Alloy Composition and Critical Temperatures in Type 410 Steel Welds

Predictive formulas for A_1 and A_3 temperatures in Type 410 steel welds were developed using the design of experiment approach

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ABSTRACT

The design of experiment (DoE) approach using thermodynamic simulations with ThermoCalc™ was applied to evaluate the effect of alloy composition on the critical temperatures in Type 410 steels and welding consumables. A predictive equation and predictive diagram for the A_1 temperature were developed and verified through experimentation and comparison with published data. This was also complemented with the development of a predictive equation for the A_3 temperature.

The results of this study show that the combined ASTM and American Welding Society (AWS) compositional specifications for Type 410 materials provide a range of A_1 temperatures that is significantly wider than the postweld heat treatment (PWHT) temperature range specified by the American Society of Mechanical Engineers (ASME). This creates a potential risk of exceeding the A_1 temperature during PWHT, resulting in formation of fresh martensite, and can be related to difficulties meeting hardness and toughness requirements for Type 410 welds experienced in industry. Narrowing the ASTM and AWS compositional specifications by introduction of lower limits for all alloying elements, including nitrogen and copper, was identified as a potential solution to this problem.

The predictive tools developed in this study can be applied for selection of welding consumables and base metals, postweld heat treatment (PWHT) temperature selection, and compositional optimization of Type 410 steels and welding consumables.

KEYWORDS

- 410 Steel Welds • Postweld Heat Treatment
- Computational Model-Based Design of Experiment
- Predictive Tools • Materials Selection

Introduction

ASTM A240 Type 410 martensitic stainless steel is an iron-chromium-carbon alloy with balanced carbon and chromium content that provides a useful combination of moderate corrosion resistance, high hardenability and strength, and accept-

able toughness (Refs. 1–3). Under equilibrium conditions, martensitic stainless steels are predicted to solidify as delta ferrite, which transforms to austenite upon cooling, followed by decomposition to ferrite and $M_{23}C_6$ carbides (Ref. 2). However, due to their high hardenability, at normal processing conditions (accelerated or air cooling), the austenite in these steels transforms to martensite. The latter transformation occurs in a temperature range of 200°C and is completed above room temperature (Ref. 4). Nonequilibrium solidification, such as that found in welding, leading to partitioning of alloying elements, followed by accelerated cooling through the temperature range of stable delta ferrite may result in retaining of significant amounts of delta ferrite in the final martensitic microstructure (Ref. 2). The optimal combination of hardness, strength, and toughness in martensitic stainless steels is achieved through normalization and a tempering heat treatment (Refs. 1, 4–6).

Compared to austenitic stainless steels, the martensitic stainless grades have significantly higher hardness and strength, and lower cost in combination with good resistance to atmospheric corrosion (Refs. 2–4, 6). Specific advantages of the martensitic grades is their better resistance to sulfur attack and oxidation at higher temperatures, and lower susceptibility to stress corrosion cracking in halide and polyphonic acid-containing environments (Ref. 7). Their application range includes blades for turbines operating in relatively lower temperatures, valves, pumps, shafts, and piping in power generation, oil and gas, and refinery applications. Type 410 steel has found widespread application in refineries as fabricated (welded) components in hydrocrackers, hydrotreaters, and distilling units for crude oil with high sulfur content (Refs. 4, 7).

Type 410 steel is normally welded using consumables with matching composition. However, experience with poor weldability of this steel has been related to formation of hard and brittle martensite in the weld zone, hydrogen-induced cracking, or retention of delta ferrite in the weld metal that negatively affects toughness (Refs. 4, 7). Increasing the weld metal nickel content above 1 wt-% or using austenitic stainless steel consumables are not considered viable solutions for improved weldability because of compromising the weld metal service properties at high temper-

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Fig. 1 — Equilibrium phase fraction vs. temperature diagram in DoE Alloy D3 generated using ThermoCalc™.

atures in comparison to the 410 steel base metal (Refs. 5, 7).

The risk of hydrogen-induced cracking in matching filler metal welds of Type 410 steel is reduced by preheating, maintaining proper interpass temperature, and using low-hydrogen welding consumables (Ref. 4). The weld metal and heat-affected zone (HAZ) hardness and toughness are controlled by postweld heat treatment (PWHT) applied to temper the martensitic microstructure and relieve welding residual stresses (Refs. 3, 4, 7). However, problems with inconsistent and unpredictable toughness and hardness, and with meeting the requirements of related American Petroleum Institute (API), NACE, and American Society of Mechanical Engineers (ASME) standards (Refs. 8–11) have been frequently reported by the petrochemical industry.

This study explores the hypothesis that inconsistent hardness and toughness behavior in Type 410 welds can be related to the wide composition ranges of the base metal and matching welding consumables, resulting in wide variations of the A_1 temperature and providing potential for random-performing PWHT above this temperature. The effect of this wide composition range on retention of delta ferrite in Type 410 steel welds, as a factor negatively affecting toughness, is addressed in a separate study (Ref. 12).

For Type 410 steel, ASTM A240 specifies compositional ranges for chromium and carbon, and maximum contents of nickel, manganese, and silicon, but does not include molyb-

Fig. 2 — Light radiation furnace and test sample setup used in SS DTA experiments.

denum, copper, and nitrogen (Table 1) (Ref. 13). For Type 410 welding filler metals, AWS A5.4-06 and A5.9-17 define the compositional range for chromium and maximum contents for all other specified alloying elements, but do not include nitrogen (Refs. 14, 15). The commercially available wrought alloys and welding filler metals do not utilize this entire compositional space. However, variations in the content of a single specified alloying element and/or presence of small quantities of nonspecified elements could result in significant variations of the A_1 temperature. For Type 410 steel welds, ASME B31.3 recommends a PWHT temperature range of 760° to 800°C, and ASME Section VIII D1 specifies a minimum PWHT temperature of 760°C (Refs. 8, 9). Such a wide PWHT temperature range could potentially overlap with the A_1 temperature range, resulting in heat treatment above the A_1 temperature.

