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Welding Procedure Development for a 13Cr-5Ni-2Mo (UNS S41426) Super Martensitic Stainless Steel

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ABSTRACT

To obtain heat affected zone (HAZ) hardness levels below maximums specified in the current (2015) edition of NACE⁽¹⁾ MR0175/ISO⁽²⁾ 15156-3 for sour service use, welded super martensitic stainless steels (SMSS) need post weld heat treatment (PWHT). PWHT is mainly done by stress relieving or tempering post welding as re-austenitizing, quenching, and tempering is not practical in many applications. Double stress relief thermal cycles may be needed so that any martensite which forms due to transformation during the first stress relief cycle is tempered by the second stress relief cycle. Overall, design of PWHT can be challenging to ensure not only meeting maximum hardness requirements but also ensuring meeting minimum design yield strength. This study investigates the austenite start and finish (A_1 and A_3) phase transformation temperatures as a function of heating rate and reports the martensite start and finish temperatures (M_s and M_f). Phase transformation temperatures in 13Cr-5Ni-2Mo (UNS S41426) alloy are measured using a resistance heating physical simulator coupled with dilatometry. Dilatometry-based phase transformation temperatures are compared with HAZ hardness results in 13Cr-5Ni-2Mo SMSS welds after PWHT. Mechanical properties associated with the different PWHT temperatures are measured to understand the effect of PWHT on design mechanical properties like yield strength.

Key words: Welding, Super Martensitic Stainless Steel, Post Weld Heat Treatment, NACE MR0175/ISO 15156, Heat Affected Zone (HAZ), UNS S41426

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INTRODUCTION

Overview

Supermartensitic stainless steels (SMSS) are an important class of engineered alloys for oil and gas applications in which intermediate corrosion resistance is required with high yield strength such as 95 – 110 ksi Minimum Yield (MY) strength in the quenched and tempered condition.¹ Possessing less than 0.03 wt% carbon for improved weldability,^{2,3} 11.5-13.5 wt% Cr, 4.5-6 wt% Ni, and 1.5-3 % Mo for improved corrosion resistance,¹ SMSS display a good balance of corrosion resistance,⁴⁻⁶ yield strength above 95 ksi,^{1,4} and good weldability,^{2,3} but with lower cost than alloys like duplex stainless steels.¹ However, in welded downhole tubing applications that are required to meet current (2015) edition of NACE MR0175/ISO 15156-3,⁷ as-welded heat affected zone hardness (HAZ) is limited to 27 HRC (nominal 280 HV per ASTM⁽³⁾ E140-12b conversion⁸) for qualification of welded UNS S41426 components by hardness survey for sour service.⁷ As-welded HAZ hardness in SMSS grades exceeds 300 HV,^{2,3} above the maximum hardness allowed for sour service,⁷ and therefore requires application of post weld heat treatment (PWHT) to reduce the as-welded HAZ hardness and reduce likelihood of in service failures.⁹ For many applications, re-austenitizing, quenching, and tempering is not a practical PWHT method for control of HAZ hardness, and PWHT is therefore mainly carried out with one^{2,3} or two² stress relieving or tempering thermal cycles at an appropriate temperature after welding. However, nickel additions to SMSS, required to stabilize the gamma loop and enable martensite formation,¹ also lower the A_1 temperature into the range typically targeted for PWHT.^{2,3} PWHT via stress relieving or tempering of these alloys to meet the sour service hardness limits can therefore be challenging.^{2,3,10} Development of economical, reliable PWHT procedures is therefore a critical step to deploy SMSS successfully into oil and gas applications where welding is needed.

