CORROSION RESISTANCE OF INCONEL® alloy 725 WELD OVERLAY

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Abstract

Alloy 725 (UNS N07725) is a highly corrosion resistant alloy capable of being age hardened to 0.2% yield strengths of above 827 MPa. The alloy can be easily welded using slight modifications to standard techniques during fabrication. This is typically accomplished by using the GMAW process at low currents. Alloy 725 is resistant to pitting, sulfide stress cracking (SSC) and stress corrosion cracking (SCC) in Deep Sour Gas Well (DSGW) environments containing NaCl, H_2S and S. This paper is an in-depth summary of the mechanical properties and corrosion resistance of alloy 725 weld overlays on steel.

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Introduction

High performance alloys have traditionally been specified in oil field applications, where corrosion resistance is required[1,2]. Historically, welding has been used to overlay the corrosion resistant alloy on low alloy steel[3] and for joining wrought age-hardenable nickel alloys. One of the main concerns has been the
mechanical properties.

Historically, alloy 625 has been used for weld overlay applications. Because of relatively low room temperature mechanical properties, alloy 625 weld overlays has been limited in areas where galling and high contact stress are of concern. Alloy 725 is a corrosion resistant alloy, which provides an excellent high strength alternative to alloy 625 weld overlays.

Procedure

Weld Overlay

Welding of the overlay was performed on AISI 4130 and AISI 4140 tube 25.4 cm O.D. x 15.25 cm I.D. x 30.48 long. On the 4130 steel, a single 1.02 cm layer of alloy 725 was deposited on the inside diameter. On the 4140 steel, 1.02 cm layers were deposited[4].

GMAW (gas metal-arc welding) was done utilizing the globular transfer mode. Following welding, various stress relief treatments were performed on the weld overlays as shown in Table I. The stress relieving temperatures for the 4130 and 4140 steels are within the aging temperature range for alloy 725.

The chemical compositions (wt.%) of wrought alloys 625 and 725 are as follows:

Alloy	C	S	Si	Mn	Al	Cr	Ni	Mo	Nb	Ti	Fe
625*	0.10	0.015	0.50	0.50	0.40	21.5	61	9	3.65	0.40	2.5
725	0.010	0.001	0.03	0.07	0.23	20.9	56.3	8.1	3.54	1.50	9.1

* Analysis of welding wire unknown, nominal values are listed along with maximums for C, S, Si, Mn, and Al.

Slow Strain Rate Test of Weld Overlay

The slow strain rate test (SSRT) specimens were machined from 1 and 2 pass weld overlays. SSRT's were conducted in accordance with the latest draft of the National Association of Corrosion Engineers (NACE) Technical Activities Committee T-1F-9 standard on "Slow Strain Rate Test Method for Screening Corrosion Resistant Alloys (CRA's) for Stress Corrosion Cracking in Sour Oil Field Service." As the material was age-hardened, the specimens for SSR testing were completely wet ground to avoid machining stress. SSR tests were conducted in a 5% NaCl + 0.517 MPa (75 psig) H_2S + 2.758 MPa (400 psig) CO_2 environment at 149°C and 177°C at a strain rate of 4×10^{-6} sec^{-1}.

Results and Discussion

Weld Overlay

Mechanical Properties. Table I displays the room temperature tensile (RTT) properties for as-welded alloy 725 weld overlays aged at 635°C and at 663°C for 2, 3 and 8 hours at temperature. A 663°C age produced material with a 5 to 10% higher yield strength than material aged at 635°C for the same time at temperature. Depending on aging temperature and time at temperature, the yield strength varied from 591.6 to 730.2 MPa. As expected, yield strength increased with increasing time at temperature.