A_1 and A_3 denote the equilibrium lower and higher critical temperatures in steels. Ferrite (BCC) is the stable equilibrium phase below the A_1 temperature. Upon exceeding the A_1 temperature on heating, ferrite gradually transforms to austenite (FCC) with the latter becoming the stable equilibrium phase upon exceeding the A_3 temperature. The A_1 and A_3 temperatures are determined at equilibrium heating and cooling conditions, such that would allow for completion of all metallurgical reactions occurring at a particular temperature. Faster heating rates, as those experienced in welding or PWHT, would shift the nonequilibrium critical temperatures (denoted correspondingly as A_{c1} and A_{c3}) to higher temperatures. However, the equilibrium critical temperatures A_1 and A_3 are of particular importance for PWHT. Independently of the heating rate, exceeding the A_1 temperature during PWHT of Type 410 steel would result in partial reversion of the superheated fresh martensite in the weld metal and

Table 1 — ASTM A240, AWS A5.9-93, and A5.4-92 Composition Specifications for Type 410 Steels and Welding Consumables (wt-%)

Standard	C	Cr	Ni	Mo	Mn	Si	P	S	Cu	N
AWS A5.5	0.12	11.0–13.5	0.7*	0.75	1.0	0.9	0.04	0.03	0.75	—
AWS A5.9	0.12	11.0–13.5	0.7	0.75	0.6	0.5	0.03	0.03	0.75	=
ASTM A240	0.08–0.15	11.5–13.5	0.75	—	1.0	1.0	0.04	0.03	—	—
Model-Based DoE	0.01–0.15	11.0–13.5	0–0.75	0–0.75	0–1.0	0–1.0	0–0.04	0–0.03	0–0.75	0–0.04

*Single values are maxima.

Table 2 — ThermoCalc™ Model-Based DOE: Chemical Compositions (wt-%) and Predicted A₁ and A₃ Temperatures

DOE#	C	Cr	Ni	Mo	Si	Mn	Cu	N	A1	A3
D1	0.01	11	0.75	0.75	0	1	0.75	0	697	816
D2	0.01	11	0	0	1	1	0.75	0.04	752	839
D3	0.08	12.25	0.375	0.375	0.5	0.5	0.375	0.02	777	878
D4	0.01	13.5	0.75	0	0	0	0.75	0	770	954
D5	0.15	11	0.75	0	1	0	0.75	0.04	768	902
D6	0.15	13.5	0	0.75	0	1	0	0	803	957
D7	0.15	13.5	0	0.75	1	0	0	0	889	983
D8	0.01	11	0.75	0	0	0	0	0.04	782	821
D9	0.01	11	0	0.75	0	0	0	0.04	839	950
D10	0.15	13.5	0.75	0.75	1	1	0.75	0.04	708	968
D11	0.01	11	0.75	0	0	1	0	0	725	801
D12	0.15	13.5	0	0	1	1	0.75	0.04	759	937
D13	0.15	11	0	0	1	0	0	0.04	829	887
D14	0.15	11	0.75	0.75	1	0	0	0.04	808	928
D15	0.15	13.5	0	0	0	1	0.75	0	750	942
D16	0.01	13.5	0.75	0	1	0	0.75	0.04	780	887
D17	0.15	11	0	0.75	0	1	0.75	0.04	740	929
D18	0.01	13.5	0.75	0.75	0	1	0	0.04	749	941
D19	0.01	13.5	0.75	0.75	1	1	0	0	784	952
D20	0.15	11	0.75	0	0	0	0.75	0	755	913
D21	0.01	11	0.75	0.75	1	1	0.75	0.04	712	849
D22	0.15	11	0	0	0	1	0	0.04	766	891
D23	0.01	13.5	0.75	0	0	1	0.75	0.04	700	799
D24	0.15	11	0.75	0	1	1	0.75	0	703	913
D25	0.01	13.5	0	0	0	1	0	0.04	786	941
D26	0.01	11	0	0.75	1	0	0	0	879	1014
D27	0.01	11	0	0	0	0	0.75	0.04	801	830
D28	0.15	13.5	0	0.75	1	1	0	0.04	808	955
D29	0.01	11	0	0.75	1	1	0	0.04	807	913
D30	0.15	13.5	0	0	0	0	0.75	0.04	806	932
D31	0.15	11	0	0	1	1	0	0	790	898
D32	0.01	11	0.75	0	1	0	0	0	809	885
D33	0.01	13.5	0	0	0	0	0	0	859	980
D34	0.15	13.5	0.75	0	1	1	0	0.04	745	930
D35	0.15	13.5	0	0	1	0	0.75	0	833	942
D36	0.15	13.5	0.75	0.75	0	0	0.75	0.04	767	962
D37	0.15	11	0	0.75	1	1	0.75	0	763	939
D38	0.15	11	0	0.75	0	0	0.75	0	816	939
D39	0.15	11	0.75	0.75	0	0	0	0	797	934
D40	0.01	13.5	0	0.75	1	1	0.75	0	805	958
D41	0.15	11	0	0	0	0	0	0	824	900
D42	0.01	11	0	0.75	0	1	0	0	801	925
D43	0.15	13.5	0.75	0	1	0	0	0	817	936
D44	0.01	13.5	0.75	0.75	0	0	0	0	834	967
D45	0.01	11	0.75	0	1	1	0	0.04	739	816
D46	0.15	13.5	0.75	0	0	1	0	0	734	935
D47	0.01	13.5	0	0	1	0	0	0.04	864	983
D48	0.01	11	0.75	0.75	0	0	0.75	0.04	771	834
D49	0.15	11	0.75	0.75	0	1	0	0.04	720	925
D50	0.01	11	0.75	0.75	1	0	0.75	0	796	920
D51	0.15	13.5	0.75	0.75	1	0	0.75	0	791	975
D52	0.01	13.5	0	0	1	1	0	0	822	962
D53	0.15	11	0.75	0.75	1	1	0	0	746	935
D54	0.01	13.5	0.75	0.75	1	0	0	0.04	838	974
D55	0.01	13.5	0	0.75	0	1	0.75	0.04	773	945
D56	0.01	13.5	0	0.75	0	0	0.75	0	860	974
D57	0.01	11	0	0	0	1	0.75	0	744	810

Table 2 — continued

DOE#	C	Cr	Ni	Mo	Si	Mn	Cu	N	Al	A3
D58	0.15	13.5	0.75	0.75	0	1	0.75	0	697	968
D59	0.01	13.5	0.75	0	1	1	0.75	0	717	878
D60	0.15	13.5	0.75	0	0	0	0	0.04	787	926
D61	0.15	11	0	0.75	1	0	0.75	0.04	827	932
D62	0.15	11	0.75	0	0	1	0.75	0.04	687	904
D63	0.01	13.5	0	0.75	1	0	0.75	0.04	862	978
D64	0.01	11	0	0	1	0	0.75	0	824	903
D65	0.15	13.5	0	0.75	0	0	0	0.04	842	952
D66	0.01	12.25	0.375	0.375	0.5	0.5	0.375	0.02	785	900
D67	0.15	12.25	0.375	0.375	0.5	0.5	0.375	0.02	773	936
D68	0.08	11	0.375	0.375	0.5	0.5	0.375	0.02	773	864
D69	0.08	13.5	0.375	0.375	0.5	0.5	0.375	0.02	785	891
D70	0.08	12.25	0	0.375	0.5	0.5	0.375	0.02	803	876
D71	0.08	12.25	0.75	0.375	0.5	0.5	0.375	0.02	751	879
D72	0.08	12.25	0.375	0	0.5	0.5	0.375	0.02	771	852
D73	0.08	12.25	0.375	0.75	0.5	0.5	0.375	0.02	786	892
D74	0.08	12.25	0.375	0.375	0	0.5	0.375	0.02	770	877
D75	0.08	12.25	0.375	0.375	1	0.5	0.375	0.02	788	880
D76	0.08	12.25	0.375	0.375	0.5	0	0.375	0.02	809	878
D77	0.08	12.25	0.375	0.375	0.5	1	0.375	0.02	743	877
D78	0.08	12.25	0.375	0.375	0.5	0.5	0	0.02	793	874
D79	0.08	12.25	0.375	0.375	0.5	0.5	0.75	0.02	760	882
D80	0.08	12.25	0.375	0.375	0.5	0.5	0.375	0	785	882
D81	0.08	12.25	0.375	0.375	0.5	0.5	0.375	0.04	777	874
D82	0.08	12.25	0.375	0.375	0.5	0.5	0.375	0.02	778	878