Prior Work

Prior investigations of SMSS have used heat treatment to control base SMSS alloy microstructure¹⁰⁻¹³ and hardness.^{14,15} Leem et al. showed that in a 13Cr7Ni3Si martensitic stainless alloy the A_1 and A_3 transformation temperatures increase with heating rate up to 10 °C/s¹¹ and showed that an intercritical heat treatment temperature of 625 °C maximizes stable reverted austenite upon subsequent cooling.¹¹ Song et al. suggested that in a 13Cr4Ni0.5Mo martensitic alloy that $M_{23}C_6$ carbides formed during an initial PWHT at 680 °C nucleate reverted austenite during the second PWHT cycle at 600 °C, with strong partitioning of Ni, Cr, and Mn into the reverted austenite.¹² Bojack et al. suggested that slow (3 °K/min) heating in a 13Cr6Ni2Mo alloy yields a “two-step” austenite reversion due to partitioning of nickel into the austenite upon entering the intercritical temperature range, thereby raising the transformation temperature of the untransformed martensite.¹³ In a series of papers, Escobar et al. reported the transformation kinetics and stabilization of reverted austenite in a 12Cr6Ni2Mo (UNS S41426) SMSS alloy.^{10,14,15} In-situ heating and diffraction experiments demonstrated that while the kinetics of austenite reversion are accelerated at 650 °C and 700 °C, the stability of reverted austenite upon cooling is maximized for a single tempering cycle of 2.5 hours at 625 °C.¹⁰ Composition enrichment during triple intercritical heat treatments further increase the fraction of reverted austenite at room temperature.¹⁵ Investigation of hardness as a function of single cycle peak tempering temperature (2.5 h soak time) yielded the lowest hardness at 625 °C, with a second tempering cycle reducing hardness by 10 HV to approximately 265 HV.¹⁴

⁽³⁾ ASTM International (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA, 19428-2959.

A few investigators have also reported the evolution of the weld metal and HAZ properties in SMSS after PWHT. Gooch investigated the weld metal and HAZ hardness response of early SMSS materials and found that hardness could be minimized by reducing carbon content and using a double PWHT with cooling to 0 °C between thermal cycles.² Bilmes et al. studied the mechanical properties of 12Cr5Ni0.5Mo 0.028 wt% C SMSS weld metal following single and double PWHT, showing that a second PWHT thermal cycle allowed for growth of reverted austenite grains formed in the first cycle and produced the lowest hardness of 266 HV and 29.2 vol% retained austenite.¹⁶ Zappa et al. also showed that a double PWHT (650 °C and 600 °C) after austenitizing all weld metal specimens resulted in the lowest hardness and the greatest elongation in tensile specimens.¹⁷ For HAZ studies, Ramirez studied the PWHT response of a 12Cr6Ni2.5Mo 0.007 wt% C (~80 ksi yield) SMSS using resistance heated physical simulated HAZ to show that short (10 min) PWHT cycles at 640 °C could reduce simulated HAZ hardness to 289 HV.³ Akselsen et al. also studied the mechanical response to resistance heated physical simulated HAZs in SMSS base metal with short tempering cycles, finding that the greatest hardness reduction occurred with tempering temperatures from 600 to 700 °C.¹⁸

Prior study on the PWHT response of SMSS alloys informs understanding of SMSS susceptibility to both intergranular stress corrosion cracking (IGSCC) and sulfide stress cracking (SSC).^{19–21} Short PWHT, such as Skar and Olson report of 610 °C (5 min), 630 °C (3 and 5 min), and 650 °C (3 min),²⁰ reduced susceptibility to IGSCC through mitigation of sensitized prior austenite and delta-ferrite/martensite grain boundaries.^{19,22} Furthermore, properly designed PWHT can increase reverted austenite,^{4,6} which has been previously correlated to lower hydrogen diffusivity,^{4,5} which may improve resistance to hydrogen embrittlement and sulfide stress cracking (SSC).⁴ Increasing austenite fraction during PWHT may also lower yield strength,⁴ and reduced yield strength is suggested to improve SSC resistance.²¹