Table I Alloy 725 Weld Overlays, Room Temperature Tensile Properties

Condition	*0.2% Yield Strength (MPa)*	*Tensile Strength (MPa)*	*Percent Elongation*	*Percent Reduction of Area*	*Hardness*
1	466	804	36	43	97Rb
2	592	863	36	42	24-25Rc
3	623	914	36	45	26-27Rc
4*	525	854	33	31	96-97Rb
4**	533	843	41	35	96-97Rb
5*	631	911	36	46	26-27Rc
5**	665	929	25	45	26-27Rc
6*	665	947	31	42	30Rc
6**	703	939	28	40	30Rc
7	664	923	26	40	22-23Rc
8	730	1003	23	41	28-29Rc

Condition:
1 = 1 pass, as-welded.
2 = 1 pass, 635°C/ 2h/ air cool.
3 = 1 pass, 663°C/ 2h/ air cool.
4 = 2 pass, as-welded.
5 = 2 pass, 635°C/ 3h/ air cool.
6 = 2 pass, 663°C/ 3h/ air cool.
7 = 2 pass, 635°C/ 8h/ air cool.
8 = 2 pass, 663°C/ 8h/ air cool.
* = cap pass.
** = root pass

For comparison, the room temperature tensile properties for alloy 625 two pass weld overlay given 625°C for 2 hours are, 0.2% yield strength 526.8 MPa, tensile strength 827.4 MPa, 45% elongation, with a hardness of Rockwell b 97.

Iron Dilution. Table II and III display the chemical composition of one and two pass alloy 725 weld overlays, respectively. Iron dilution of the welds was minimal. i.e., the weldments fell within the iron content range of the alloy, mentioned earlier. Of importance is that critical elements such as Cr and Mo are not significantly reduced by weld overlaying.

Table II Chemical Composition of Alloy 725, 1 Pass Weld Overlay

	Distance from Outside Surface of Weld Toward Alloy 725/ Steel Interface (cm)		
	0.000	**0.254**	**0.508**
C	0.021	0.020	0.020
Mn	0.06	0.14	0.10
Fe	9.16	8.93	8.59
S	<0.005	<0.005	<0.005
Si	0.07	0.16	0.12
Ni	52.41	52.28	50.07
Cr	17.83	16.89	17.33
Al	0.24	0.19	0.24
Ti	1.26	1.26	1.25
Mo	7.90	7.93	7.76
Nb	3.51	3.46	3.48
P	0.011	0.007	0.007

Table III Chemical Composition of Alloy 725, 2 Pass Weld Overlay						
	Distance from Outside Surface of Weld Toward Alloy 725/ Steel Interface (cm)					
	0.000	**0.254**	**0.508**	**0.762**	**1.016**	**1.270**
C	0.010	0.011	0.011	0.021	0.021	0.021
Mn	0.020	0.120	0.120	0.088	0.080	0.098
Fe	7.68		7.63	8.12	9.22	9.09
S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Si	0.12	0.18	0.08	0.22	0.14	0.18
Ni	54.45	54.29	53.94	52.52	51.63	52.05
Cr	18.17	17.08	17.94	17.49	17.69	17.54
Al	0.24	0.21	0.20	0.24	0.25	0.23
Ti	1.27	1.27	1.29	1.26	1.23	1.23
Mo	8.01	8.05	8.04	7.91	7.83	7.79
Nb	3.57	3.52	3.49	3.54	3.45	3.46
P	0.011	0.006	0.007	0.005	0.007	0.006

Pass/Fail Criteria for SSR Lot Acceptance Test. In review, the most common pass/fail criteria for SSR testing is a ratio of Time to Failure(TTF), % Reduction of Area (%RA) and/or % Elongation (%El) measured in a simulated oil patch environment relative to the same parameter in an inert environment (air or nitrogen). TTF and %RA ratios of ≥0.80 typically represent passing behavior in SSR tests. If the ratios are below 0.90, the specimen is examined under the Scanning Electron Microscope (SEM) for evidence of ductile or brittle fracture of the primary fracture surface. Ductile behavior passes and brittle behavior fails. All specimens are examined for secondary cracking in the gage length, away from the primary fracture. The absence of secondary cracking is indicative of good Stress Corrosion Cracking resistance and is considered to be passing. The presence of secondary cracks fails. One to two inert SSR tests were conducted along with one to three environmental SSR tests for each test lot of weld overlay[5]. Air test results were averaged for calculation of critical ratios.

