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Welding and Repair Technology Center: Evaluation of Post Weld Heat Treatment (PWHT) Exemption Thickness Limitations

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PRODUCT DESCRIPTION

The Welding and Repair Technology Center is working with the American Society of Mechanical Engineers (ASME) Code Committees to eliminate inconsistencies in post-weld heat treatment (PWHT) requirements among the various Codes specified for use in the power-generation industry. Although the current PWHT exemption thickness limits follow good historical engineering practice, it is believed that they may be overly conservative or restrictive in some cases. This document provides technical insight and a technical basis for increasing or modifying current Code thickness limits. The goal of this project is to develop criteria for PWHT exemption thickness limits that are technically justified.

Results and Findings

The test results and data provided in this report show that relaxation of the current Code thickness limitations for PWHT exemption is technically sound. Select steels grouped in P Number 1, 3, 4, and 5A base material classifications that exceeded the current Code PWHT exemption thickness limits were successfully welded and thoroughly evaluated and mechanically tested to support Code changes.

Challenges and Objectives

Utility personnel responsible for repair and modification activities will find the information in this report beneficial when considering alternatives to PWHT. Setup and performance of PWHT can add significant time and cost to fabrication, modification, and repair of carbon and low-alloy steel components. Expansion of the current PWHT exemption thickness limits can provide significant savings for a large modification project or critical repair activity. The immediate challenge is to introduce and promote these changes to the ASME Code Committees.

Application, Value, and Use

Welding and Repair Technology Center members and key ASME Code experts are actively engaged in initiatives to change the PWHT rules and requirements in the various ASME Codes used in the power-generation industry. The results and data in this report will be used to provide the technical data to support these initiatives.

EPRI Perspective

EPRI is in a unique position to work with utility representatives and industry experts to identify, promote, and provide the technical support and participate on the ASME Code Committees to facilitate safe and beneficial changes of ASME Code rules and requirements.

Approach

The goal of this project is to provide technical data to support changes of the PWHT rules and requirements in the ASME Codes.

Keywords

Post-weld heat treatment (PWHT)
Carbon steel
Low-alloy steel

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1
INTRODUCTION

1.1 Background

The Codes generally specified and used in the power generation industry have significant differences in thickness exemption limits and thickness definitions that pertain to rules and requirements for application of Post Weld Heat Treatment (PWHT). The technical bases for the different PWHT thickness limitations and definitions for similar materials in the various Codes are unfortunately not well documented. There are however two basic reasons given for requiring PWHT [1]; the first is to reduce weld residual stress, and the second is to lower the excessive hardness that may occur in hardenable carbon and low alloy steels during the welding. The purpose of this study and report is to provide a technical basis for establishing consistent application of PWHT requirements between the Codes and to increase the thickness exemption limits where possible.

Reducing weld residual stress will typically improve resistance to corrosion or fatigue. In fact, severe corrosion environments may necessitate application of supplemental heat treatment beyond that specified by the Codes. These heat treatments are typically specified in the design documents and would be selected by the design engineer. Similarly, the design engineer may select specific heat treatments for systems or components that will be subject to extreme cyclic or thermal fatigue conditions. The purpose of this study is not to evaluate heat treatment for extreme service conditions. Rather the purpose is to provide a sound basis for consistent and reasonable PWHT rules for general applications.

Selection of base materials is typically based on material properties such as corrosion resistance, fatigue strength, tensile strength, toughness, weldability, wear resistance, etc. Welding can, however, significantly alter the properties of carbon and low alloy steels. Rapid cooling rates, high carbon contents, or alloy additions can increase the potential for the welding process to alter the mechanical properties of the base material. Steels with high hardenability due to alloy composition and/or with high carbon content can have a strong propensity to form martensite under fast cooling conditions such as welding. Martensite is a very hard microstructure with high strength but with very low ductility and toughness. Code specified PWHT at the designated temperature and holding time works to temper and soften the martensitic microstructure. In addition to reduced hardness, tempered martensite has improved toughness properties. PWHT also reduces and levels out the hardness gradient across the weldment.

The local cooling rate in a weldment can vary substantially depending on location relative to the weld bead. The highest hardness values normally occur in the base material heat affected zone (HAZ) closet to the weld fusion line where the cooling rates are rapid and in the 1470ºF to 930ºF (800ºC to 500ºC) temperature range when the martensite phase transformation occurs. The local cooling rate in the HAZ is a function of the weld process, heat input, weld technique, material thermal conductivity, substrate temperature during welding (preheat and interpass temperatures), and the heat sink provided by the base material. The cooling rate is generally considered to be more rapid with thicker materials due to the increased heat sink effect of the larger mass of

surrounding material. High heat input welding parameters and inherently high heat input welding processes will decrease the cooling rate which reduces the propensity for the formation of martensite. Finally, preheating the base material prior to welding will decrease the cooling rate in the HAZ.

The Codes used in the power generation industry generally define requirements and exemptions for PWHT on thickness criteria, material grouping, and/or preheat temperature. For example, for full penetration butt welded circumferential or longitudinal joints, the thickness criteria considered for PWHT application or exemption is typically the base material thickness at the weld joint. The weldability number, or P Number, defined by ASME Section IX is the grouping criteria used to define material properties for application of PWHT. Finally, elevated preheat temperature applied during welding may permit PWHT exemption.

This study and report compares and evaluates the current P Number groupings and thickness exemption limits specified for application of Code PWHT requirements and rules. In addition, the affect of elevated preheat temperature, multipass welding, and weld process heat input is considered. Mechanical test data is also presented that can potentially support modification and refinement of Code PWHT exemption thickness limitations.

1.1.1 Current Code Rules

Following are the specific rules of various Codes regarding PWHT for the materials covered in this report. The materials investigated and the ASME Section IX assigned P Numbers are:

- SA-515 Grade 70 – P No. 1, Group 2
- SA-516 Grade 70 – P No. 1, Group 2
- SA-204 Grade C – P No. 3, Group 2
- SA-387 Grade 11 Class 2 – P No. 4, Group 1
- SA-335 Grade P11 – P No. 4, Group 1
- SA-387 Grade 22 Class 1 – P No. 5A, Group 1
- SA-335 Grade P22 – P No. 5A, Group 1

All of the above listed materials are permitted by the Codes listed below with the exception of SA-204 Grade C which is not a listed material in B31.1. The PWHT of SA-204 Grade C material is evaluated in this study but the restriction for B31.1 applications should be noted. Several Codes have extensive exemptions based on conditions other than the thickness of the materials, such as weld joint configuration, preheat level, or specific application. The weld configuration assumed for this analysis is a full penetration circumferential or longitudinal butt weld between pressure retaining components.

1.1.1.1 ASME Section I, Power Boilers – 2007 (PW-39)

The exemption thickness is the lesser of the weld thickness or the thinner base material thickness. It would apply to the pressure retaining material for attachment welds. There are also additional alloy limitations and preheat requirements listed in order to use the exemption. The exemption thicknesses for the listed materials are:

- P No. 1 – PWHT not required for thicknesses ≤ ¾".
- P No. 3 –The exemption for Groups 1 & 2 materials applies for thicknesses ≤ ⅝".
- P No. 4 – PWHT not required for thicknesses ≤ ⅝".
- P No. 5A – PWHT not required for thicknesses ≤ ⅝".

1.1.1.2 ASME Section III, Subsections NB and NC, Rules for Construction of Nuclear Facility Components – 2007 (NX-4620)

The exemption thickness is the lesser of the weld thickness, the thickness of the pressure retaining material for a structural attachment weld, or the thinner material thickness between pressure retaining materials. Some additional exceptions to the PWHT requirement apply for certain types of welds. There are also additional alloy limitations and preheat requirements listed in order to use the exemption. The exemption thicknesses for the listed materials are:

- P No. 1 – PWHT not required for thicknesses ≤ 1½".
- P No. 3 – The exemption for Groups 1 & 2 materials applies for thicknesses ≤ ⅝" (requires the WPS be qualified with thickness equal to or greater than thickness being welded).
- P No. 4 – PWHT not required for thicknesses ≤ ½".
- P No. 5A – PWHT not required for thicknesses ≤ ½".

1.1.1.3 ASME Section VIII, Div. 1, Pressure Vessels – 2007 (UCS-56)

The exemption thickness is the lesser of the weld thickness, the thickness of the pressure retaining material for a structural attachment weld, or the thinner material thickness between pressure retaining materials. Some additional exceptions to the PWHT requirement apply for certain types of welds. There are also additional alloy limitations, preheat requirements, and welding procedure qualification requirements listed in order to use the exemption. The exemption thicknesses for the listed materials are:

- P No.1 – PWHT not required for thicknesses ≤ 1½".
- P No.3 –The exemption for Groups 1 & 2 materials applies for thicknesses ≤ ⅝".
- P No. 4 – PWHT not required for thicknesses ≤ ⅝".
- P No. 5A – PWHT not required for thicknesses ≤ ⅝".

1.1.1.4 ASME B31.1, Power Piping – 2007 (Para. 132)

The exemption thickness is the lesser of the weld thickness or the greater material thickness for P Nos. 1 and 3 only. For P Nos. 4 and 5A, the exemption thickness is the greater material thickness. Some additional exceptions to the PWHT requirement apply for certain types of welds. There are also additional alloy limitations and preheat requirements listed in order to use the exemptions. The exemption thicknesses for the listed materials are:

- P No. 1 – PWHT not required for thicknesses ≤ ¾". If the carbon equivalent (see 2.1.1) is ≤ 0.50 and the preheat increased to 250ºF (121ºC), the exemption thickness may be increased to 1½ in. (This would have applied to the SA-516 Grade 70 and the SA-515 Grade 70 plates if a 250ºF preheat was done.)
- P No. 3 – The exemption for Groups 1 & 2 materials applies for thicknesses ≤ ⅝".
- P No. 4 – PWHT not required for thicknesses ≤ ½".
- P No. 5A – PWHT not required for thicknesses ≤ ½".

1.1.1.5 ASME B31.3, Process Piping – 2006 (Para. 331)

The exemption thickness is the greater material thickness for all materials. Some additional exceptions to the PWHT requirement apply for certain types of welds. There are also additional alloy limitations and preheat requirements listed in order to use the exemptions. The B31.3 Code also requires a sampling of production welds that have been subjected to PWHT to be tested for hardness for P Nos. 3, 4, and 5A. The requirement is to meet specified Brinell hardness levels where “the hardness limit applies to the weld and heat affected zone (HAZ) tested as close as practicable to the edge of the weld.” Additionally, B31.3 also uses tensile strength criteria for determination of the PWHT exemption in P Nos. 3 and 4 materials. These criteria would have resulted in required PWHT for both the P Nos. 3 and 4 materials used in this study. The exemption thicknesses for the listed materials are:

- P No. 1 – PWHT not required for thicknesses ≤ ¾".
- P No. 3 – The exemption applies for thicknesses ≤ ¾".
- P No. 4 – PWHT not required for thicknesses ≤ ½".
- P No. 5A – PWHT not required for thicknesses ≤ ½".

2
DESCRIPTION

This project was developed in an attempt to understand the effect of welding various thicknesses of materials commonly utilized in power plants. In doing so there could then be reasoning or technical justification which allow code committee members to more accurately develop rules and guidelines for exempting or requiring PWHT.

Recommendations from industry experts working with various code bodies was both encouraged and required for this project so that discrepancies to code issues could be resolved. This work is a culmination of the efforts undertaken to address some of the questions that have arisen to more accurately define the rules that are currently in place for determination of thickness limit exemptions to PWHT. The goal is to provide data needed that identifies what limit can be permitted for PWHT exemption while maintaining the safe and reliable operation of the welded component once it is placed into service. The recommendations developed in this project are based on tests performed from some of the most commonly used materials from P Nos. 1, 3, 4 and 5A groups and is not all encompassing. Efforts are aimed at developing criteria from the data gathered which will then be used to establish the thickness to which PWHT can be exempted for other materials within the same P Number. The materials investigated to date and their descriptions are discussed in the following section.