HAZ and/or the tempered martensite in the base metal to austenite. Due to the high hardenability of Type 410 steel, on cooling, the newly formed austenite transforms back to fresh martensite. Unexpectedly high hardness and/or low toughness values have been reported as a result of exceeding the A_1 temperature during heat treatment of martensitic stainless steels (Refs. 16–19).

There is insufficient information for A_1 temperature values in Type 410 steels and on the related effects of alloying elements. This was attributed to difficulties in determination of A_1 temperatures related to slower diffusion and transformation kinetics compared to the martensitic transformation (Ref. 4). Rickett et al. experimentally determined A_1 temperature values between 766° and 804°C in nine steels within the Type 410 compositional range (Ref. 18). Marshall and Farrar reported A_1 temperature values of about 800°C for Type 410 matching welding consumables (Ref. 4). Based on published data, Gooch et al. developed an empirical equation for the A_1 temperature in 13 wt-% chromium steels with carbon content below 0.05 wt-%, stating that the equation should only be used as an approximation and requires further study (Equation 1) (Ref. 5). PWHT in the range of 650° to 750°C has been suggested for Type 410 welds (Refs. 4, 5, 7). However, there is no published information on the effectiveness of PWHT in that temperature range for meeting the hardness and toughness requirements in materials with A_1 temperatures closer to 800°C.

$$AC_1(^{\circ}C) = 850 - 1500(C + N) - 50Ni - 25Mn + 25Si + 25Mo + 20(Cr - 10) \quad (1)$$

In contrast to Type 410 steel, significant amounts of information has been generated for the A_1 temperature in Grade 91 and 92 steels, which represent another class of high-chromium martensitic alloys. Thermodynamic simulations with ThermoCalc™ (Ref. 19) and model-based design of experiment (DoE) studies based on physical determinations and on computational modeling (Refs. 21–23) were used to determine ranges of variation and generate predictive equations for the A_1 temperature.

In this study, similarly, a model-based DoE using thermodynamic simulations with ThermoCalc™ was applied to quantify the effect of alloying elements on and develop predictive tools for the A_1 temperature in Type 410 steel welds and base metals. The latter were verified using experimental measurements with dilatometry and single-sensor differential thermal analysis, and by comparison to published results.

Materials and Procedures

Model-Based Design of Experiment

The effect of alloying elements on the A_1 temperature in Type 410 steel welding consumables and base metals was quantified through development of a model-based DoE within a compositional range that simultaneously covers the corresponding AWS A5.4-06, A5.9-17, and ASTM A240 specifications (see Table 1). An eight factor, $\frac{1}{2}$ factorial surface response design was selected to generate a range of

Fig. 3 — Dilatometry experimental setup in the Gleeble™ thermomechanical simulator.

model alloy compositions. The primary alloying elements in Type 410 steel, carbon, chromium, molybdenum, silicon, nickel, copper, and manganese were chosen as DoE factors. Although not specified by ASTM and AWS, nitrogen was also included as a DoE factor. Nitrogen is a strong austenite stabilizer and the goal of including it was to evaluate the effect on the A_1 temperature of typical trace amounts of nitrogen of up to 0.04 wt-% found in Type 410 steels.

The model alloys were generated with the MiniTab 17 statistical software using the alloying elements maximum and minimum composition values specified by AWS or ASTM. For elements with no specified minimum, a value of 0 wt-% was used. For the eight-factor surface response design, 62 theoretical compositions were initially generated to account for linear interactions. The nonlinear interactions were accounted for by generating 20 additional model alloys with the factors set at their mid-range values. This resulted in a DoE with a total of 82 model alloys (Table 2).

The DoE study utilized the thermodynamic software ThermoCalc™ for prediction of the A_1 temperatures in the 82 model alloys. The ThermoCalc™ simulations were performed using the TCFE8 database with one degree steps within the temperature range between 500° and 1600°C. Equilibrium diagrams of phase fraction vs. temperature were developed for each of the 82 model alloys and used to determine the corresponding A_1 temperatures — Fig. 1. The results generated by the model-based DoE were processed using the statistical software MiniTab 17. The processing involved regression analysis as a surface response design using a stepwise method to eliminate insignificant terms and interactions. Predictive formulas for the A_1 and A_3 temperatures in Type 410 steel weld and base metals were developed. A simplified predictive formula for the A_1 temperature that excludes the first order interactions terms between alloying elements was also generated.

Using Excel, 2000 random Type 410 steel compositions were generated within the ASTM and AWS specification ranges. The A_1 temperature values for these compositions were calculated using the simplified A_1 prediction formula. The 2000 A_1 temperature values were plotted in 25°C bins on a predictive diagram using the ferrite and austenite promoting terms of the simplified equation, correspondingly

Fig. 4 — Relative effects of alloying elements on the A_1 (a) and A_3 (b) temperatures in Type 410 steel base metal and welding consumables.

the chromium and nickel equivalents (Cr_{Eq} and Ni_{Eq}), as the diagram axis.

Validation Experiments

Samples Preparation

The developed predictive formula for the A_1 temperature in Type 410 steel weld and base metals was validated through experimental determination of the A_1 temperature in 19 alloys within the standard Type 410 steel compositional range (Table 3). These included five commercially available welding consumables (Alloys A1–A5) and 14 custom-made alloys (B1–B8 and C1–C6). The custom alloys were produced by melting charges composed of predetermined fractions of welding consumables (Alloys A1–A5) and 99.9% pure alloying elements in the form of wire, foil, or powder. The melting was performed using a button-melting apparatus with a copper crucible enclosed within a glass chamber, topped with a gas tungsten arc welding (GTAW) torch. The chamber was purged three consecutive times with 99% pure argon shielding gas and then held at pressure before melting the material into button samples using a GTAW power supply. All samples were flipped over and

Fig. 5 — Effect of varying austenite stabilizing elements within the AWS compositional range on the A_1 temperature of commercially available ER410 filler metal (Alloy 4).

remelted two times to ensure proper mixing of alloying elements and uniform composition. The chemical composition in all custom-made and commercial alloys was determined using optical emission spectroscopy.