Slow Strain Rate Test Results at ***149°C.*** Tables IV to VIII display the SSRT results for test specimens from 1 and 2 layer weld overlays of alloy 725, and Table IX displays SSRT data for a 1 layer weld overlay of alloy 625 evaluated in the 5% NaCl + 0.517 MPa H_2S + 2.758 MPa CO_2 environment at 149°C. The alloy 725 weld overlays exhibited excellent stress corrosion cracking resistance, equivalent to or better than the alloy 625 weld overlay.

Table IV SSR Test Data for alloy 725, 1 Pass Weld Overlay on 4140 Steel, Condition: 663°C/2h/AC

Test	TTF (h)	TTF Ratio	%RA	%RA Ratio	%EL	%EL Ratio	SC
Air	23.7		39.3		30.2		
Air	28.7		42.0		37.4		
Avg. Air	26.2		40.7		33.8		
Env.	25.7	0.98	45.2	1.11	33.7	1.00	No
Env.	28.1	1.07	39.3	0.97	37.4	1.11	No

Table V SSR Test Data for alloy 725, 2 Pass Weld Overlay on 4140 Steel, Condition: 635°C/3h/AC

Test	TTF (h)	TTF Ratio	%RA	%RA Ratio	%EL	%EL Ratio	SC
Air	24.5		44.0		31.5		
Air	23.0		41.3		29.5		
Avg. Air	23.8		42.7		30.5		
Env.	27.3	1.15	47.1	1.10	35.8	1.17	No

Table VI SSR Test Data for alloy 725, 2 Pass Weld Overlay on 4140 Steel, Condition: 663°C/3h/AC

Test	TTF (h)	TTF Ratio	%RA	%RA Ratio	%EL	%EL Ratio	SC
Air	21.5		37.0		27.1		
Air	23.6		40.1		29.8		
Avg. Air	22.6		38.6		28.5		
Env.	24.4	1.08	47.8	1.24	31.6	1.11	No
Env.	23.1	1.02	42.1	1.09	29.2	1.02	No

Table VII SSR Test Data for alloy 725, 2 Pass Weld Overlay on 4130 Steel, Condition: 635°C/8h/AC

Test	TTF (h)	TTF Ratio	%RA	%RA Ratio	%EL	%EL Ratio	SC
Air	23.7		45.0		29.8		
Air	26.4		40.1		34.0		
Avg. Air	25.1		42.6		31.9		
Env.	26.0	1.04	43.0	1.01	33.8	1.06	No
Env.	20.8	0.83	46.9	1.10	26.1	0.82	No
Env.	25.6	1.02	43.0	1.01	33.3	1.04	No

Table VIII SSR Test Data for alloy 725, 2 Pass Weld Overlay on 4140 Steel, Condition: 663°C/8h/AC							
Test	**TTF (h)**	**TTF Ratio**	**%RA**	**%RA Ratio**	**%EL**	**%EL Ratio**	**SC**
Air	26.0		39.1		33.1		
Air	20.0		28.6		24.2		
Avg. Air	23.0		33.9		28.7		
Env.	20.8	0.90	40.1	1.18	26.1	0.91	No
Env.	19.7	0.86	36.0	1.06	24.6	0.86	No

Table IX SSR Test Data for alloy 625, 1 Pass Weld Overlay on 4130 Steel, Condition: 635°C/2h/AC							
Test	**TTF (h)**	**TTF Ratio**	**%RA**	**%RA Ratio**	**%EL**	**%EL Ratio**	**SC**
Air	35.2		41.5		47.7		
Env.	33.4	0.95	49.6	1.20	45.2	0.95	No
Env.	31.7	0.90	38.1	0.92	42.8	0.90	No

For SSRT's at *149°C*, the TTF, %RA and %El ratios were high (average ≥ 1.00) and there was no secondary cracking as summarized below:

	Alloy 725 Overlays		*Alloy 625 Overlay*	
	Mean	*Range*	*Mean*	*Range*
TTF Ratio	1.00	0.83-1.15	0.93	0.90-0.95
%RA Ratio	1.09	0.97-1.24	1.06	0.92-1.20
%El Ratio	1.01	0.82-1.17	0.93	0.90-0.95