2.1 Test Materials

The test materials for this project are categorized by the P Number assigned by ASME Section IX. The P Number groups base materials with similar composition and mechanical properties based on weldability. The purpose is to allow code rules to be applied to groups of similar base materials instead of writing specific rules for each individual engineering material that is allowed for use. While type grouping is convenient and necessary for administrative reasons the applicability of the rules to every material contained within the set may not be appropriate for all applications. In fact grouping materials in this manner has the tendency to promote rules which are overly conservative for some of the base materials in the group. For instance, in ASME Section XI, underwater welding rules use a carbon equivalent (CE) number to determine what material can be used for weld qualification. If the exact composition of the material to be welded is unknown then an adder for the hardenability elements is utilized to calculate the CE number. The problem is that when the adder is utilized to represent the unknown elements, the CE can become unrealistically high for some grades of materials identified. This can make it difficult, if not impossible, to locate and purchase the material needed to qualify a welding procedure [2].

Previous work and investigation on exemption thickness has been focused primarily on P No. 1 materials where hardenability properties were expected to be minimal. EPRI report 1008277 *PWHT Exemptions for Low Hardenability Materials* [3], discussed the discrepancies between the various code bodies (e.g., Section III, VIII) that allowed PWHT exemptions in P No. 1 materials up to 1½" thick to those that previously limited the exemption to ¾" and below (e.g., B31.1, B31.3, Sect I). This project investigates the appropriate limits for the P No. 1 materials but also investigates P Nos. 3, 4 and 5A that have higher alloy content. The thickness of materials tested includes up to 1½". This project also investigates the mechanical behavior of the base metal in the as welded condition without PWHT.

2.1.1 Effect of Hardenability

The importance of hardenability on the determination of materials weldability is well known. Furthermore, the correlation between increased hardenability and susceptibility to hydrogen assisted cracking is well documented in the literature. It is critical to understand and differentiate the distinctions between hardenability and hardness when studying the affects of welding various thicknesses of materials. Hardenability is defined as the relative ability of a ferrous alloy to form martensite when quenched from a temperature above the upper critical temperature. Hardenability is gauged by measuring the depth or distance from the quenched surface to which a specified hardness (e.g., 50Rc) or volume percent martensite is achieved. It is quite possible that a material with a lower maximum hardness could have a greater hardenability than a material with a higher maximum hardness and vice versa. For example if an increase in hardenability of a certain material is desired it could be done without increasing the maximum hardness attained at the quenched end through selective alloying additions (most commonly one or more combinations of C, Mn, Si, Cr, Mo, V, Ni, Cu). If, however, the increase in hardenability was achieved through carbon additions then the maximum hardness would change at the quenched end as carbon is the most potent element addition that drives maximum attainable hardness in carbon and low alloy steels. Carbon content can also significantly affect the quench rate required to produce martensitic structures. Lower carbon variations of the same alloy compositions require faster quench rates to achieve equivalent through wall hardness properties. It is important to understand hardenability when working with higher strength carbon steels and low alloy steels with P No. 1 through P No. 5A classification.

The carbon equivalent (CE) number is a common value often used for determination of a material's hardenability. The CE formula most often used for ASME applications is shown below (see ASME Section IX, QW-403.26).

$$CE = C + \frac{Si + Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

A calculated CE number based on the specification limits is often significantly higher than a CE number calculated using actual heat composition recorded on the Certified Material Test Report (CMTR). While it is potentially possible to have compositions for these materials that reach the maximum limited by the specification, it would be the exception for this to occur in typical steel manufacturing practice.

2.1.2 Base Materials

Seven base materials have been selected for this study based on common use in the power generation industry. Two P No. 1 materials, one P No. 3 material, one P No. 4 material and one P No. 5A material were selected in plate product form. Additionally, one P No. 4 material and one P No. 5A material were selected in pipe product form. Base materials representing a composition which would fall within the mid to upper allowable ranges (i.e. strength and hardenability levels) for each P Number material were selected for testing. This was desired so that the effects of welding on the selected range of thicknesses could be studied on materials which were toward the higher alloy and hardenability range for the P Number represented. The results of the testing would then be representative of the higher alloyed materials for the classifications studied which would represent the worst case scenario, or rather provide the best chance for less than optimum as welded mechanical properties by omitting a PWHT. It should be mentioned that there are virtually infinite compositional ranges possible depending on manufacturing process and manufacturer preference associated with each of the materials listed in each P Number classification. Every effort was made to acquire commonly used materials that would be representative of the worst case results for welding thicker sections without PWHT.

The chemical composition, CE number (see Section 2.1.1), and the mechanical properties for the specific materials selected for testing and evaluation are given in Tables 2-1 and 2-2. The composition values for the listed materials were obtained from the CMTR for each material. The element composition entered for the specifications are maximums unless otherwise noted. If the chemical composition limits are listed for both heat analysis and product analysis, the values given are the heat analysis. These tables also provide the composition limits required by the specifications and the maximum carbon equivalent that could be achieved within the composition limits.

Material specifications often permit unspecified trace elements provided the elements are listed and controlled per specification SA-20. Review of the unspecified trace elements permitted by SA-20 indicate that these unspecified elements may increase the maximum potential CE number calculated in Table 2-1 by as much as 0.12.

Table 2-1:
Composition of Base Materials Tested

		Element														
Material	CE (3)	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Nb	Al	B	Sn
SA-516-70 HT#C4843 (1)	0.46	0.20	1.04	0.007	0.001	0.38	0.08	0.05	0.08	0.01	0.001	0.003	NS	NS	0.0002	0.005 (4)
SA-516-70 Specification (2)	0.55	0.28	0.85 to 1.20	0.035	0.035	0.15 to 0.40	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SA-515-70 HT#U2739 (1)	0.48	0.26	0.64	0.009	0.009	0.22	0.32	0.25	0.11	0.07	0.001	0.001	NS	0.003	NS	NS
SA-515-70 Specification (2)	0.62	0.33	1.20	0.035	0.035	0.13 to 0.45	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SA-204-C HT#62973 (1)	0.54	0.199	0.87	0.011	0.000 6	0.314	0.189	0.114	0.115	0.511	0.003	NS	0.002	NS	NS	NS
SA-204-C Specification (2)	0.64	0.26	0.90	0.035	0.035	0.15 to 0.40	NS	0.40 to 0.70	NS	0.45 to 0.60	NS	NS	NS	NS	NS	NS
SA-387-11 HT#524835 (1)	0.66	0.15	0.57	0.010	0.007	0.51	0.17 (4)	0.120 (4)	1.09	0.47	0.005 (4)	NS	NS	NS	NS	0.013 (4)
SA-387-11 Specification (2)	0.83	0.05 to 0.17	0.40 to 0.65	0.035	0.035	0.50 to 0.80	NS	NS	1.00 to 1.50	0.45 to 0.60	NS	NS	NS	NS	NS	NS

SA-335-P11 HT#244235 (1)	0.65	0.11	0.48	0.012	0.002	0.62	0.17 (4)	0.120 (4)	1.19	0.48	NA	NS	NS	NS	NS	0.003 (4)
SA-335-P11 Specification (2)	0.85	0.05 to 0.15	0.30 to 0.60	0.025	0.025	0.50 to 1.00	NS	NS	1.00 to 1.50	0.44 to 0.65	NS	NS	NS	NS	NS	NS
SA-387-22 HT#527078 (1)	0.88	0.12	0.52	0.010	0.006	0.33	0.15 (4)	0.107 (4)	2.06	0.92	0.009 (4)	NS	NS	NS	NS	NS
SA-387-22 Specification (2)	1.05	0.05 to 0.15	0.30 to 0.60	0.035	0.035	0.50	NS	NS	2.00 to 2.50	0.90 to 1.10	NS	NS	NS	NS	NS	NS
SA-335-P22 HT#248955 (1)	0.89	0.11	0.50	0.015	0.003	0.24	NS	NS	2.34	0.95	NS	NS	NS	NS	NS	NS
SA-335-P22 Specification (2)	1.08	0.05 to 0.15	0.30 to 0.60	0.025	0.025	0.50	NS	NS	1.90 to 2.60	0.87 to 1.13	NS	NS	NS	NS	NS	NS

(1) Composition reported in CMTR
(2) Composition limits set by material specification
(3) Calculated Carbon Equivalent (CE) for specific heat of material or calculated maximum possible CE for material composition limits per specification
(4) Element not included in the SA specification or in trace element specifications but was included in the CMTR

Table 2-2:
Specification and Measured Mechanical Properties for Base Materials Tested

Material	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	% Elongation in 2"
SA-516-70 HT#C4843 (1)	74.6	46.3	29.0
SA-516-70 Specification (2)	70 to 90	38 min	21 min
SA-515-70 HT#U2739 (1)	80.5	46.3	22.0
SA-515-70 Specification (2)	70 to 90	38 min	21 min
SA-204-C HT#62973 (1)	81.1	59.2	22.0
SA-204-C Specification (2)	75 to 95	43 min	20 min
SA-387-11 HT#524835 (1)	80.1 (3)	60.0 (3)	23.8
SA-387-11 Specification (2)	75 to 100	45 min	18 min
SA-335-P11 HT#244235 (1)	68.7	42.1	35
SA-335-P11 Specification (2)	60 min	30 min	14 min
SA-387-22 HT#527078 (1)	80.1	61.5	44. (4)
SA-387-22 Specification (2)	60 to 85	30 min	18 min
SA-335-P22 HT#248955 (1)	84.1	62.8	29
SA-335-P22 Specification (2)	60 min	30 min	14 min

(1) Mechanical properties listed in CMTR

(2) Mechanical property limits set by material specification

(3) Converted from MPa

(4) Tenth percentage digit unreadable in CMTR

2.1.2.1 P No. 1 – SA-516 Grade 70

SA-516 Grade 70 was selected as a representative material for P No. 1. Manufacturers commonly produce this material to a dual certified grade of 60/70. The grade 70 represents the P No. 1, Group 2 classification. The specification requires normalization of plates > 1½" thick. Plates ≤ 1½" thick are normally supplied in the as rolled condition but can be supplied in the normalized condition. The plate used in this project was normalized at the mill. The specification permits trace amounts of Boron up to 0.001% to increase the hardenability.

2.1.2.2 P No. 1 – SA-515 Grade 70

SA-515 Grade 70 was selected as a second representative material for P No. 1. The grade 70 represents the P No. 1, Group 2 classification. Plates ≤ 2" thick are typically supplied in the as-rolled condition, which is coarse grained. Plates can be ordered normalized or stress relieved, or both. Plates > 2" thick must be normalized. This material was selected since it shows an increase in carbon content and alloying as well as a coarse grained microstructure compared to the SA-516 grade 70 material. The plate used in this project was supplied in the as rolled condition.

2.1.2.3 P No. 3 – SA-204 Grade C

SA-204 Grade C was selected as a representative material for P No. 3. This material can be produced to three classes or strength levels (A, B or C). This alloy is listed as a P No. 3 Group 2 material. The specification requires normalization of plates > 1½" thick. Plates ≤ 1½" thick may be normalized or stress relieved or both. The plate used in this project was normalized at the mill.

2.1.2.4 P No. 4 – SA-387-11 Class 2

SA-387 Grade 11 was selected as a representative material for the P No. 4 Group 1 classification. A more common product form for this material composition is SA-335 for piping and SA-213 for tubing. With the exception of higher silicon, the composition specifications of SA-213 and SA-335 product forms are typically lower in maximum alloy limits as compared SA-387 Grade 11 plate. The slightly higher alloy additions permitted in the SA-387 plate product form is conservative for this testing program since slightly higher alloy content typically leads to higher hardenability. Finally, the carbon allowable is higher in the SA-387 plate specification, which allows for a potentially greater as quenched hardness in the plate when compared with the more common pipe and tubing product forms. The SA-387 Grade 11 plate specification requires the final product to be delivered in the fully annealed or normalized and tempered condition. The plate used in this project was normalized and tempered at the mill.

2.1.2.5 P No. 4 – SA-335 Grade P11

SA-335 Grade P11 was selected as a second representative material for the P No. 4 Group 1 classification. This is one of the most common product forms in the power industry for this material composition. A pipe product form was selected to evaluate the behavior of the more common material. In addition, higher heat input flux cored arc welding (FCAW) was used to weld on this material for comparison to the lower heat input shielded metal (SMAW) process . The pipe used in this project was normalized and tempered at the mill.