The A_1 temperatures in the 19 alloys were determined using dilatometry and/or single-sensor differential thermal analysis (SS DTA). Samples intended for SS DTA were produced by casting into 12-mm cubes using a square copper mold within the button-melting apparatus and cutting into $12 \times 12 \times 4$ mm samples. Samples intended for

dilatometry were cast into 100-mm-long, 5-mm-diameter cylindrical rods within an induction levitation casting device using copper molds. The actual chemical composition of test samples from the 19 alloys was determined using optical emission spectroscopy (see Table 3).

The microstructure in samples of selected alloys was characterized after completion of the phase transformation analysis. Samples were prepared using standard metallography techniques and etched with Vilella's reagent, followed by examination under a light optical microscope.

Table 3 — Chemical Composition of Commercial (A1–A5) and Custom Made (B1–B8, C1–C6) Alloys Used in Validation Experiments (wt-%)

Alloy #	C	Cr	Ni	Mo	Mn	Si	P	S	N	Cu
A1	0.105	11.8	0.13	0.018	0.54	0.37	0.03	0.03	0.021	0.18
A2	0.08	12.2	0.2	0.02	0.4	0.3	0.02	0.01	0.04	0.03
A3	0.11	12.27	0.16	0.02	0.45	0.33	0.02	0.001	0.037	0.08
A4	0.12	12.36	0.23	0.04	0.48	0.47	0.02	0.001	0.012	0.04
A5	0.13	12.3	0.17	0	0.82	0.25	0.015	0.006	0.04	0.01
B1	0.1	12.3	0.108	0.241	0.674	0.359	0.03	0.003	0.00805	0.549
B2	0.078	12.43	0.793	0.333	0.33	0.24	0.018	0.004	0.017	0.0217
B3	0.08	13.67	0.276	0.141	0.396	0.286	0.0175	0.003	0.018	0.222
B4	0.113	13.32	0.634	0.0153	0.81	0.612	0.0166	0.00339	0.018	0.206
B5	0.105	11.25	0.334	0.243	0.622	0.281	0.0166	0.00323	0.016	0.467
B6	0.0853	11.18	0.476	0.0132	0.38	0.749	0.0138	0.00325	0.015	0.501
B7	0.115	13.77	0.29	0.0177	0.472	0.695	0.0193	0.00379	0.016	0.2
B8	0.0904	12.21	0.421	0.0915	0.547	0.651	0.0208	0.00437	0.016	0.178
C1	0.14	11.48	0.24	0.019	1.168	1.74	0.014	0.0043	0.0175	0.909
C2	0.148	12.64	0.231	0.458	0.797	0.583	0.023	0.0039	0.0179	0.085
C3	0.128	11.43	0.787	0.703	0.35	0.969	0.015	0.0032	0.0152	0.846
C4	0.138	12.85	0.546	0.035	0.489	0.559	0.025	0.0038	0.0168	0.086
C5	0.225	14.45	0.35	0.796	0.529	0.703	0.019	0.0032	0.0189	0.661
C6	0.094	14.11	0.263	0.187	0.337	0.656	0.017	0.0038	0.0173	0.528

Fig. 6 — A — Distribution of the A_1 temperature in 2000 random Type 410 steel weld and base metal compositions predicted with the simplified formula (Equation 4); B — A_1 temperature predictive diagram for Type 410 steel weld and base metals.

Phase Transformation Analysis: Single-Sensor Differential Thermal Analysis

Single-sensor differential thermal analysis (SS DTA) is a specialized technique for thermal analysis that determines enthalpy variations associated with phase transformations and structural changes in metallic alloys (Refs. 24, 25). The enthalpy variations are identified by comparing recorded thermal histories in materials undergoing phase transformations to calculated reference curves.

In this study, SS DTA could not be used for direct A_1 temperature determinations. The Curie transition in Type 410 steel is closely below the onset of the martensite to austenite transformation on heating, partially overlapping the endothermic effect of that transformation. Predicted A_1 temperatures were validated by the presence or absence of martensitic transformation on the cooling curves of samples heated correspondingly above and below the predicted A_1 temperature of the particular alloy. At normal cooling conditions, the austenite formed above the A_1 temperature in Type 410 would transform to martensite. Thus, presence of martensitic transformation on a cooling curve would indicate exceeding the A_1 temperature during heating. On the contrary, absence of martensitic transformation on a cooling curve can be accepted as a proof that the A_1 temperature was not exceeded.

Using a light radiation furnace (Fig. 2), test samples were heated to temperatures below or above the predicted A_1 with a heating rate of $20^\circ\text{C}/\text{min}$ temperature, held for 30 min, and free cooled. Thermal histories in the test samples were measured with a Type K thermocouple, recorded using fast sampling rate data acquisition system, and processed with SS DTA to identify potential on-cooling martensitic trans-

formation. Using fresh samples, this procedure was performed repeatedly until the minimum PWHT temperature that resulted in martensitic transformation on cooling in each of the tested alloys was determined within a range of $\pm 10^\circ\text{C}$ of the predicted A_1 temperature.

Phase Transformation Analysis: Dilatometry

Dilatometry is a technique for thermomechanical analysis that determines volume changes associated with phase transformations. In this study, dilatometry was performed using the GleebleTM thermomechanical simulator with a set of low-force jaws. The latter allows avoiding thermal strain buildup that would be caused by restricted longitudinal expansion and contraction during heating and cooling. This provides conditions for more accurate measurement of the lateral expansion and contraction in test samples caused by phase transformations. The dilatometry experimental set-up in the GleebleTM is shown in Fig. 3.

The A_1 temperatures in test samples were determined following the ASTM A1033-10 procedure that involves dilatometry analyses at a heating rate of $28^\circ\text{C}/\text{h}$ through the anticipated A_1 – A_3 intercritical temperature range (Ref. 26). The A_1 temperature was determined as the starting point of negative volume change on the heating portion of the dilation vs. temperature curve, which represents the starting point of martensite to austenite transformation.

Comparison to Published Experimental Results

The developed predictive formula for A_1 temperature in Type 410 steel weld and base metals was also validated through comparison with experimentally generated data for

Fig. 7 — Statistical distribution of the A_1 temperature in Type 410 steel weld and base metals predicted with the model-based DoE. Probability for exceeding the A_1 temperature during PWHT in the ASME-specified temperature range: at 760°C, 31%; at 800°C, 66%.

