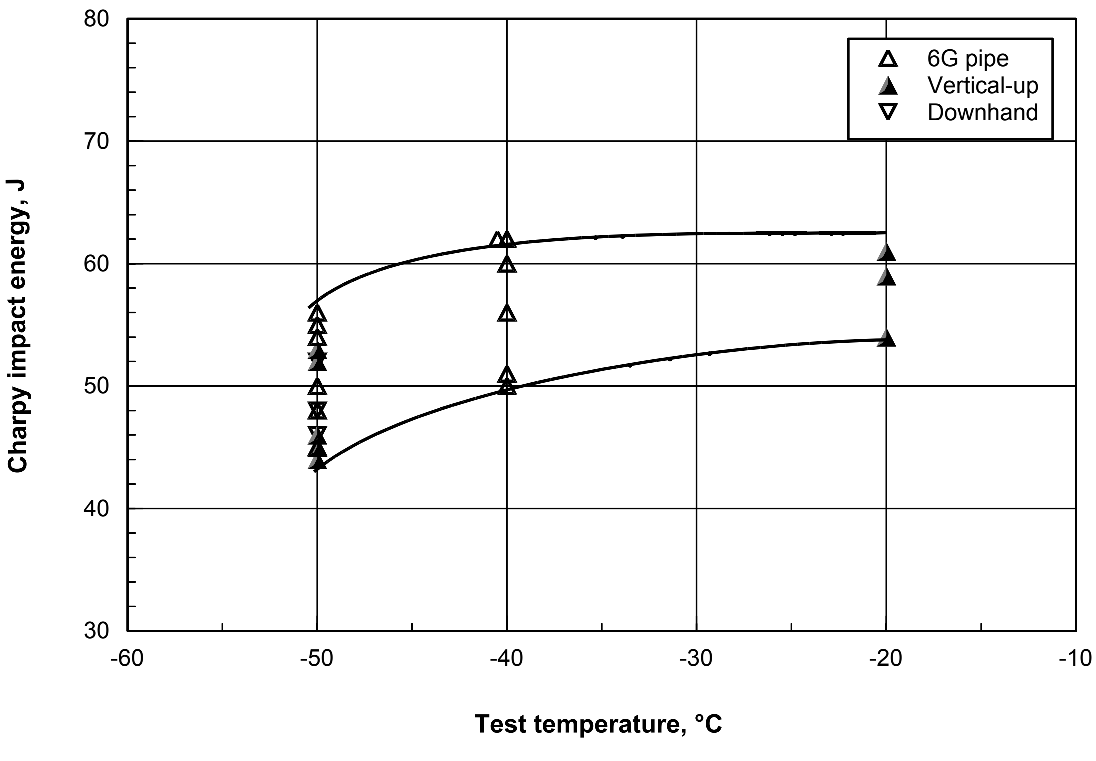


Figure 4. Charpy impact properties of weld metal of Supercore 2205P

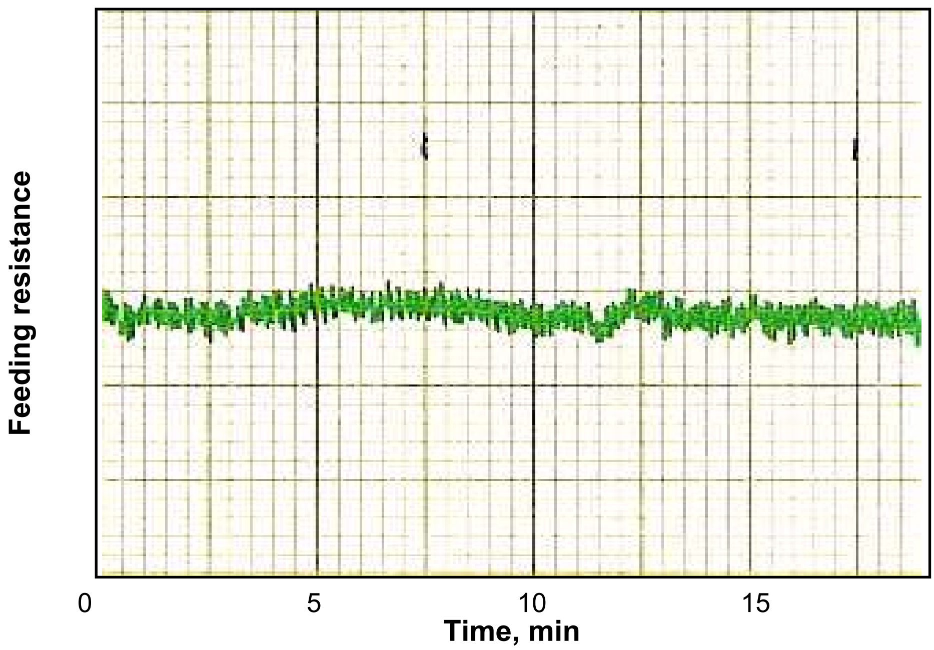