2.1.2.6 P No. 5A – SA-387-22 Class 1

SA-387 Grade 22 was selected as a representative material for the P No. 5A Group 1 classification. Plate material was used so that welding geometries and test samples could be removed consistently. The more common product form for this material chemistry is SA-335 for piping and SA-213 for tubing. The composition specifications for these product forms are very similar in alloy limits as compared with the SA-387-22 plate specification with the exception of slightly higher (0.1%) Cr and (0.03%) Mo allowed by the tube and pipe specifications. The plate specification allows the final product to be delivered without normalization and temper heat treatment but requires annealing or stress relief prior to shipping. The plate used in this project was normalized and tempered at the mill.

2.1.2.7 P No. 5A – SA-335 Grade P22

SA-335 Grade P22 was selected as a second representative material for the P No. 5A Group 1 classification. This is one of the most common product forms for this material and is typically used for high temperature piping in the power industry. The piping product form was selected for testing and evaluation. As with the SA-335 Grade P11 material, the flux core arc welding (FCAW) process with a higher heat input was used to make the weld, thus providing some additional variations. The pipe used in this project was normalized and tempered at the mill.

2.1.3 Selection and Machining of Base Materials

Base materials were selected or machined to represent the PWHT exemption thickness limitations in the applicable industry Codes. See Table 2-3 for current Code PWHT thickness exemption limits. One heat of each plate material was ordered to a 1½" thickness. This was done so that various thicknesses up to 1½" could be machined from material of the same composition. Variations in the testing results due to heat to heat composition differences could also then be eliminated. Three different plate thicknesses (½", ¾", and 1½") were used for each material with the exception of the SA-516-70 and SA-515-70 carbon steel plates where no ½" plate was used because the thinnest exemption thickness for this material is currently set at ¾". In addition, one heat of each pipe material was ordered to a 1½" thickness. This required one pipe, the SA-335 Grade P11, to be machined down to 1½" prior to starting the tests as it was only available in a thickness of 1¾". Final machining of the two pipe base materials to 1½, ¾, and ⅝" thickness was then performed.

Table 2-3:
PWHT Exemption Thickness (upper limit) for Various Codes (2)

P No.	B31.1	B31.3	Sec. I	Sec. III	Sec. VIII
1	¾" (1)	¾"	¾"	1½"	1½"
3	⅝"	¾"	⅝"	⅝"	⅝"
4	½"	½"	⅝"	½"	⅝"
5A	½"	½"	⅝"	½"	⅝"

(1) The exemption thickness may be up to 1½" for specific conditions as described in 1.1.1.4.

(2) The exemptions are for information only. Additional notes or requirements in the specific Code section should be referenced.

2.1.4 Weld Filler Metals and Welding Process Parameters

Shielded metal arc welding (SMAW) was used for both the full thickness groove welds and bead-on-plate welds on plate materials. Flux cored arc welding (FCAW) was used for full thickness groove welds and bead-on-pipe welds on the piping base materials.

Compatible weld filler metals were selected for each base material and thickness. Selection of weld filler metal was not critical to this project since the focus of investigation was the affect of welding on the base metal heat affected zone (HAZ) properties. For the plate base materials, the welding was carried out using ⅛" diameter SMAW electrodes. All electrodes were removed from clearly identified hermetically sealed packages. For the pipe base materials, the welding was done using 0.045" diameter FCAW consumable.

All welds were made using a stringer bead technique. Base materials were not buttered and there was no attempt to deposit the weld layers in a “temperbead” like fashion. For each process, an attempt was made to keep the same approximate welding parameters and travel speeds for each weld made, thereby keeping the heat input constant for all of the SMAW welds and for the fill layers of the FCAW welds. Welding parameters used in this project are given in Table 2-4.

Bead-on-plate welds and bead-on-pipe welds were made as follows: Single stringer bead, 3 bead wide two layer deposit and 4 bead wide three layer deposit. The 1B1L designation is for the one bead one layer or single stringer bead deposit, 3B2L designation is for the 3 bead wide two layer deposit and 4B3L designation is for the 4 bead wide three layer deposit. Figure 2-2 shows the typical bead placement and sequence for the bead-on-plate and bead-on-pipe welds. Full thickness groove welds were made using stringer bead technique without specific guidance for bead placement or sequencing. Figure 2-1 shows the general configuration and a typical bead placement and sequence for a full thickness groove weld.

The bead-on-plate and bead-on-pipe welds were made without preheat except for a few single stringer bead samples on 1½" plate were done with preheat. The samples with preheat provided data to compare the HAZ hardness of a single stringer bead (1B1L deposit) with and without preheat. Weld preheat and interpass temperatures for the full thickness groove welds are listed in Table 2-5.

Table 2-4:
Welding Parameters for Bead-on-Plate, Bead-on-Pipe, and Full Thickness Groove Weld Tests

Base Material	Welding Electrode	Electrode Diameter (in.)	Amperage (A)	Voltage (V)	Travel Speed (in./min.)	Heat Input (KJ/in.)	Gas Mix	Gas Flow (SCFH)
SA-515-70 (1)	E7018	⅛	119	23-25	8	20.5-22.3	--	--
SA-516-70 (1)	E7018	⅛	119	23-25	8	20.5-22.3	--	--
SA204-C (1)	E7018-A1	⅛	119	23-25	8	20.5-22.3	--	--
SA-387-11 (1)	E8018-C3	⅛	119	23-25	8	20.5-22.3	--	--
SA-387-22 (1)	E9018- B3	⅛	119	23-25	8	20.5-22.3	--	--
SA-335-P11 (Hot Pass)	91T1-B3M	0.045	170	23.6	8-10	24.1-30.1	75Ar-25CO_2	35-38
SA-335-P11 (2 Layers)	91T1-B3M	0.045	190	24.2	8-10	27.6-34.5	75Ar-25CO_2	35-38
SA-335-P11 (1) (Fill Passes)	91T1-B3M	0.045	202	24.7	10-11	27.4-29.9	75Ar-25CO_2	35-38
SA-335-P22 (Hot Pass)	91T1-B3M	0.045	170	23.6	8-10	24.1-30.1	75Ar-25CO_2	35-38
SA-335-P22 (2 Layers)	91T1-B3M	0.045	190	24.2	8-10	27.6-34.5	75Ar-25CO_2	35-38
SA-335-P22 (1) (Fill Passes)	91T1-B3M	0.045	202	24.7	10-11	27.4-29.9	75Ar-25CO_2	35-38

(1) Listed welding parameters were also used for the bead-on-plate or bead-on-pipe test samples

Table 2-5:
Weld Preheat and Interpass Temperatures for Full Thickness Groove Welds

Base Material	Preheat (ºF)	Interpass (ºF)
SA-515-70	200	≤ 550
SA-516-70	200	≤ 550
SA-204-C	200	≤ 550
SA-387-11	250	≤ 550
SA-387-22	300	≤ 550
SA-335-P11	250	≤ 550
SA-335-P22	300	≤ 550

(1) Preheat was not used for bead-on-plate/pipe tests (e.g., 1B1L, 3B2L, and 4B3L) except where indicated

2.1.4.1 Weld Joint Configuration

The weld configurations used for this project are shown in Figures 2-1 and 2-2. The single bevel joint preparation (full thickness groove weld) was selected to facilitate micro-hardness testing and for more accurate placement of Charpy impact specimens. The bead-on-plate and bead-on-pipe configuration was designed to investigate and compare the effect of single and multipass welding on the base metal HAZ hardness.

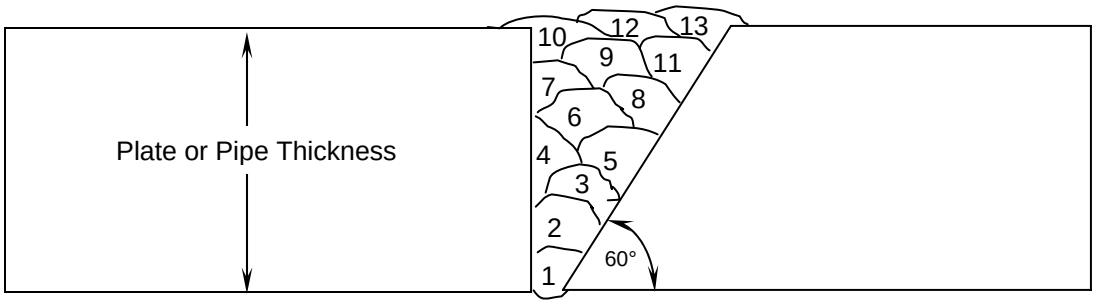


Figure 2-1:
Full Thickness Groove Weld Configuration and Typical Bead Sequence

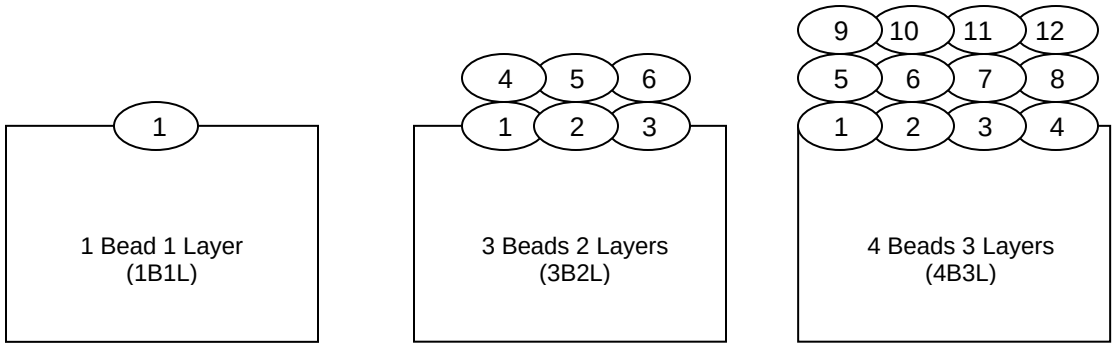


Figure 2-2:
Bead-on-Plate/Bead-on-Pipe Configurations with Typical Bead Placement

2.2 Testing Overview

Hardenability testing was performed to determine the maximum achievable hardness and to characterize the hardenability behavior of each of the selected base material specifications. A hardness traverse across the HAZ and fusion line of each of the bead-on-plate, bead-on-pipe, and full thickness groove welds was used to evaluate the influence of section thickness and multipass welding. Charpy impact, full thickness tensile, side bend, and low cycle fatigue testing was performed on the full thickness groove weld samples of each thickness of plate and pipe material specification. All samples were tested in the as-welded condition with no post weld thermal processing. Sample preparation, machining, and testing were done after an approximately three week delay following the welding. This three week delay provided ample time for hydrogen assisted cracking to occur.

2.2.1 Hardenability Testing

Hardenability testing was conducted on each base material selected for this project using the Jominy end quench test per ASTM A 255-02. The Jominy test was selected to establish baseline information that is critical for understanding hardenability behavior of each material. Specifically, the Jominy end quench test will show what the maximum attainable hardness at the quenched end is for each of the selected heats of material. The maximum hardness should be representative of steels with similar compositions and particularly of the same approximate carbon content. The Jominy test also provides a relative look at the hardness levels associated with various quench rates. Lastly, the Jominy test provides data relative to the materials ability to sustain a level of hardness through a specified depth or distance from the quenched end. All of this data will then be compared with the hardness characteristics of welded component with the fusion line representing the quenched end of the Jominy test bar. Part of the thickness exemption limit determination from traditional engineering practice has been to consider that thicker sections being welded create a larger heat sink, producing a higher quench rate. For hardenable materials the higher quench rate will result in higher HAZ hardness up to a maximum based on the carbon content. Base metal HAZ with high hardness is generally considered to be susceptible to hydrogen assisted cracking and also exhibits a loss in local ductility.