12% chromium stainless steels published by Rickett et al. (Ref. 18). The chemical compositions of nine alloys tested in that study (Table 4) are within the compositional range of the model-based DoE (see Table 1). The A_1 temperatures were determined by identification of the lowest PWHT temperature that resulted in higher hardness compared to fully tempered microstructure. The authors noted that the actual A_1 temperature could be lower than the one determined using their experimental approach. The latter is similar to the SS DTA approach applied in the presented study.

Results

A_1 Temperature Predictions

An example of equilibrium phase fraction vs. temperature diagram generated using ThermoCalc™ within the model-based DoE that shows predicted A_1 and A_3 temperatures is presented in Fig. 1. The predicted A_1 and A_3 temperatures in all 82 model alloys within the compositional range of Type 410 steel weld and base metals are summarized in Table 2. The predicted A_1 temperatures vary in a range of

Fig. 8 — Dilatometry curve used for determination of the A_1 temperature in Alloy A3 following the ASTM 1033-10 procedure.

202° from 687° to 889°C. The predicted A_3 temperatures vary in a range of 215° from 799° to 1014°C.

The developed predictive formulas for the A_1 and A_3 temperatures in Type 410 steel weld and base metals are given in Equations 2 and 3. The A_1 temperature predictions for the 82 theoretical compositions made with Equation 2 had a linear relationship (R^2 value) of 99.5%, with the corresponding A_1 temperatures generated using ThermoCalc™. A simplified version on the A_1 temperature predictive formula that excludes the interaction terms is given in Equation 4. Compared to A_1 temperatures generated using ThermoCalc™, the simplified predictive formula provides an R^2 value of 97.81% along with a standard deviation of 6.5. The austenite and ferrite promoting elements in Equation 4 were used to establish nickel (Ni_{Eq}) and chromium (Cr_{Eq}) equivalents for Type 410 steel weld and base metals (Equations 5, 6).

$$A_1 = 712.54 + 211.1C + 10.83Cr - 15.77Ni + 14.73Mo + 19.07Si - 55.06Mn - 5.26Cu - 281.0N + 10918N^2 - 22.71C \times Cr + 35.3C \times Ni - 97.7C \times Mo - 3.87Cr \times Ni + 1.97Cr \times Mo - 2.55Cr \times Cu - 43.8Cr \times N - 12.12Ni \times Mo - 10.20Ni \times Mn - 11.21Ni \times Cu + 189.2Ni \times N + 3.50Mo \times Si - 9.54Mo \times Mn - 130.3Mo \times N - 5.0Si \times Cu - 12.19Mn \times Cu + 81.6Mn \times N + 201.1Cu \times N \quad (2)$$

Table 4 — Chemical Composition (wt-%) of Alloys Tested by Rickett et al. (Ref. 17) and Reported A_1 Temperatures

	C	Cr	Ni	Mo	Mn	Si	P	S	N	Reported A_1 (C)
E1	0.08	11.28	0.35	0.05	0.43	0.22	0.013	0.01	0.033	766
E2	0.11	12.18	0.16	0.02	0.44	0.37	0.014	0.01	0.033	799
E3	0.11	13.24	0.15	0.02	0.62	0.31	0.013	0.013	0.019	796
E4	0.055	12.46	0.12	0.02	0.35	0.26	0.016	0.016	0.037	804
E5	0.14	12.54	0.22	0.03	0.49	0.17	0.024	0.019	0.047	785
E6*	0.09	12.28	0.32	0.4	0.6	0.29	0.025	0.342	—	793
E7	0.08	11.94	0.44	0.53	0.38	0.16	0.02	0.008	0.046	766
E8	0.016	12.12	0.12	0.01	0.84	0.98	0.008	0.025	0.036	804
E9	0.016	11.93	0.2	0.01	0.85	0.96	0.011	0.025	0.046	796

*Free machining heats with a high S content.

Fig. 9 — SS DTA curves on cooling from PWHT in Alloy A2: A — Exothermic effect of martensitic transformation after PWHT at 809°C (above the predicted A_1 temperature); B — absence of martensitic transformation after PWHT at 797°C (at the predicted A_1 temperature).

$$A_3 = 569.9 + 45C + 31.60Cr - 64.11Ni + 54.93Mo + 22.15Si - 49.00Mn - 50.54Cu - 699N + 8432C^2 - 124.2C \times Cr + 455.4C \times Ni - 146.1C \times Mo - 128.3C \times Si + 272.9C \times Mn + 411.3C \times Cu + 399Mo \times N + 385Mn \times N \quad (3)$$

$$A_1 = 772.66 + 6.5Cr + 20.91Mo + 18.5Si - 90.5C - 70.4Ni - 65.4Mn - 45.3Cu - 242.6N \quad (4)$$

$$Cr_{Eq} = Cr + 3.55Mo + 2.85Si \quad (5)$$

$$Ni_{Eq} = Ni + 0.93Mn + 0.64Cu + 1.28C + 3.45N \quad (6)$$

The relative effects of alloying elements on the A_1 temperature were also predicted through the model-based DoE — Fig. 4. The effect of variation of the austenite stabilizing elements within the AWS compositional specification on the A_1 temperature was demonstrated using the composition of a commercially available ER410 welding consumable (Alloy A4, see Table 3). The content of most alloying elements in this welding consumable was close to the middle of the AWS compositional specification. The A_1 temperature was predicted using Equation 2 with each of the austenite stabilizers at their minimum and maximum values in the AWS compositional range — Fig. 5.

The A_1 temperature distribution diagram for the 2000 random Type 410 compositions plotted using the Cr_{Eq} and Ni_{Eq} as axes is shown in Fig. 6A. A simplified version of this plot that can be used as an A_1 temperature predictive diagram in Type 410 steel base and weld metals is shown in Fig. 6B. This diagram incorporates the combined ASTM and AWS composition ranges of Type 410 steel weld and base metals, the PWHT temperature range for Type 410 steel welds specified by ASME, and the model-based DoE predicted maximum and minimum A_1 temperatures.

A statistical distribution of the A_1 temperatures in Type 410 steel weld and base metals predicted with the model-based DoE is shown in Fig. 7. This distribution curve allows es-

timating the probability of exceeding the A_1 temperature during PWHT within the ASME-specified temperature range.

Experimental Validation

The developed predictive equation for the A_1 temperature in Type 410 steel base and weld metal was validated through comparison of predicted and experimentally determined A_1 temperatures in the commercially available and custom-made alloys listed in Table 3. Figure 8 shows a typical dilatometry curve used for determination of the A_1 temperatures following the ASTM1033-10 procedure in the tested validation alloys. Typical SS DTA curves of the PWHT cooling cycle in the validation study are shown in Fig. 9. Strong exothermic effects of martensitic transformation were identified when the PWHT was conducted above the corresponding A_1 temperatures of the tested alloys — Fig. 9A. PWHT below the A_1 temperatures did not result in on-cooling exothermic effects related to martensitic transformation — Fig. 9B.