Figure 5. Feeding trace of Supercore 2205P wire

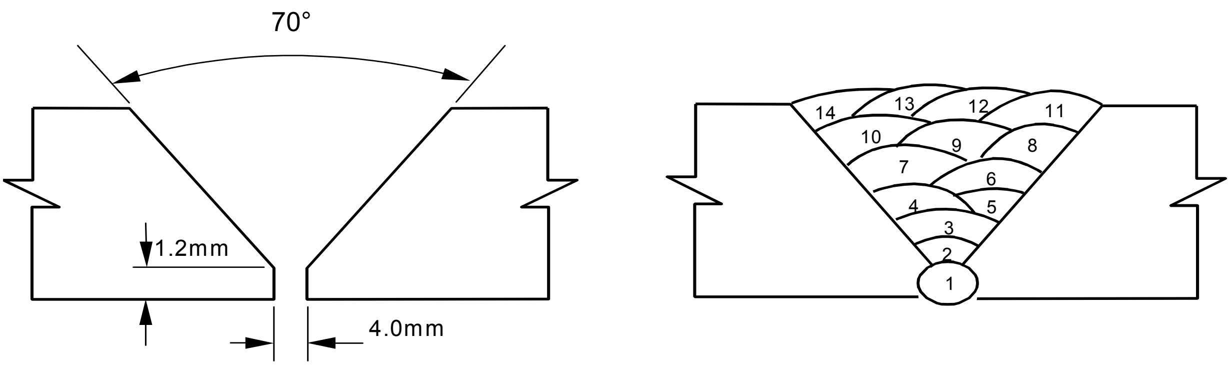


Figure 6. Joint preparation and weld run sequence of the procedure testing with the 6G pipe