2.2.2 Hardness Testing

2.2.2.1 Test Locations

Micro-hardness testing was performed to investigate the heat affected zone (HAZ) hardness for various thicknesses of each material. For full thickness groove welds on plate and pipe base materials a hardness traverse was conducted at three through-wall locations; a hardness traverse near the weld face, one at midwall, and one near the root. Figure 2-3 is a macrograph showing the approximate location of the hardness traverse locations for the full thickness groove welds. For bead-on-plate and bead-on-pipe weld deposits a hardness traverse was conducted along the center line of the weld deposit area down through the base metal as shown in Figure 2-4.

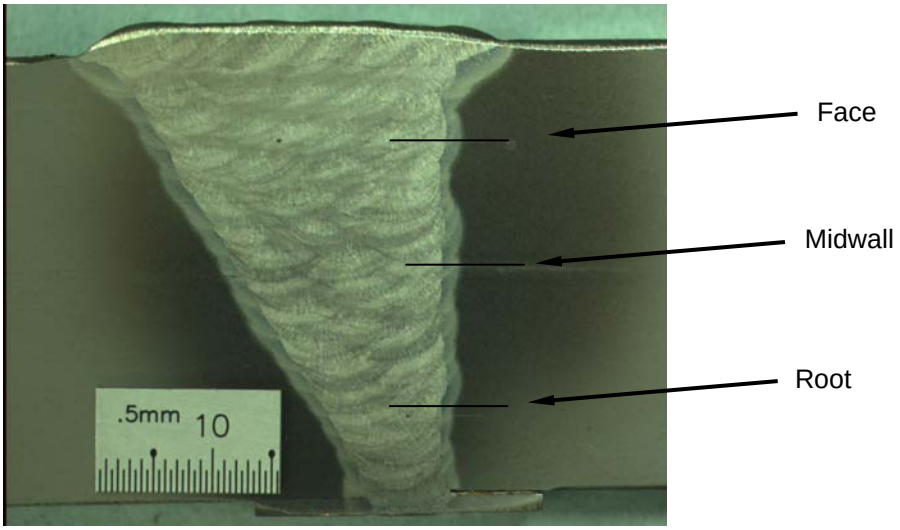


Figure 2-3:
Cross Section Showing Face, Midwall and Root Microhardness Traverse Locations

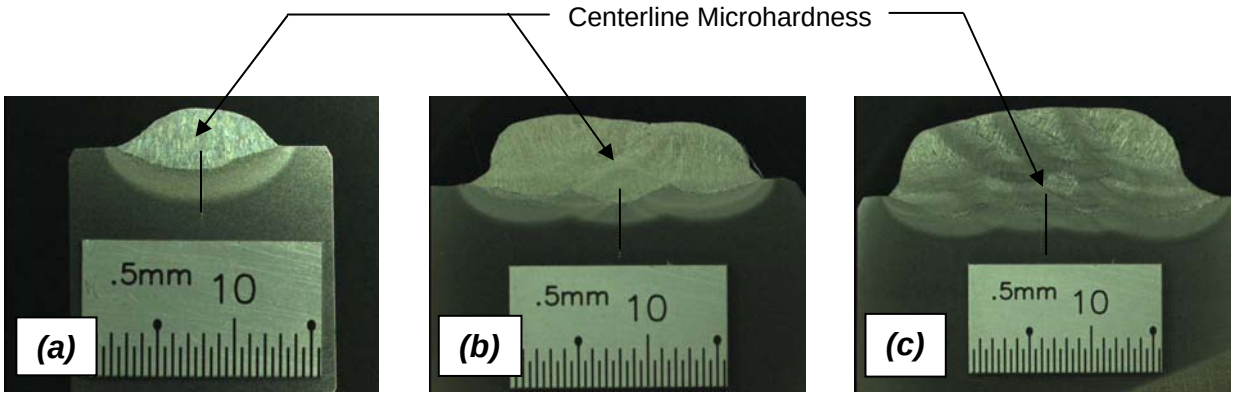


Figure 2-4:
Cross Sections Showing Bead-on-Plate Deposits and Hardness Traverse Locations
(a) 1 Bead 1 Layer (1B1L) (b) 3 Beads 2 Layers (3B2L) (c) 4 Beads 3 Layers (4B3L)

Bead-on-plate and bead-on-pipe tests were conducted to evaluate and compare single stringer bead (1B1L), three bead wide two layer (3B2L), and four bead wide three layer (4B3L) deposits. This approach permitted a comparative investigation of multipass weld deposits compared to single stringer beads and to the Jominy hardness data.

The single stringer bead, or 1B1L weld, is intended to show the worst case scenario when the cooling rate is a maximum and there is no beneficial tempering by reheating from subsequent welds passes and layers. The 1B1L peak hardness values are compared to the Jominy end quench maximum hardness results. Note that hardness conversion from Rockwell C scale to Vickers for the Jominy data was done to compare the results of the two sets of data.

2.2.2.2 Hardness Test Method

Hardness testing varies between microhardness and macrohardness methods. For this project, all hardness data was taken using the Vickers method with a 500 gram load. The microhardness method was selected to provide more consistent hardness data, to minimize spacing issues, and provide more accurate peak hardness values.

2.2.3 Tensile Testing

Full-section tensile tests were performed for each of the full thickness groove welds. Tensile test coupons were machined from full plate or pipe thicknesses to determine the mechanical behavior relative to the full weldment (see Figure 3-25). The gage section of the tensile specimen contained the groove weld and base metal HAZ as well as unaffected base metal on both sides of the weld. Tensile testing was performed at room temperature per ASME Section IX, QW-150. Ultimate tensile strength and failure locations were calculated and recorded for each test. The results of the tensile tests provide mechanical strength data for each weldment and specify if the tensile test would pass or fail the Section IX procedure qualification requirements.

2.2.4 Charpy Impact Testing

Standard size 0.394" X 0.394" Charpy V-Notch (CVN) impact specimens were removed from each full thickness groove weld sample. Base metal HAZ and weld metal CVN specimens were removed for each plate or pipe thickness welded. The 90° side of the single bevel weld joint (see Figure 3-28) enabled accurate placement of the CVN specimen notch. The specimens were removed from near the top (face) surface of the weldment for the ¾" and 1½" thicknesses as this would be considered the worst case location for the CVN tests because this depth location would receive the least amount of tempering from subsequent weld passes. The ½" and ⅝" thicknesses only provided enough material to remove the CVN specimens so by default was taken from a similar location. The CVN testing provides data relative to the amount of absorbed energy that a material can endure while withstanding impact type loading. It is a measure of the materials toughness or resistance to dynamic crack propagation. By measuring the toughness in the HAZ, unaffected base metal, and weld metal, conclusions can be drawn as to the affect of welding on thicker sections.

2.2.5 Side Bend Testing

Side bend specimens were removed from each weldment thickness that is Code exempt from PWHT and the 1½" thick weld plates. Side bend specimens were bent 180º in a bend testing

fixture to measure the weld quality and to evaluate any base metal HAZ degradation in ductility in the as welded condition. The bend tests were done in accordance with standard weld procedure qualification methods per ASME Section IX, QW-466.1 (i.e., with ⅜" thick specimens bent with a radius of ¾").

2.2.6 Low Cycle Fatigue Testing

Cross weld round bar specimens (0.250" dia.) were removed from the full thickness groove weld samples to test the low cycle fatigue properties of the as welded plate and pipe HAZ. Each specimen was removed so that the test area would be a composite of the base metal and weld metal with the HAZ centered in the gage section of the specimen. Base metal samples were also machined and tested for baseline comparisons to welded samples. These samples were run to failure under load control at various stress levels above the endurance limit. The loads were applied axially at room temperature with a 1 Hz. frequency and a triangle waveform. The stress ratio was -1.0. The results of the base metal tests were used to generate a failure trend for each specific material. Samples from the welded plates were then tested at the same conditions and plotted on the same graphs to compare with the base metal trend. Some reasonable degree of scatter is expected in this type of testing. However, any significant degradation in the fatigue performance of weldment in the as welded condition would be identified through the results and the post mortem fracture surface examination.

3
RESULTS

3.1 Hardenability Testing

3.1.1 Individual Hardenability Results

The ASTM A-255-02 Jominy end quench hardenability curves for each of the base materials are shown in Figures 3-1 and 3-2. As a result of standardizing the specimen size and mass flow rate of the impinging water quench of the testing apparatus the actual cooling rates have been determined for each sixteenth inch position located along the bar at 1300ºF. The Jominy quench, or approximate cooling rates, along the Jominy bar are listed in Table 3-1 for reference.

Table 3-1:
Approximate Cooling Rates at Hardness Locations (see ASTM A-255)

Location ($^1/_{16}$" increments)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cooling Rate (ºF/Sec @ 1300ºF)	490	305	195	125	77	56	42	33	26	21	18	16	14	12	11

3.1.2 Hardenability Results Summary

The hardenability for each of the base materials in the test protocol are plotted in Figures 3-1 and 3-2. Each material is identified with the actual carbon content, P Number and Group Number (e.g. P1 G1) assigned by ASME Section IX, and the calculated CE number.

A concern with the current code exemption thickness methodology is the assumption that hardenability increases from lower to higher P Number. In actuality the hardenability of a lower P Number material can approach if not exceed that of a higher P Number material as a result of the numerous material grades covered within the P Number groups. The P No. 5A and P No. 1 groupings for the materials evaluated in this project behaved in an expected manner with relation to level of hardenability. The highest CE number for P No. 5A materials (0.88 and 0.89 CE) exhibited the highest hardenability and the lowest CE number for P No. 1 material (0.46 CE) showed the lowest overall hardenability. The SA-515-70 carbon steel material with 0.26 wt% carbon actually showed a higher maximum hardness than any of the other materials at approximately $^3/_{16}$" from the quenched end due to its higher carbon content. Note that this is not the hardenability but the hardness at the quenched end. However, the P No. 3 material showed a higher hardenability as compared with the P No. 4 materials. This may be a result of the strong effect that the high carbon and manganese has on the overall hardenability of these steels and with the other composition specification limits associated with these specific materials. This could be the case in many instances throughout the P No. 1 through P No. 4 groupings. Increasing CE values were expected to correlate to increased hardenability but this obviously is not entirely true in all cases. The higher CE valued P No. 4

materials (0.65 and 0.66 CE) exhibited a lower hardenability compared to the P No. 3 material (0.54 CE). The actual hardness of the SA-335-P11 material even dropped below the hardness of the SA-515-70 (normalized) material with the quench rates beyond approximately 1- $^{9}/_{16}$" from the quenched end.

The high hardness at the quenched end of the low hardenability materials points out an important fact (see Figure 3-1). The maximum hardness that can be achieved will occur with the material that has the highest carbon content. The carbon steel materials have the highest carbon content so the high hardness at the quenched end is as expected. There was a transition region at approximately the $^{5}/_{16}$" position on the test bars for the materials tested. It can be seen that for positions further down the length of the Jominy test bar (away from the quenched end) the results of each hardenability curve for each material remains reasonably consistent. The data to the left of the $^{5}/_{16}$" position or closer to the quenched end produces different results depending on how fast the quench rate is at that particular location of the test bar. This is due to the material's ability to form a harder microstructure as a result of faster quench rates. The delineating quench rate was anything faster than approximately 77 ºF/sec at 1300ºF. By increasing the quench rate to 490 ºF/sec at 1300ºF at the $^{1}/_{16}$ position the P No. 1 (0.26 C) material became the hardest followed by the P No. 3 material (0.20 C) and P No. 1 (0.20 C), because of their carbon content. Microhardness of the quenched end of the Jominy test bar revealed the materials with the lowest overall hardenability (P No. 1) had the highest quenched end hardness while the highest hardenability material (P No. 5A) had the lowest quenched end hardness of all the materials investigated. This is due solely to the effect of the carbon content of the materials investigated. It is clearly shown by extrapolating the trend curves over to the hardness (y axis) value at the quenched end that the P No. 1 (0.26 and 0.20 C) materials would have the highest quenched end hardness followed by the P No. 3 material (0.20 C), the P No. 4 materials (0.15 and 0.11 C), and lastly the P No. 5A materials (0.12 and 0.11 C).