Literature Gaps and Current Study

While previous studies^{2,3,16,17} have sought to optimize PWHT conditions to reduce weld metal and HAZ hardness below NACE MR0175/ISO 15156-3 limits for sour service,⁷ only a few report heat treatment effects on SMSS weld tensile properties.^{2,16,17} No research to date has reported how PWHT optimized for HAZ hardness reduction affects base metal yield strength. To resolve this gap, this work reports the effect of PWHT on both HAZ hardness and base metal tensile strength in UNS S41426 SMSS with 95 ksi MY. Importantly, several of the PWHT conditions that yield large reductions in HAZ hardness are found to reduce base metal yields strength below the target 95 ksi minimum. The current study shows a 625 °C single cycle PWHT for 1 h is found to balance HAZ hardness reduction to 286 HV while maintaining base metal yield strength at 93 ksi, very close to 95 ksi MY. A process development map is introduced to guide development of welding procedures in SMSS.

Experimental Procedure

To guide PWHT thermal cycle selection, metallurgical phase transformations are first measured using dilatometry. Second, an autogenous gas tungsten arc (GTA) welding method is developed that produces HAZ microstructures and properties that are in quantitative agreement with pulsed gas metal arc (GMA) weldments made between UNS S41426 and nickel Alloy 625. The autogenous GTA weldments are used to screen the PWHT impact on HAZ properties and identify PWHT conditions that optimally reduce HAZ hardness. Finally, the tensile properties of base metal UNS 41426 is measured following various heat treatment conditions and compared to HAZ hardness in welds under similar heat treatment conditions.

Materials

The welding response of quench and tempered UNS S41426-95 tubing [5.5 in (139.7 mm) outer diameter; 0.35 in (8.9 mm) wall thickness] was investigated with GTA welds in two heats of material, as well as with dissimilar pulse GMA fillet weld using ERNiCrMo-3 filler metal to Alloy 625 (UNS N06625). The basic elemental composition of the UNS S41426 tubing heats, ERNiCrMo-3 welding filler alloy, and Alloy 625 (UNS N06625) are reported in Table 1. UNS S41426 Heat 1 was used for all experiments, except for the dissimilar weld that used UNS S41426 Heat 2. Base material mechanical properties of UNS S41426-95 tubing, along with reported tempering temperature, are reported in Table 2. Composition (Table 1) and properties (Table 2) correspond to material test report information, except for composition of Alloy 625 (UNS N06625) which was determined by scanning electron microscopy (SEM) energy dispersive spectroscopy.

Phase Transformation Temperatures

Metallurgical phase transformation temperatures upon heating and cooling were measured using contact c-gauge dilatometry with resistive heating performed under K-type thermocouple control in a Gleeble® 1500⁽⁴⁾ thermomechanical simulator. Cylindrical 0.323 ± 0.005 in (8.2 ± 0.13 mm) diameter specimens were machined from UNS S41426-95 (Heat 1) and heated at rates varying from 0.1 °C/s to 5 °C/s under force control of overall force of 0 kN. As summarized in Table 3, a single specimen (D14) was repeatedly tested at 5 °C/s, 1 °C/s and 0.5 °C/s heating rates, with follow-on experiments performed in fresh samples (D15, D16, and D18) at 0.5 °C/s and 0.1 °C/s. An argon purge was used during experiments to reduce surface oxidation. Axial stroke, total system force, specimen temperature, and c-gauge dilatometry displacement were measured during experiments. C-gauge dilatometry data was plotted against specimen temperature, along with the derivative of radial displacement versus temperature, and analyzed to identify phase transformations.

Table 1
Chemical Composition of Materials

Alloy	Heat	Fe	C	Cr	Ni	Mo	Si	Mn	P	S	Ti	V	Nb+Ta
(wt %)													
(UNS S41426-95)	Heat 1	Bal.	0.01	12	5.5	1.9	0.24	0.45	0.02	0	0.1	0.06	
	Heat 2	Bal.	0.01	11.9	5.4	1.9	0.25	0.45	0.01	0	0.1	0.06	
ERNiCrMo-3	--	0.38	0.02	22.3	64.7	8.52	0.09	0.02	0.01	0	0.19		3.660
Alloy 625	--	4.7		23.3	58.4	9.0							3.9

Table 2
Mechanical Properties and Tempering Temperature of UNS S41426-95 Heats

UNS S41426	YS (ksi)	TS (ksi)	Elong. (%)	Hardness (HRC)	Tempering Temp. °C (± 10 °C)
Heat 1	104.2	120.1	28	24.6	625
Heat 2	103.9	119.3	28	24.1	620

⁽⁴⁾ Trade name.