The presence or absence of fresh martensite in the microstructure of samples subjected to phase transformation analysis with SS DTA after PWHT above and below the A_1 temperature was validated by metallurgical characterization. In the as-cast condition, the microstructure of Alloy A3 contained precipitate free packets of fresh martensite and separate grains of delta ferrite retained from the original solidification — Fig. 10A. PWHT at 787°C (below the A_1 temperature) resulted in a microstructure of fully tempered martensite composed of finely dispersed precipitates, most probably $M_{23}C_6$, in a ferritic matrix — Fig. 10B. Separate grains of retained delta ferrite, unchanged during PWHT, are also present in the microstructure. Packets of fresh and partially tempered martensite, identified correspondingly by the absence or presence of precipitates along the packet boundaries and within the packets, were found in the microstructure after PWHT at 806°C (above the A_1 temperature) — Fig. 10C.

Fig. 10 — A — Alloy A3 in the as-cast condition: Matrix of fresh martensite (FM) with separate grains of delta ferrite (DF); B — Alloy A3 after PWHT at 787°C (below the A_1 temperature): Matrix of tempered martensite (TM) with a separate grain of retained delta ferrite (DF); C — Alloy A3 after PWHT at 806°C (above the A_1 temperature): Fresh martensite (FM), partially tempered martensite (PTM), grain of retained delta ferrite (DF).

The A_1 temperatures in the five commercially available welding consumables (Alloys A1–A5) and six custom-made alloys (C1–C6) determined using dilatometry, and in the nine alloys tested by Rickett et al. (Ref. 18), (Alloys E1–E9), are compared in Table 5 to the corresponding A_1 values predicted using Equation 2. The experimentally determined A_1 temperatures varied between 730° and 807°C and the predicted ones varied in a range from 724° and 808°C. The differences (deviations) predicted from experimentally determined A_1 temperatures and their average and standard deviations are also shown in Table 5. The average deviation can be used as a measure of accuracy for the developed predictive formula, while the standard deviation can be related to its precision. Plots demonstrating the correlation of A_1 temperatures predicted using Equation 2 to experimentally determined A_1 temperatures are presented in Fig. 11.

The SS DTA validation results of the predicted A_1 temperatures in Alloys A1 through A5 and B1 through B8 are summarized in Table 6 and Fig. 12. The validation experiments covered a range of predicted A_1 temperatures between 748° and 800°C. A total of 58 SS DTA validation experiments were performed in ranges of up to 30°C below and above individual-predicted A_1 temperatures.

Discussion

Typical heat treatments for welds in martensitic steels include tempering, stress relief, and normalization that can be followed by tempering. The tempering and stress relief heat treatments, known also as PWHT, are usually performed close below the A_1 temperature to provide sufficient degree of tempering of the fresh martensite formed in the weld metal and HAZ, and to relieve welding residual stresses. Exceeding the A_1 temperature during PWHT would result in formation of fresh martensite on cooling to room tempera-

ture and eventually in loss of toughness and/or increased susceptibility to hydrogen-assisted cracking. Normalization that aims at complete recrystallization and carbide dissolution is performed close above the A_3 temperature to avoid excessive grain growth. Thus, accurate prediction and/or determination of the equilibrium intercritical temperature range (the A_1 and A_3 temperatures) in martensitic steels is critical for the selection of appropriate PWHT and normalization temperatures.

For Type 410 steel welds, ASME B31.3 specifies a PWHT temperature range of 760° to 800°C, and ASME Section VIII D1 specifies a minimum PWHT temperature of 760°C. The conducted model-based DoE study has shown that within the AWS and ASTM specified compositional ranges, the A_1 temperature in Type 410 steel weld and base metals can vary between 687° and 889°C (see Table 2). Therefore, it is possible to subject welds in Type 410 steel to PWHT significantly above the A_1 temperature (about 73° to 113°C) when following the current ASME specifications.

The results of the model-based DoE were subjected to regression analysis aiming at identification of all significant terms and interactions and generation of predictive formulae for the A_1 and A_3 temperatures in Type 410 steel weld and base metals. All alloying elements included in the DoE study (see Table 1), including copper and nitrogen, were shown to have a significant effect on the A_1 and A_3 tempera-

Table 5 — Validation: Predicted and Experimentally Determined A_1 Temperatures in Commercial (A₁–A₅) and Custom-Made (C₁–C₆) Alloys Using Dilatometry, and in Alloys Tested by Rickett et al. (E₁–E₉)

Alloy #	Predicted A_1 (C)	Dilatometry (C)	Difference from Dilatometry (C)	Reported A_1 (C) (Ref. 17)	Difference from Reported (C)
A1	786	784	2		
A2	797	795	2		
A3	794	791	3		
A4	798	805	-7		
A5	773	781	-8		
C1	724	730	-6		
C2	784	780	4		
C3	750	746	4		
C4	776	776	0		
C5	770	772	-2		
C6	800	807	-7		
E1	781			766	15
E2	797			799	-2
E3	797			796	1
E4	808			804	4
E5	789			785	4
E6	799			793	6
E7	803			796	7
E8	795			804	-9
E9	790			796	-6
Average Difference (Deviation)			-1.4 4.9		2.2 7.2
Standard Deviation					

Table 6 — Validation: PWHT Temperatures without and with On-Cooling Martensitic Transformation in Commercial (A₁–A₅) and Custom Made (B₁–B₈) Alloys Determined Using SS DTA

Alloy #	PWHT Temperatures without Martensitic Transformation (C)	Predicted A_1 (C)	PWHT Temperatures with Martensitic Transformation (C)
A1	—	786	793, 802, 804
A2	760, 797	797	799, 809, 814, 815
A3	787, 795	794	804, 806, 809, 811, 812
A4	797	798	806, 803, 811
A5	775	773	781, 796, 797, 801
B1	—	776	784, 792, 798
B2	757, 771	777	777, 781, 784
B3	—	800	805, 813, 818
B4	747	748	753, 756, 759, 768, 774
B5	752	757	763, 767, 772
B6	750	766	772, 777
B7	—	798	804, 815, 822
B8	—	779	789, 797, 810, 817

tures ($p < 0.05$). Most of the first order interactions between the alloying elements also had a significant effect on the A_1 temperature (see Equation 2). For the A_3 temperature, the effect of first-order interactions of carbon with all alloying elements and of nitrogen with molybdenum and manganese (see Equation 3) was significant.