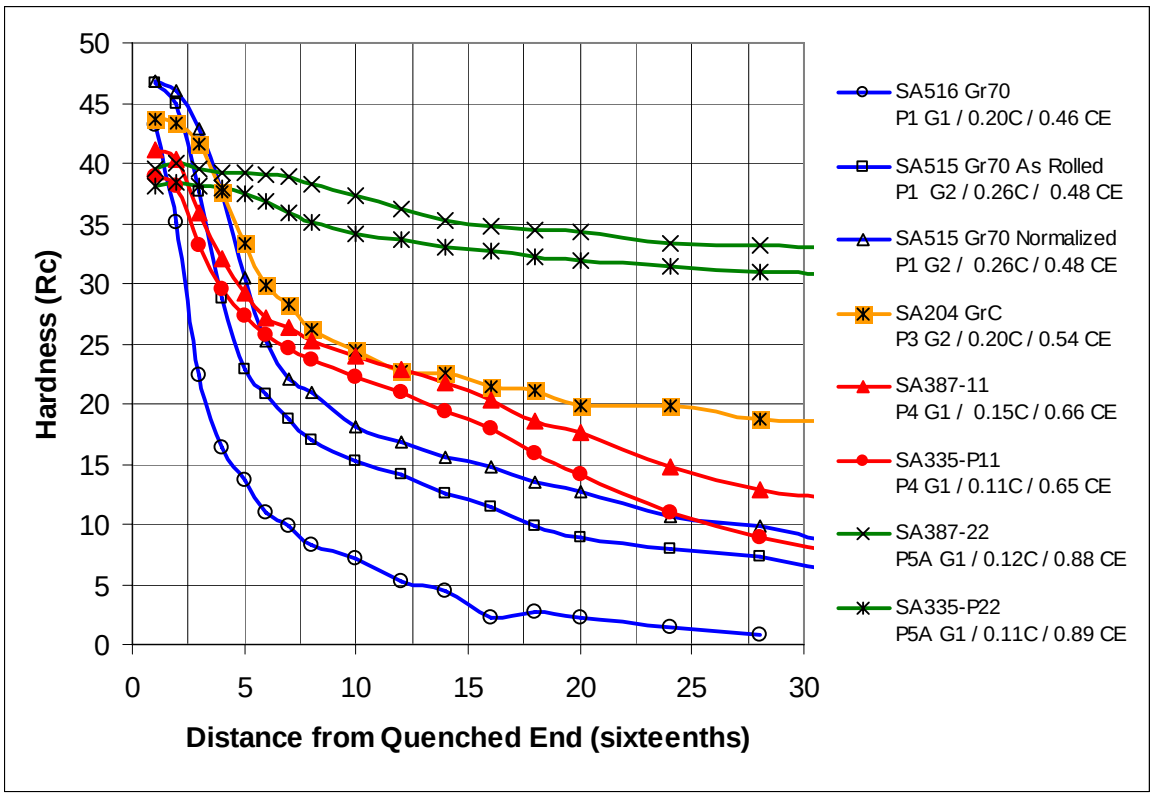


Figure 3-1:
Jominy End Quench Hardness Curves ($^{1}/_{16}$" to 1-$^{3}/_{4}$")

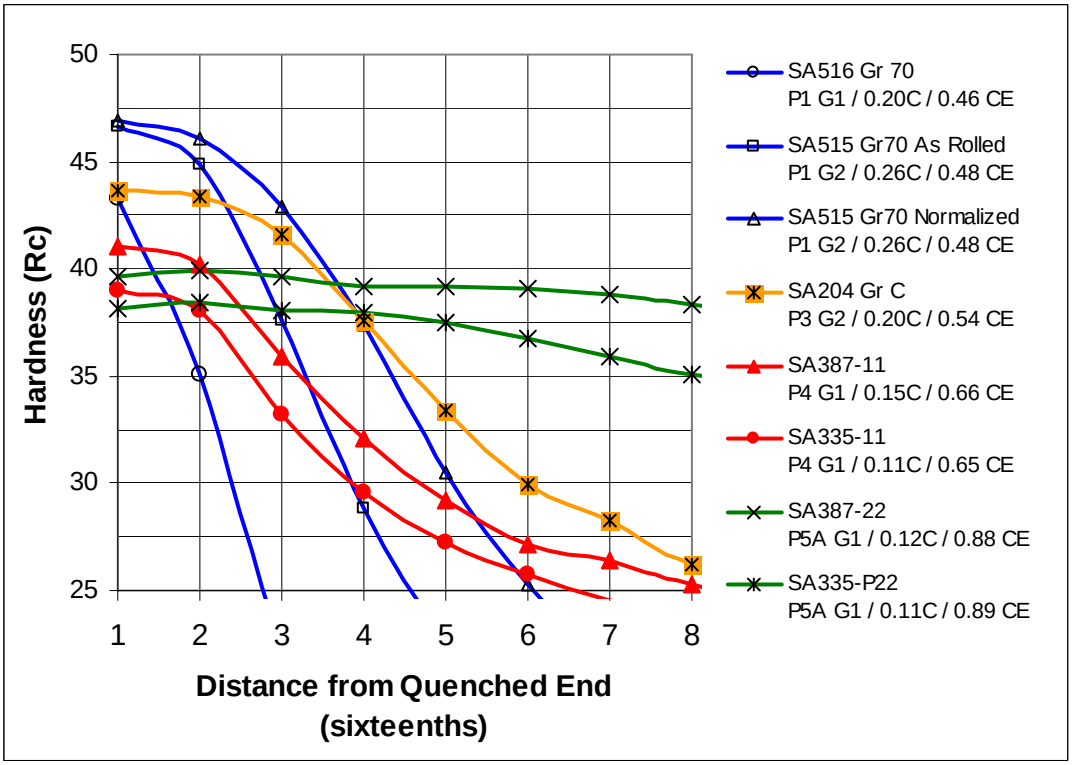


Figure 3-2:
Jominy Hardness Curves Close to Quenched End ($^{1}/_{16}$" to ½")

3.2 Hardness Testing

Microhardness testing was conducted on each bead-on-plate, bead-on-pipe, and full thickness groove weld fabricated for each material in the manner described in Section 2.2.2. All hardness measurements were taken using a Vickers indenter with a 500 gram load. The following sections give the results specific to each material and each type of deposit (bead-on-plate, bead-on-pipe and full thickness groove weld). The hardness curves show the hardness traverse, or hardness curve, starting close to the weld fusion line moving out into the base material to reveal the effect of welding on each thickness of plate and pipe material tested. The x-axis zero point is the weld fusion line. The first hardness measurement is located approximately 0.010" from the fusion line in the base material heat affected zone (HAZ). Hardness measurements were taken at 0.010" increments until the hardness reached the nominal values of the unaffected base material. The average unaffected base metal hardness is given in a note in the hardness summary table for each material tested.

Intermittent hardness increases associated with micro hardness testing are inherent where small areas of slightly harder microstructures may be present. Variation in hardness results is not uncommon, particularly in a hardness traverse across a weld metal through the HAZ and into unaffected base metal. The objective and focus should be to look at general trends such as influence and effect of multiple passes and layers, base material thickness, weld process heat input, and material hardenability.

The hardness traverse for the bead-on-plate and bead-on-pipe tests are along the center line of the weld deposit across the fusion line into the HAZ and down into the unaffected base material (see Figure 2-4). The hardness values plotted for the bead-on-plate and bead-on-pipe are single readings. The hardness traverse for the full thickness groove weld tests are parallel to the plate surface at the face, midwall, and root locations (see Figure 2-3). The hardness values plotted for the full thickness groove welds are an average of the face, midwall and root hardness values.

3.2.1 Hardness Results: P No. 1 – SA-516 Grade 70

3.2.1.1 Bead-on-plate Welds

Figures 3-3 and 3-4 show the hardness curves for bead-on-plate welds made without preheat on the ¾" and 1½" thick SA-516-70 plate material. The effect on hardness from subsequent beads and layers without preheat are shown by the 3B2L and 4B3L curves. The thinnest plate evaluated was ¾" since it is the minimum thickness currently exempted from PWHT in the applicable codes reviewed.

A peak HAZ hardness of 399 HV was measured on the ¾" thick 1B1L bead-on-plate test at 0.010" from the fusion line. A peak hardness of 398HV was measured in the same location on the 1½" thick 1B1L test. For comparison, a hardness of 428HV (43.3Rc) was measured at the $^{1}/_{16}$" mark on the Jominy bar (see Figure 3-2). The hardness values of the bead-on-plate welds all level out to the base metal hardness of 182HV at a distance of approximately 0.090" from the fusion line.

Figures 3-3 and 3-4 also show the hardness curves of the second 3B2L and third 4B3L bead-on-plate layers. While the effect of multiple layers are evident in the ¾" thick plate, the reduction of HAZ hardness between the second and third layers for the 1½" thick plate was more pronounced. The second 1½" thick 3B2L bead-on-plate layer reduced the 1B1L peak HAZ hardness by

130HV. The third 1½" thick 4B3L bead-on-plate layer reduced the 1B1L peak HAZ hardness by 189HV

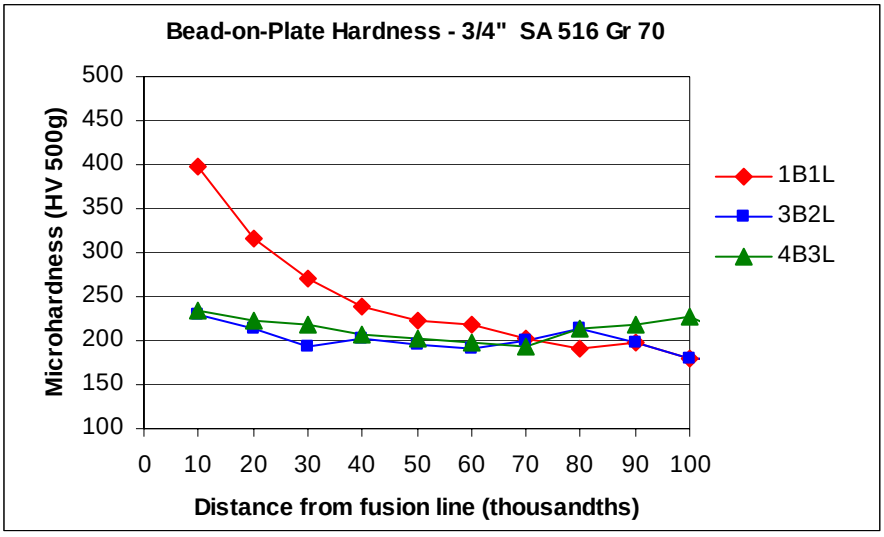


Figure 3-3:
SA-516-70 Bead-on-Plate Hardness Curves for ¾" Plate

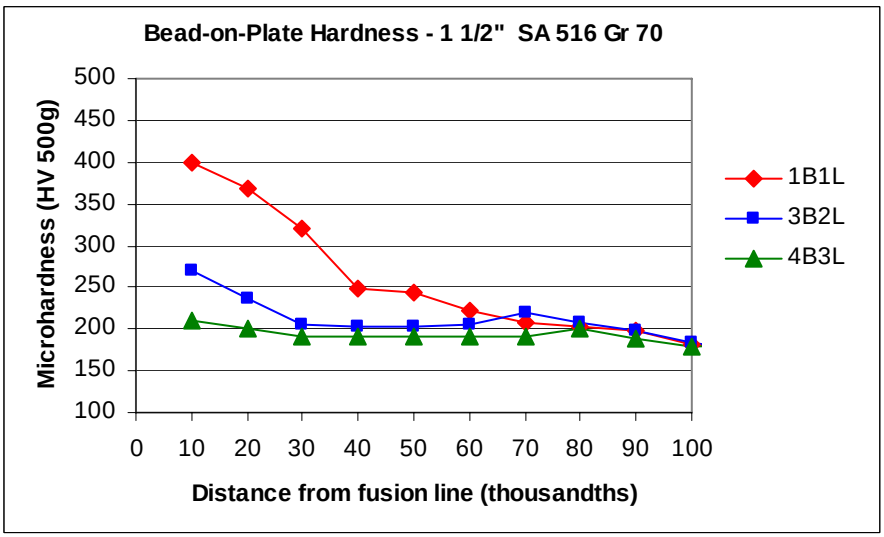


Figure 3-4:
SA-516-70 Bead-on-Plate Hardness Curves for 1½" Plate

3.2.1.2 Full Thickness Groove Welds

Figure 3-5 shows the average HAZ hardness curves for the full thickness groove welds on ¾" and 1½" thick SA-516-70 plate. The peak HAZ hardness at 0.010" from the fusion line on 1½" plate is 52HV higher compared to the ¾" plate but drops to similar hardness values at 0.050".