Slow Strain Rate Test Results at ***177°C***

Tables X to XII display the SSRT results for test specimens from a 2 layer weld overlay of alloy 725, and Table XIII displays SSRT data for a 1 layer weld overlay of alloy 625 evaluated in the 5% NaCl + 0.517 MPa H_2S + 2.758 MPa CO_2 environment at 177°C. The aged alloy 725 weld overlays aged at 635°C/3h/AC and at 663°C/8h/AC exhibited excellent stress corrosion cracking resistance, equivalent to or better than the alloy 625 weld overlay. i.e., The TTF, %RA and %El ratios were high, i.e., ≥0.90. Compare Table X, XI and XIII.

Table X SSR Test Data for alloy 725, 2 Pass Weld Overlay on 4140 Steel, Condition: *635°C/3h/AC*							
Test	**TTF (h)**	**TTF Ratio**	**%RA**	**%RA Ratio**	**%EL**	**%EL Ratio**	**SC**
Air	23.7		47.8		30.3		
Air	28.0		45.0		36.6		
Avg. Air	25.9		46.4		33.5		
Env.	23.7	0.92	46.9	1.01	30.3	0.90	No
Env.	25.4	0.98	43.3	0.93	33.0	0.99	No

Table XI SSR Test Data for alloy 725, 2 Pass Weld Overlay on 4140 Steel, Condition: *663°C/8h/AC*							
Test	**TTF (h)**	**TTF Ratio**	**%RA**	**%RA Ratio**	**%EL**	**%EL Ratio**	**SC**
Air	21.1		29.9		26.4		
Air	24.1		41.0		30.3		
Avg. Air	22.6		35.5		28.4		
Env.	21.0	0.93	43.0	1.22	26.4	0.93	No
Env.	21.5	0.95	38.3	1.08	27.1	0.95	No

Table XII SSR Test Data for alloy 725, 2 Pass Weld Overlay on 4140 Steel, Condition: *663°C/3h/AC*							
Test	**TTF (h)**	**TTF Ratio**	**%RA**	**%RA Ratio**	**%EL**	**%EL Ratio**	**SC**
Air	26.6		50.8		34.4		
Air	22.4		45.2		28.4		
Avg. Air	24.5		48.0		31.4		
Env.	21.3	0.87	45.0	0.94	26.6	0.85	No
Env.	21.8	0.89	40.3	0.84	27.7	0.88	No

Table XIII SSR Test Data for alloy 625, 1 Pass Weld Overlay on 4130 Steel, Condition: *635°C/2h/AC*							
Test	**TTF (h)**	**TTF Ratio**	**%RA**	**%RA Ratio**	**%EL**	**%EL Ratio**	**SC**
Air	33.9		43.3		45.9		
Air	32.1		47.1		43.1		
Avg. Air	33.0		45.2		44.5		
Env.	34.8	1.05	52.6	1.16	47.2	1.06	No
Env.	34.2	1.04	46.2	1.02	46.0	1.03	No

For SSRT's at *177°C*, the TTF, %RA and %El ratios were high (average ≥ 0.90) and there was no secondary cracking as summarized below:

	Alloy 725 Overlays		*Alloy 625 Overlay*	
	Mean	*Range*	*Mean*	*Range*
TTF Ratio	0.92	0.87-0.98	1.04	1.04-1.05
%RA Ratio	1.00	0.84-1.22	1.09	1.02-1.16
%El Ratio	0.92	0.85-0.99	1.04	1.03-1.06

Conclusions

1. Weld overlays of alloy 725 (N07725) deposited on 4130 and 4140 steel and aged in the 635° to 663°C tempering range of the steels for 2 to 8 hours exhibited, excellent SCC resistance to a sour oil field environment at 149°C and 177°C.
2. SCC resistance of the aged alloy 725 (N07725) weld overlays was equivalent to or better than that exhibited by alloy 625 (N06625) weld overlay.
3. The alloy 725 weld overlay provides an excellent high strength alternative to alloy 625 weld overlay currently used in the oil patch.

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