The relative effects of alloying elements on the A_1 and A_3 temperatures were also predicted through the model-based DoE (see Fig. 4). Similar rankings of the effect of manganese, nickel, silicon, and molybdenum on the A_1 temperature have been reported by Pickering (Ref. 1). As expected,

all austenite stabilizers acted to suppress the A_1 temperature, with manganese, nickel, and copper having the strongest effects (see Fig. 4A). All ferrite stabilizers had comparable effects on increasing the A_1 temperature. Similarly, the ferrite stabilizers acted on increasing the A_3 temperature, with chromium and molybdenum having the strongest effects (see Fig. 4B). Carbon, a strong austenite stabilizer, was also predicted to increase the A_3 temperature. Such behavior could be related to the strong first-order interactions of carbon with other alloying elements, as can be seen in Equation 3, and to the effect of carbides dissolution

Fig. 11 — Validation of the A_1 temperature predictive equation: Predicted vs. experimentally determined A_1 temperatures using dilatometry and published by Rickett et al. (Ref. 7).

Fig. 12 — Validation of the A_1 temperature predictive equation using SS DTA: PWHT below and above predicted A_1 temperatures (without and with on-cooling martensitic transformation).

on the kinetics of austenite transformation on heating.

One way in which this study expanded past the Type 410 steel and weld metal composition ranges was through inclusion of copper and nitrogen in the DoE. Copper and nitrogen are not included in the ASTM specification, and nitrogen is not included in the AWS specifications. As shown in Fig. 4, both nitrogen and copper were found to be significant factors in suppressing both the A_1 and A_3 temperatures. The effect of nitrogen, although small, was found to reduce the A_1 temperature by an average of 9°C when running all 82 theoretical compositions with and without nitrogen. Even as a small contributor, it should be noted that nitrogen levels included into the DoE ranged from 0 to 0.04% while higher amounts could possibly lead to greater suppression of the A_1 and A_3 temperatures. Copper, which has a maximum content of 0.75 wt-% in Type 410 steel welding consumables, was found to be a significant contributor to the suppression of the A_1 temperature as the third strongest austenite stabilizing element included into the DoE.

The effect of austenite stabilizing elements on the A_1 temperature in a commercially available ER410 welding filler metal (Alloy A4, see Table 3) is demonstrated in Fig. 5. Varying the content of manganese, nickel, copper, and carbon within the AWS specification range results in A_1 temperature variations of 57°, 44°, 33°, and 7°C, correspondingly. Variations in the nitrogen content between 0 and 0.04 wt-% would result in changes of the A_1 temperature in Alloy A4 within 12°C. At their maxima, manganese, nickel, and copper would reduce the A_1 temperature with about 30°C to a level that is very close to the ASME minimum-specified PWHT temperature of 760°C. Thus, any combination of a maximum content and an elevated content in any two of

these three elements would drive the A_1 temperature below 760°C. Elevated nitrogen and carbon content would contribute to additional A_1 temperature reduction. On the other hand, at their minimum-specified content, any of the austenite stabilizing elements would drive the A_1 temperature in Alloy A4 above the ASME maximum-specified PWHT temperature of 800°C.

The cumulative effects of the ferrite stabilizing (Cr_{Eq}) and the austenite stabilizing alloying elements (Ni_{Eq}) on the A_1 temperature are demonstrated in Fig. 6, using the developed chromium and nickel equivalent formulae for Type 410 steel. The diagrams in Fig. 6 were generated using the simplified A_1 temperature predictive formula (Equation 4) that has comparable predictive accuracy to the full-predictive formula in Equation 2. The combined ASTM and AWS Type 410 steel weld and base metal composition field is located in a window of approximately 9 Cr_{Eq} units by 2.5 Ni_{Eq} units. Variation of the chromium and nickel equivalents within this window would result in A_1 temperature variations of 50° and 190°C, correspondingly, demonstrating about three times stronger a cumulative effect of the austenite stabilizers on the A_1 temperature. The A_1 temperatures in most of the randomly generated 2000 Type 410 steel compositions are concentrated in the temperature range between 725° and 825°C, showing high probability in exceeding the A_1 temperature when following the PWHT specification of ASME (see Fig. 6A). The diagram in Fig. 6B can be used as a reference tool for development of welding consumables, matching of base metals with welding consumables in terms of A_1 temperatures, and selection of PWHT temperatures.

The probability of exceeding the A_1 temperature was evaluated by generating a statistical distribution of DoE predict-

ed A_1 temperatures (listed in Table 2) within the AWS and ASTM compositional ranges (see Fig. 7). Based on this evaluation, the estimated probability of exceeding the A_1 temperature and forming fresh, untempered martensite in Type 410 steel welds varies between 31% and 66% when PWHT is performed in the ASME specified range of 760° to 800°C.

It has to be noted that the chemical composition of commercially available Type 410 steel base metals and welding consumables may not vary throughout the entire ASTM and AWS compositional specifications. For example, the five commercially available welding consumables (Alloys A1–A5 in Table 3) used for validation purposes in this study have a composition of well-balanced ferrite and austenite stabilizers. Carbon content close to the upper bound of AWS A5.4 and A5.9 specifications, intermediate content of manganese, and low nickel and copper content are balanced with intermediate content of chromium and silicon, and low molybdenum content. The predicted A_1 temperatures in these five alloys and the measured A_1 temperatures in four of them are close below 800°C (see Table 5), granting low probability of forming fresh martensite during PWHT within the ASME specification range.

Application of the developed A_1 temperature predictive tools to an extensive database of chemical compositions in commercially available Type 410 base metals and welding consumables would provide a more realistic estimate for the probability of exceeding the A_1 temperature and forming fresh martensite during PWHT of Type 410 steel welds. Such a database can be used for optimization of the AWS and ASTM compositional specifications and of the PWHT temperature range specification of ASME.

The results of this study show that copper and nitrogen have a significant effect on the phase balance and transformations occurring during PWHT in Type 410 steel base and weld metals, and need to be included into the corresponding ASTM and AWS compositional specifications. Further optimization of these specifications could include tightening of the composition ranges of all alloying elements by specifying minimum contents. Currently, the ASTM specification provides low limits only for the carbon and chromium contents, and the AWS specification only for the chromium content.

The developed predictive formula for the A_1 temperature in Type 410 steel base and weld metals (see Equation 2) was validated through comparison with three independent experimental methods. These included direct A_1 temperature determination using dilatometry, as well as indirect identification by the presence or absence of martensitic transformation on cooling from PWHT temperatures determined using SS DTA and hardness comparison to fully tempered microstructure published by Rickett et al. (Ref. 18).