Table 3-2 summarizes the peak hardness results of the bead-on-plate and full thickness groove welds. The peak HAZ hardness (not the average) was 226HV for the ¾" plate which is very close to the 234HV peak HAZ hardness of the ¾" 4B3L test. The peak HAZ hardness was

263HV for the 1½" plate which again was very close to the 210HV peak HAZ hardness of the 1½" 4B3L test. This demonstrates that the tempering that occurred during multipass welding on the full thickness groove weld was similar to the tempering that occurred with the controlled multiple layer bead-on-plate tests.

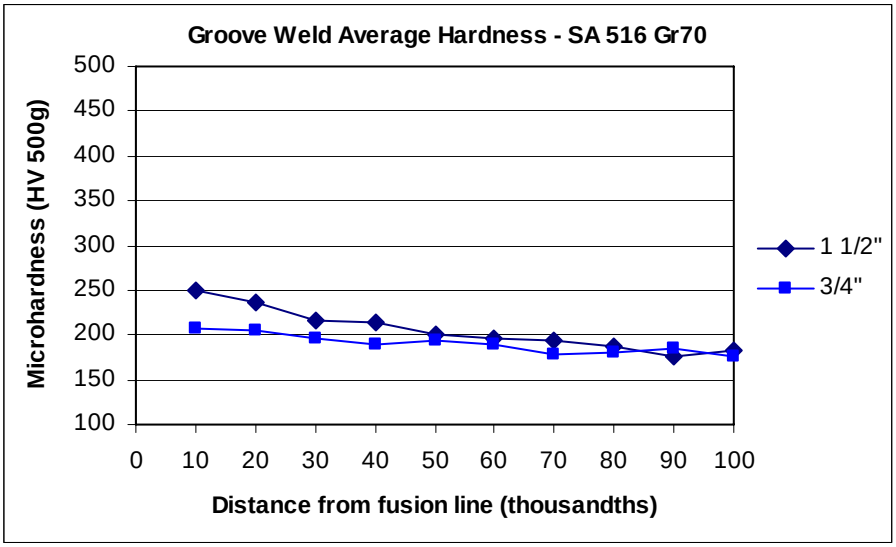


Figure 3-5:
SA-516-70 Groove Weld Average Peak Hardness Curves for ¾" and 1 ½" Plates

Table 3-2:
SA-516-70 Peak Hardness Summary of Bead-on-Plate and Groove Welds

Specimen	Average Peak HAZ Hardness [(2)] (HV_{500})	Peak HAZ Hardness (HV_{500})	HAZ Width (Thousandths)
1B1L – ¾"	—	398	100
3B2L – ¾"	—	229	100
4B3L – ¾"	—	234	100
1B1L – 1½"	—	399	100
3B2L – 1 ½"	—	269	100
4B3L – 1½"	—	210	100
Groove Weld – ¾"	207	226 (midwall)	80-100
Groove Weld – 1½"	251	263 (midwall)	80-100

(1) The average unaffected base metal hardness was 182 HV_{500}
(2) Average of root, midwall, and face peak hardness values

3.2.2 Hardness Results: P No. 1 – SA-515 Grade 70

3.2.2.1 Bead-on-Plate Welds

Figure 3-6 shows the hardness curves for bead-on-plate welds on 1½" thick SA-515-70 plate material. The single pass 1B1L bead-on-plate weld was made without preheat and with a 200°F preheat. The effect on hardness from subsequent beads and layers without preheat are shown by the 3B2L and 4B3L curves.

A peak HAZ hardness of 494HV was measured on the single pass 1B1L bead-on-plate test without preheat at 0.010" from the fusion line. This is the highest hardness of the base materials tested in this program. This high hardness is due to the high 0.26wt% carbon content of the SA-515-70 plate. This high 494HV peak hardness is slightly higher, but relatively close, to the hardness of 472HV (47.0Rc) at the $^{1}/_{16}$ position on the Jominy bar (see Figure 3-2). The higher peak HAZ hardness on the 1B1L test indicates the local cooling rate at that position is equivalent to or slightly higher than the cooling rate at the $^{1}/_{16}$ position on the Jominy bar.

The 1½" 1B1L bead-on-plate test with 200ºF preheat reduced the peak HAZ hardness by 127HV. The second 1½" 3B2L bead-on-plate layer reduced the peak HAZ hardness by 192HV. The third 1½" 4B3L layer provided only a modest amount of additional tempering to the base metal HAZ hardness. The hardness curves for the single bead-on-plate tests leveled out to the base metal hardness of 182HV at approximately 0.080" to 0.090" from the fusion line.

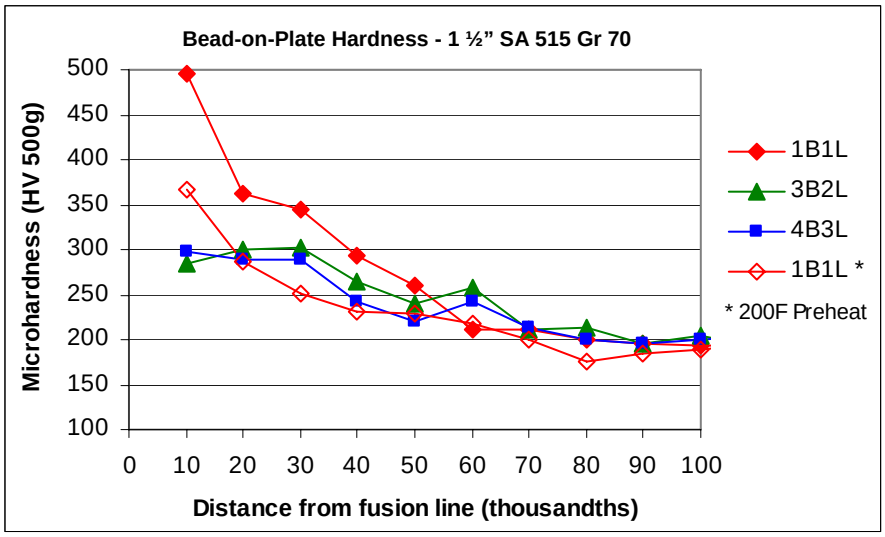


Figure 3-6:
SA-515-70 Bead-on-Plate Hardness Curves for 1 ½" Plate

3.2.2.2 Full Thickness Groove Welds

Figure 3-7 shows the average hardness curves for the full thickness groove welds performed on ½", ¾" and 1 ½" thick SA-515-70 plate. These three average hardness curves trend very close together which indicates the 200ºF preheat and multipass welding maintained uniform HAZ hardness over the thickness ranges tested. Interestingly, the average HAZ hardness close to the fusion line on the ¾" full thickness groove weld is slightly higher than the 1½" groove weld. It is not clear what caused the higher hardness in the ¾" thick groove weld.

Table 3-3 summarizes and compares the peak HAZ hardness results of the bead-on-plate and full thickness groove welds. The full thickness groove weld peak hardness values on average are slightly less than 3B2L and 4B3L bead-on-plate peak HAZ values. This is likely due to the 200°F preheat for the groove welds which lowers the cooling rate in the HAZ.

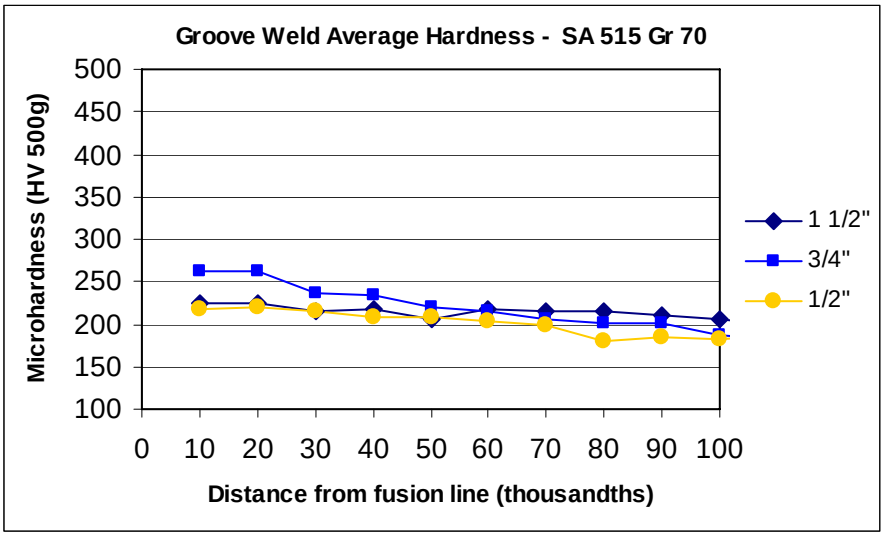


Figure 3-7
SA-515-70 Groove Weld Average Peak Hardness Curves for ½", ¾" and 1 ½" Plates

Table 3-3:
SA-515-70 Peak Hardness Summary of Bead-on-Plate and Groove Welds

Specimen	Average Peak HAZ Hardness [(2)] (HV_{500})	Peak HAZ Hardness (HV_{500})	HAZ Width (Thousandths)
1B1L – 1½"	—	494	80-100
1B1L – 1½" with 200ºF Preheat	—	367	100
3B2L – 1½"	—	302	80-100
4B3L – 1½"	—	297	80-100
Groove Weld – ½"	220	240 (root)	80-100
Groove Weld – ¾"	263	303 (midwall)	80-100
Groove Weld – 1½"	224	238 (midwall)	80-100

(1) The average unaffected base metal hardness was 182 HV_{500}
(2) Average of root, midwall, and face peak hardness

3.2.3 Hardness Results: P No. 3 – SA-204 Grade C

3.2.3.1 Bead-on-Plate Welds

Figure 3-8 shows the hardness curves for bead-on-plate welds on 1½" thick SA-204 Grade C plate material. The single pass 1B1L bead-on-plate weld was made without preheat and with a 200°F preheat. The effect on hardness from subsequent beads and layers without preheat are shown by the 3B2L and 4B3L curves.

A peak hardness of 449HV was measured on the single pass 1B1L bead-on-plate test without preheat at 0.030" from the fusion line. This hardness is slightly higher, but very close, to the hardness of 432HV (43.7Rc) at the $^{1}/_{16}$ position on the Jominy bar (see Figure 3-2). The hardness curves for the single bead-on-plate tests leveled out to base metal hardness of 208HV at approximately 0.090" to 0.100" from the fusion line.

The 1½" 1B1L bead-on-plate test with 200ºF preheat reduced the peak HAZ hardness by only 14HV. The higher hardenability of the SA-204-C plate is the likely reason why the 200°F preheat was less effective in reducing the hardness compared to the less hardenable SA-515-70 and SA-516-70 plate materials. The higher hardenability of the SA-204-C material is evidenced by more gradual drop in hardness with increasing distance from the fusion line of the SA-204-C bead-on-plate curves compared to the SA-516-70 and SA-515-70 curves. The Jominy hardness curves shown in Figures 3-1 and 3-2 also show the higher hardenability of the SA-204-C compared to SA-515-70 and SA-516-70.

The second 1½" 3B2L bead-on-plate layer reduced the 1B1L peak HAZ hardness by 127HV. The third 1½" 4B3L layer did not provide any appreciable amount of additional tempering to the base metal HAZ hardness which indicates the majority of tempering occurred with the second weld layer. Worth noting is the fact that the second 1½" 3B2L layer was much more effective in reducing peak hardness than the single 1B1L weld with 200°F preheat.