Welding

Autogenous GTA Welding

UNS S41426-95 (Heat 1) tubing was sectioned longitudinally into coupons approximately 5 in long by 1.5 in wide (127 × 38.1 mm). Before welding, coupon surfaces were ground with an abrasive flap wheel and wiped with acetone. Autogenous GTA welds were performed on a mechanized GTA welding system at 120 Amperes, 11 Volts, and 2.6 in/min (1.1 mm/s) travel speed for a nominal heat input of 30 kJ/in (1.1 kJ/mm). Arc voltage was maintained with an automated voltage controller and welds were performed with 100% Argon shielding at 30 scfh (14.2 L/min) flow rate, with pre-flow and post-flow of 30 s. After discarding 0.5 in (12.7 mm) from each end of the weld, welds were sectioned transverse to the welding direction for PWHT studies.

Dissimilar Pulsed GMA Welding

Circumferential fillet welds of UNS S41426-95 (Heat 2) tubing to an Alloy 625 (UNS N06625) end ring were performed with pulse GMA welding using 0.035 in (0.9 mm) diameter ERNiCrMo-3 welding consumable and a 90He-7.5Ar-2.5CO₂ shielding gas at wire feed speed of 600 in/min (155 Amperes), 34.5 Volts, 11.1 in/min (4.7 mm/s) travel speed, with a nominal heat input of 28.9 kJ/in (1.1 kJ/mm). The ERNiCrMo-3 consumable was chosen due to the dissimilar combination of Alloy 625 and UNS S41426 fillet weld. Pulsed welding was performed with Miller Continuum 400⁽⁵⁾ using a custom program optimized for the consumable and shielding gas, with weld pool held in the 1 to 2 o'clock position with the pipe rotating counterclockwise at a fixed rotation speed using a pipe positioner. Specimens for PWHT studies were sectioned using a metallurgical saw.

Post Weld Heat Treatment

Welds were sectioned transverse to the welding direction using a metallurgical saw to produce small coupons, approximately 0.375 – 0.5 in (9.5 – 12.7 mm) wide, for PWHT studies. Heat treatments were performed in a Thermo Fisher Isotemp⁽⁵⁾ electric furnace at heating rates of 3.4 °C/min (367 °F/h, close to the maximum 400 °F/h per ASME⁽⁶⁾ Boil and Pressure Vessel Code Section IX⁽²³⁾) to a variable peak temperature and variable isothermal soak time, followed by cooling at target rates of -3.4 °C/min. Actual specimen PWHT thermal histories were recorded with a K-type thermocouple inserted in the furnace chamber, near the specimen. Measured PWHT target soak temperatures were within 5 – 10 °C of furnace set point target values, so set point values are used for subsequent analysis [e.g. Figure 4(A)].

Characterization

Microscopy

Before and after PWHT, GTA and GMA weld specimens were mounted, ground with SiC abrasives at 240, 320, 400, 600, 800, and 1200 grit for 60 sec, before polishing with 1.0 μm alumina for 10 min and then etching with Kalling's #1 mixed per ASTM E407.²⁴ Optical microscopy was performed using a Motic⁽⁵⁾ upright metallurgical microscope and digital camera at magnification up to 500×, while SEM was performed on select specimens with a Hitachi SU3500⁽⁵⁾ tungsten filament SEM in secondary electron (SE) imaging modes at magnification up to 4,000×.

⁽⁵⁾ Trade name.

⁽⁶⁾ The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990.