Table 5 and Fig. 11 show a strong correlation of the A_1 temperatures predicted using Equation 2 with those determined using dilatometry and with the results of Rickett et al. (Ref. 18). The A_1 predictions varied between 8° below and 4°C above those determined using dilatometry. An average deviation of -1.4°C, calculated as the average of all differences between predicted and experimentally determined A_1 temperatures, evidences high accuracy of Equation 2 in predicting the A_1 temperature. The precision of

this equation is demonstrated by a standard deviation of 4.9°C determined from the differences between predicted and experimentally determined A_1 temperatures. The comparison with the A_1 temperature results published by Rickett et al., showing the average deviation of 2.2°C and standard deviation of 7.2°C, also validates the accuracy and precision of the developed A_1 temperature predictive formula.

The results of PWHT experiments instrumented with SS DTA (see Table 6 and Fig. 12) provide additional validation on the A_1 temperature predictive formula and can be used for estimation of a safety margin of PWHT temperatures. All experiments performed below predicted A_1 temperatures did not show on-cooling transformations to martensite. Examples of SS DTA curve without on-cooling exothermic effect related to martensitic transformation in Alloy A2 subjected to PWHT at the predicted A_1 temperature and of fully tempered microstructure in Alloy A3 subjected to PWHT 7°C below the predicted A_1 temperature are shown in Figs. 9B and 10B, correspondingly.

Two samples were tested at the predicted A_1 temperature, showing absence (Alloy A2) and presence of martensitic transformation (Alloy B2). All alloys subjected to PWHT above the predicted A_1 temperature experienced on-cooling martensitic transformation, except single experiments in Alloys A3 and A5 performed near the predicted A_1 temperature. Examples of SS DTA curve showing on-cooling transformation to martensite in Alloy A2 and microstructure containing fresh and partially tempered martensite in Alloy A3, both subjected to PWHT 12°C above the predicted A_1 temperature, are shown in Figs. 9A and 10C, correspondingly.

The accuracy of dilatometry and SS DTA experiments and related temperature measurements needs to be accounted for when analyzing the validation experiments. An extensive comparative study has shown that both methods have equal accuracy in determination of the starting temperatures in martensite to austenite and austenite to martensite transformations in martensitic steels (Ref. 17). It was also shown that the accuracy of SS DTA is controlled by the accuracy in temperature measurements, and SS DTA was more sensitive than dilatometry in determination of small, volume fraction transformations of austenite to ferrite and bainite. In the current study, special limit of error Type K thermocouples were used. Their accuracy of 0.4% provides an error range of about $\pm 3^\circ\text{C}$ in the studied temperature range between 730° and 807°C.

Based on the results from the validation study, it can be concluded that the accuracy of the developed A_1 temperature predictive equation is within the accuracy of temperature measurements in the validation experiments. These results also provide a general validation of the predictive accuracy of the ThermoCalc™ software and the TCFE8 steels database, which were utilized in the performed model-based DoE study. The developed predictive tools utilize the alloy chemical composition, therefore the accuracy in A_1 temperature predictions would be also controlled by the accuracy in determination of the alloying element's content.

The predictive tools developed in this study can be used in development and/or compositional optimization of

welding consumables, materials selection, matching of base metals and welding consumables in terms of A_1 temperatures, and development of PWHT procedures. In cases of significant differences between base and weld metal compositions, the proposed methodology can be applied to predict the A_1 temperature in diluted weld metals based on compositions derived from particular levels of dilution. To avoid exceeding the A_1 temperature during PWHT, a safety margin of 10°C below the predicted A_1 temperature can be utilized. The latter covers a band of two standard deviations determined in the dilatometry validation experiments and reflects the variation bands in the SS DTA validation and in the comparison to published results (see Tables 5 and 6) — Figs. 11, 12. Additional safety bands below the predicted A_1 temperature should be considered in relation to the accuracy of temperature measurement and control at particular PWHT conditions.

The approach of model-based DoE demonstrated in this study had also been successfully applied in the development of predictive equations for the A_1 temperatures in Grade 91 and 92 steel base metals and welding consumables (Refs. 21–23). Such approach can utilize various thermodynamic and kinetic software, and could be applied as a powerful tool for the development and/or optimization of metallic alloys as well as thermal and thermomechanical materials processing.

Conclusions

Predictive formulas for the A_1 and A_3 temperatures in Type 410 steel weld and base metals were developed using the design of experiment approach, based on computational modeling with the thermodynamic software ThermoCalc™. Based on the A_1 temperature predictive formula, chromium and nickel equivalent equations were established and applied to plot an A_1 temperature predictive diagram. The developed A_1 temperature predictive tools were validated through phase transformation analysis of commercially available and custom-made alloys within the AWS and ASTM compositional specification ranges, and by comparison to published data. The predictive accuracy of the A_1 temperature formula was estimated to be within the error of experimental temperature measurement ($\pm 3^\circ\text{C}$) and had a standard deviation of 5°C .

The predicted A_1 temperature range in Type 410 alloys, within the AWS and ASTM compositional specifications, is between 687° and 889°C and extends below and above the ASME recommended PWHT temperature range of 760° to 800°C. The predicted probability of exceeding the A_1 temperature during PWHT within the recommended ASME temperature range and formation of fresh martensite in Type 410 steel welds varies between 31% and 66%. Using phase transformation analysis and metallurgical characterization, it was shown that even small excursions above the A_1 temperature during PWHT would result in partial transformation to austenite and on-cooling formation of fresh martensite.

All alloying elements in the Type 410 steel weld and base metal specifications were shown to have a significant effect on the A_1 and A_3 temperatures, including copper (not included in the ASTM specification) and nitrogen (not in-

cluded in both ASTM and AWS specifications). The austenite stabilizing alloying elements, led by manganese, nickel, and copper, have a stronger effect on the A_1 temperature while the ferrite stabilizers, mostly chromium and molybdenum, have a stronger effect on the A_3 temperature. Variations in the content of a single austenite stabilizing element within the corresponding specification range may shift the A_1 temperature of a particular alloy below or above the ASME-specified PWHT temperature range.

The results of this study provide a basis for optimization of the AWS and ASTM compositional specifications for Type 410 steel welding consumables and base metals by inclusion of copper in the ASTM specification and nitrogen in both specifications, and by introduction of lower limits for the content of all alloying elements. Such compositional optimization would significantly shorten the A_1 temperature range in Type 410 steel weld and base metals and would allow for tightening of the ASME-recommended PWHT temperature range.

The developed A_1 and A_3 temperature predictive tools can be utilized in development and/or compositional optimization of welding consumables, materials selection, matching of base metals and welding consumables in terms of A_1 temperatures, and development of PWHT procedures. The benefit of their implementation is related to meeting the NACE and ASME hardness and toughness requirements for Type 410 steel welds by reducing the probability of formation of fresh martensite in the heat-affected zone and weld metal during PWHT.

The demonstrated approach of model-based DoE can utilize various computational models and software, and can be applied as a powerful tool for the development and/or optimization of metallic alloys as well as thermal and thermomechanical materials processing.

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