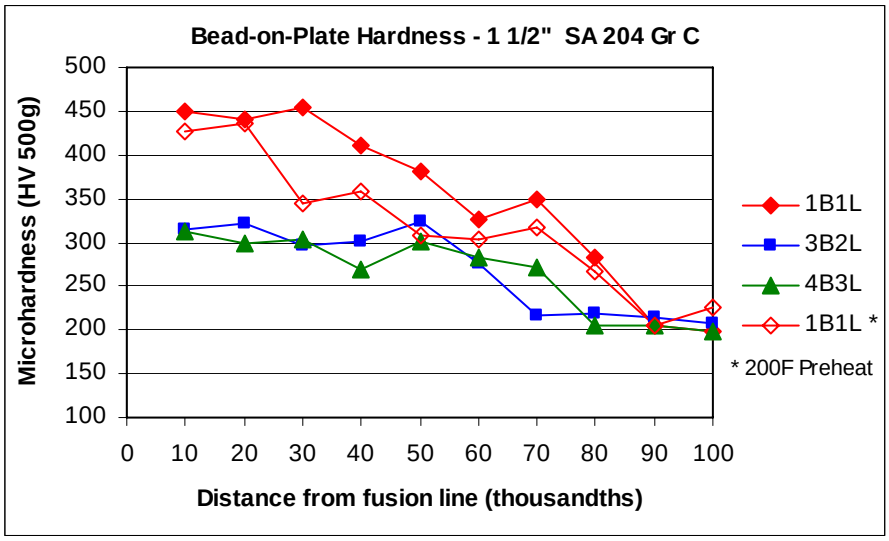


Figure 3-8
SA-204-C Bead-on-Plate Hardness Curves for 1 ½" Plate

3.2.3.2 Full Thickness Groove Welds

Figure 3-9 shows the average hardness curves for the full thickness groove welds performed on ½", ¾" and 1 ½" thick SA-204-C plate material. The full thickness groove weld average hardness curves trend very close to the multiple layer 3B2L and 4B3L bead-on-plate hardness curves. As discussed previously this is likely due to the 200ºF preheat. A maximum of 340HV peak HAZ hardness was obtained in the ¾" plate. The difference in HAZ hardness between the ½", ¾", and 1½" thick plates was not significant, which indicates the 200°F preheat and multipass welding maintained uniform HAZ hardness over the thickness ranges tested.
Table 3-4 summarizes the peak hardness results of the bead-on-plate and full thickness groove welds.

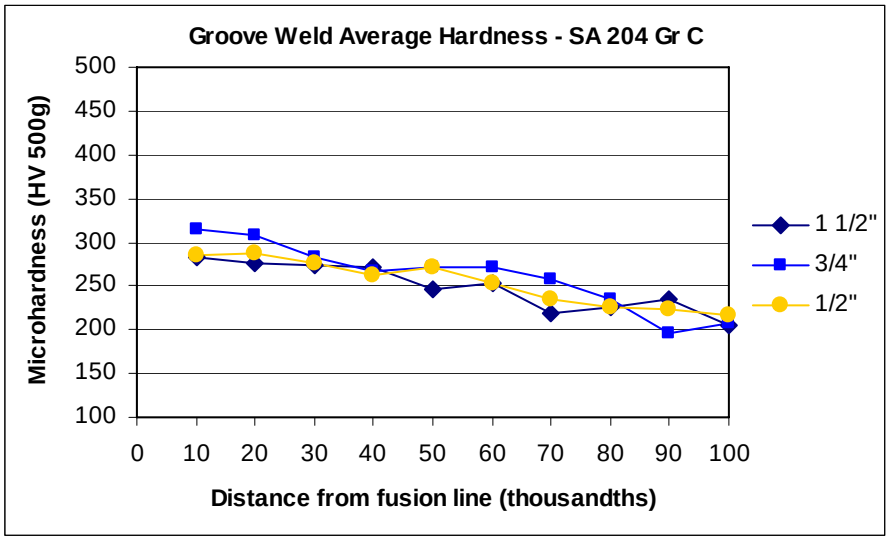


Figure 3-9
SA-204-C Groove Weld Average Peak Hardness Curves for ½", ¾" and 1 ½" Plates

Table 3-4:
SA-204-C Peak Hardness Summary of Bead-on-Plate and Groove Welds

Specimen	Average Peak HAZ Hardness (2) (HV_{500})	Peak HAZ Hardness (HV_{500})	HAZ Width (Thousandths)
1B1L – 1½"	—	449	90
1B1L – 1½" with 200ºF Preheat	—	435	90
3B2L – 1½"	—	322	80-100
4B3L – 1½"	—	312	80-100
Groove Weld – ½"	288	323 (midwall)	100
Groove Weld – ¾"	315	340 (face)	100
Groove Weld – 1½"	283	304 (root)	100

(1) The average unaffected base metal hardness was 208 HV_{500}
(2) Average of root, midwall, and face peak hardness

3.2.4 Hardness Results: P No. 4 – SA-387 Grade 11 Class 2

3.2.4.1 Bead-on-Plate Welds

Figures 3-10, 3-11 and 3-12 show the hardness curves for bead-on-plate welds made without preheat on ½", ¾", and 1½" thick SA-387-11 plate material. The thinnest plate evaluated was ½" since it is the minimum thickness currently exempted from PWHT in the applicable codes reviewed.

The peak HAZ hardness was close to the fusion line on each of the single pass 1B1L bead-on-plate welds. The peak HAZ hardness was 380HV, 418HV, and 417HV for the ½", ¾", and 1½" thick plates respectively. These maximum HAZ hardness values correlate closely to the hardness of 407HV (41.1Rc) at the $^{1}/_{16}$ mark on Jominy bar (see Figure 3-2). The HAZ hardness values level out to the base metal hardness of 196HV at approximately 0.090" and 0.100" from the fusion line.

The second 3B2L bead-on-plate layer reduced the 1B1L peak HAZ hardness by 100HV, 103HV, and 160HV for the ½", ¾" and 1 ½" plates respectively. The third 4B3L layer did not provide any appreciable amount of additional tempering to the base metal HAZ hardness which indicates the majority of tempering occurred with the second 3B2L weld layer.

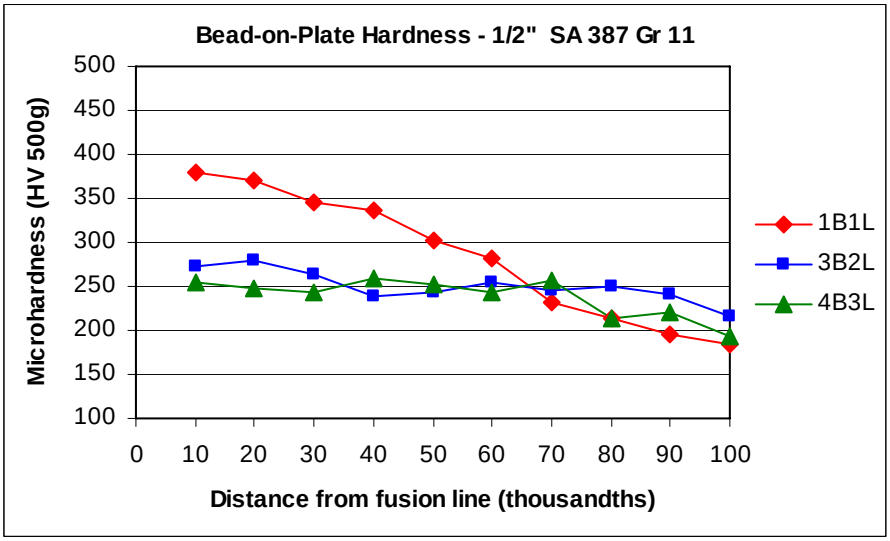


Figure 3-10:
SA-387-11 Bead-on-Plate Hardness Curves for ½" Plate

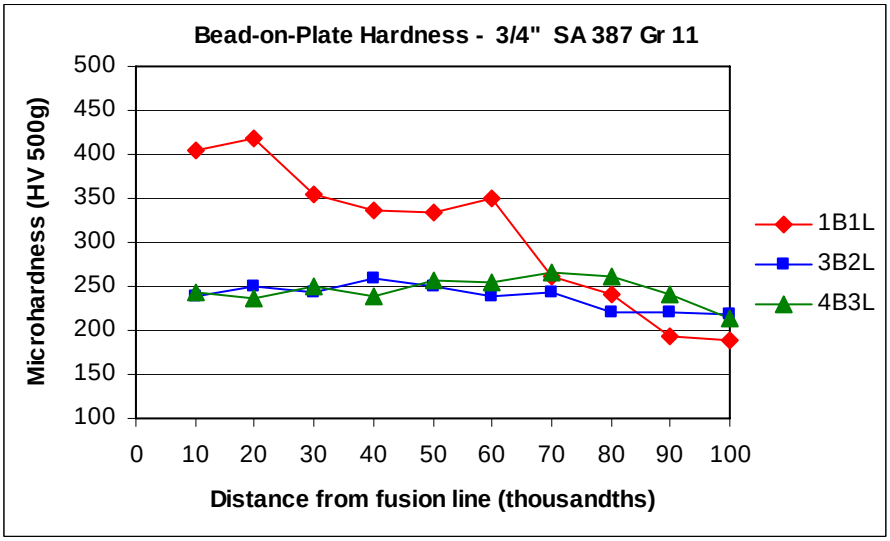


Figure 3-11:
SA-387-11 Bead-on-Plate Hardness Curves for ¾" Plate

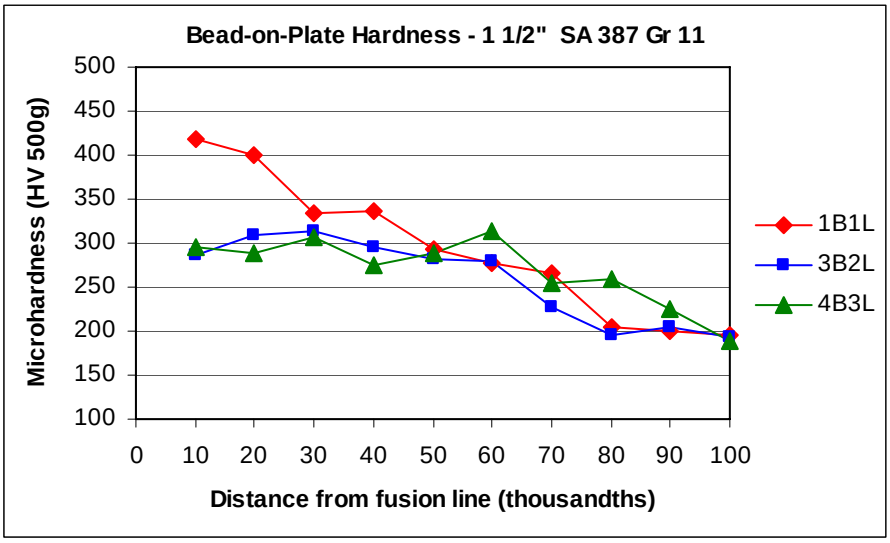


Figure 3-12:
SA-387-11 Bead-on-Plate Hardness Curves for 1½" Plate

3.2.4.2 Full Groove Thickness Welds

Figure 3-13 shows the average hardness curves for the full thickness groove welds on ½", ¾" and 1½" thick SA-387-11 plates. The groove weld average hardness curve for the 1½" plate is slightly higher near the fusion line compared to the ½" and ¾" hardness curve, but all curves trend together after 0.020" from the fusion line.