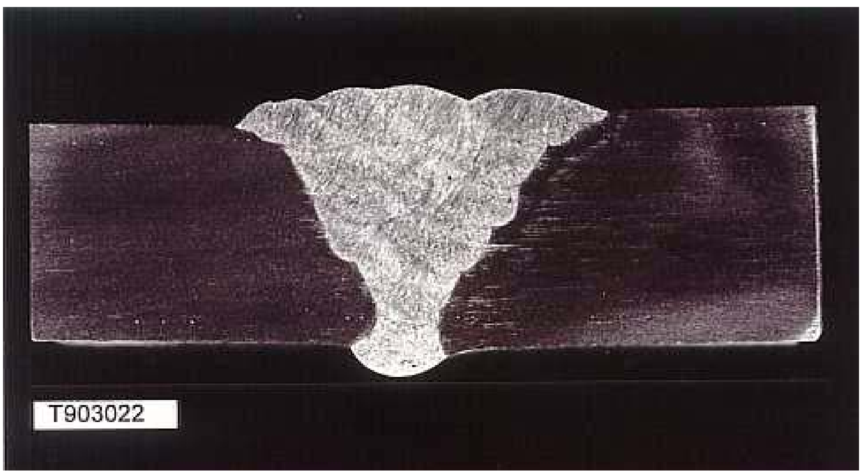


Figure 7. Macro-image of the fixed 6G pipe joint

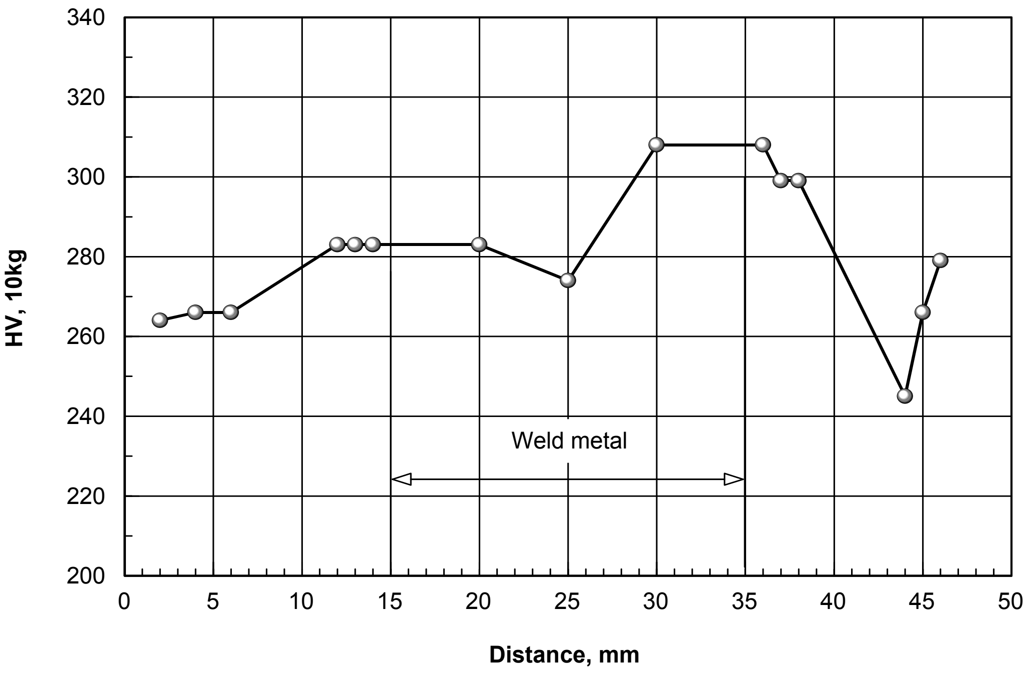
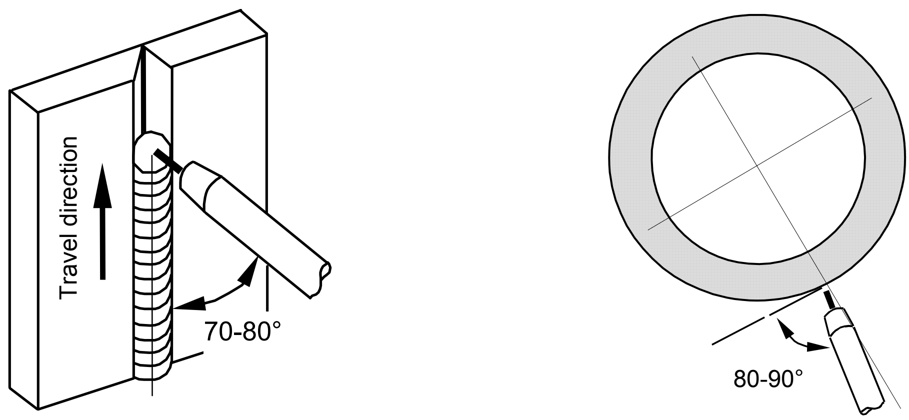


Figure 8. Hardness variation along the capping area of the fixed 6G pipe joint



(a) ASME 3G

(b) ASME 5G/6G

Figure 9. Welding gun manipulations in positional welding