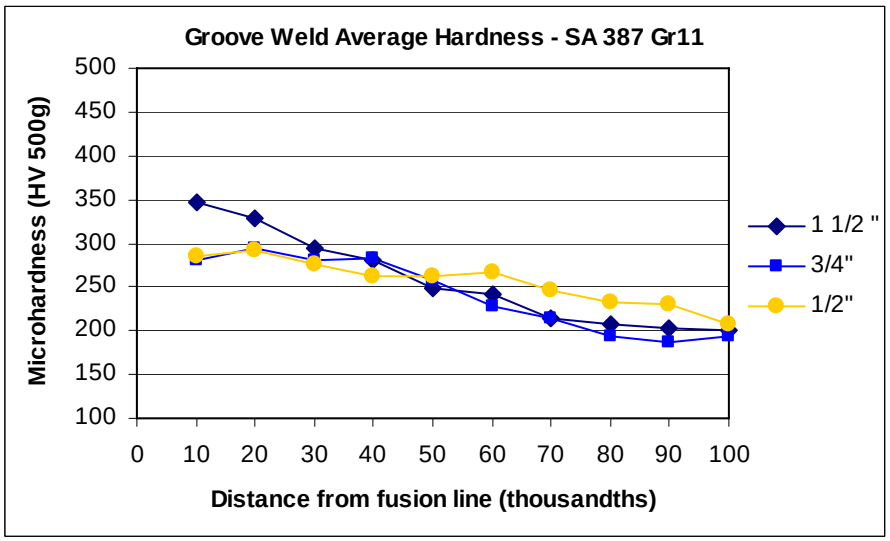


Figure 3-13:
SA-387-11 Groove Weld Average Peak Hardness Curves for ½", ¾", and 1 ½" Plates

Table 3-5 summarizes and compares the peak hardness results of the bead-on-plate and full thickness groove welds. The average peak HAZ hardness was 348HV for the 1½" plate which is 34HV higher than the peak HAZ hardness of the 1½" 3B2L bead-on-plate layer. The average peak HAZ hardness was 335HV for the ¾" plate which is 37HV higher than the peak HAZ hardness of the 1½" 3B2L layer. A peak HAZ hardness of 385HV was measured at a midwall

location for the 1½" plate which is significantly higher than any the peak HAZ hardness values on the 3B2L tests. It is not clear why peak hardness values were higher in full thickness groove weld for the SA-387-11 plate material. Considering the groove weld was made with 250ºF preheat, which should reduce the HAZ cooling rate slightly, and considering the tempering effect of the multipass welding, the average HAZ hardness in the full thickness groove welds would be expected to have a slightly lower average HAZ hardness.

Table 3-5:
SA-387-11 Peak Hardness Summary of Bead-on-Plate and Groove Welds

Specimen	Average Peak HAZ Hardness [(2)] (HV_{500})	Peak HAZ Hardness (HV_{500})	HAZ Width (Thousandths)
1B1L – ½"	—	379	100
3B2L – ½"	—	279	100
4B3L – ½"	—	259	100
1B1L – ¾"	—	418	100
3B2L – ¾"	—	258	100
4B3L – ¾"	—	265	100-120
1B1L – 1½"	—	417	100
3B2L – 1½"	—	314	100
4B3L – 1½"	—	312	100
Groove Weld – ½"	292	306 (face)	120
Groove Weld – ¾"	295	335 (root)	120
Groove Weld – 1½"	348	385 (midwall)	120

(1) The average unaffected base metal hardness was 196 HV_{500}
(2) Average of root, midwall, and face peak hardness

3.2.5 Hardness Results: P No.4 – SA-335 Grade P11

3.2.5.1 Bead on Pipe Welds

Figures 3-14 and 3-15 show the hardness curves for bead-on-pipe welds made without preheat on ⅝" and 1½" thick SA-335-P11 pipe material. A single pass 1B1L test was also made with preheat of 250ºF. The thinnest pipe evaluated was ⅝" since it is the minimum thickness currently exempted from PWHT in the applicable codes reviewed (ASME Sections I and VIII).

The peak HAZ hardness for the 1B1L tests without preheat were 354HV and 390HV for the ⅝" and 1½" thick pipes respectively. These peak hardness values were 0.010" to 0.020" distance away from the fusion line. These peak HAZ hardness values correlate closely to the hardness of 382HV (39.0Rc) at the $^1/_{16}$ mark on the Jominy bar (see Figure 3-2). The ⅝" and 1½" 1B1L tests with 250°F preheat reduced the peak HAZ hardness by 50HV and 36HV respectively. Other than the single peak values the 1B1L hardness curve with preheat showed little difference compared to the 1B1L tests without preheat.

The ⅝" and 1½" 3B2L bead-on-plate layer reduced the 1B1L peak HAZ hardness by 113HV and 128HV respectively. The third 4B3L layer did not provide any appreciable amount of additional tempering to the base metal HAZ hardness which indicates the majority of tempering occurred with the second layer. Note also that the second 3B2L weld layer is much more effective in

reducing peak hardness than the single 1B1L weld with 250°F preheat. Finally, each of the bead-on-plate hardness curves leveled out to the base metal hardness of 180HV at approximately 0.130" to 0.140" distance from the fusion line.

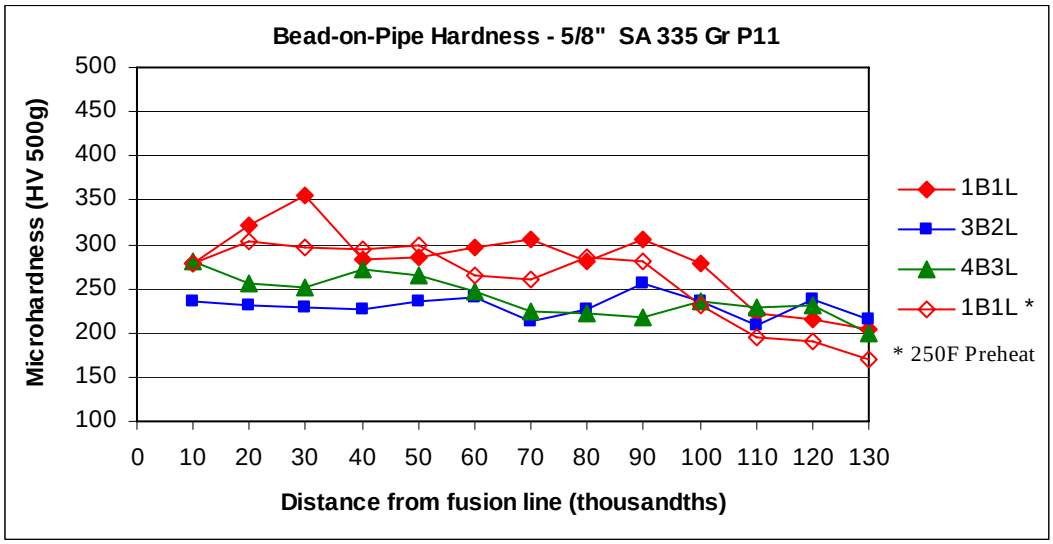


Figure 3-14:
SA-335-P11 Bead-on-Pipe Hardness Curves for ⅝" Thick Pipe

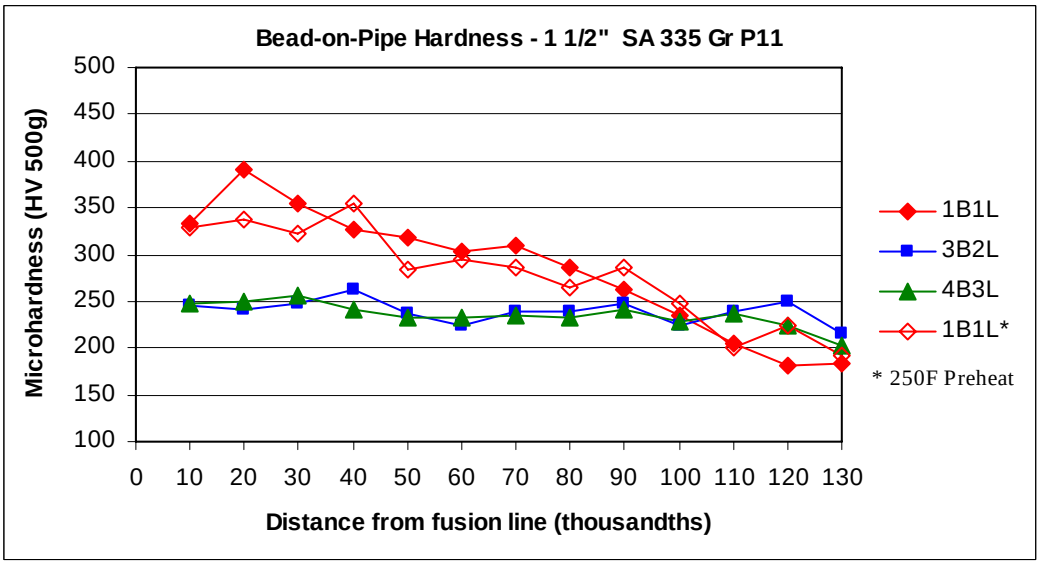


Figure 3-15:
SA-335-P11 Bead-on-Pipe Hardness Curves for 1½" Thick Pipe

3.2.5.2 Full Thickness Groove Welds

Figure 3-16 shows the average peak hardness curves for the ⅝", ½", and 1½" SA-335-P11 full thickness groove welds. The 1½" hardness curve is slightly higher close to the fusion line, but all three hardness curves trend similarly.

Table 3-6 summarizes the peak hardness results of the bead-on-pipe and full thickness groove welds. The peak HAZ hardness was 299HV for the 1½" material, which is 37HV higher than the peak HAZ hardness 1½" 3B2L bead-on-pipe test. A the peak average hardness of 259HV to 260HV for the ½" and ⅝" thick groove welds were essentially the same as the peak hardness for the multipass 3B2L and 4B3L bead-on-pipe tests of the same thickness.

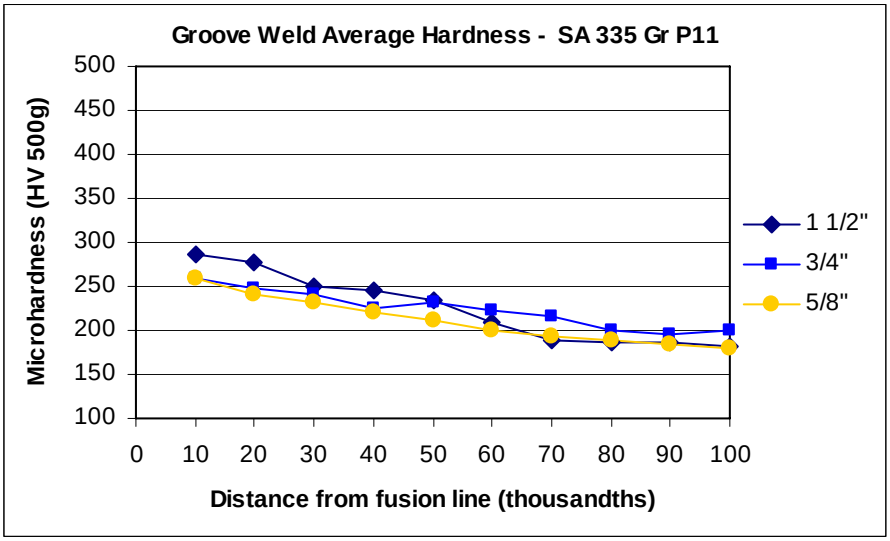


Figure 3-16:
SA-335-P11 Groove Weld Average Hardness Curves for ⅝", ¾", and 1 ½" Thick Pipe

Table 3-6:
SA-335-P11 Peak Hardness Summary for Bead-on-Pipe and Groove Welds

Specimen	Average Peak HAZ Hardness [2] (HV_{500})	Peak HAZ Hardness (HV_{500})	HAZ Width (Thousandths)
1B1L – ⅝"	—	354	110-140
1B1L – ⅝" with 250ºF Preheat	—	304	110-140
3B2L – ⅝"	—	241	110-140
4B3L – ⅝"	—	282	110-140
1B1L – 1½"	—	390	110-140
1B1L – 1½" with 250ºF Preheat	—	354	110-140
3B2L – 1½"	—	262	110-140
4B3L – 1½"	—	255	110-140
Groove Weld – ⅝"	260	272 (midwall)	90-100
Groove Weld – ¾"	259	270 (root)	100
Groove Weld – 1½"	286	299 (midwall)	90

(1) The average unaffected base metal hardness was 180 HV_{500}
(2) Average of root, midwall, and face peak hardness

3.2.6 Hardness Results: P No.5A – SA-387 Grade 22 Class 1

3.2.6.1 Bead-on-Plate Welds

Figures 3-17, 3-18 and 3-19 show the hardness curves for the 1B1L bead-on-pipe welds made without preheat on ½", ¾", and 1½" thick SA-387-22 plate material. The thinnest plate evaluated was ½" thick since it is the minimum thickness currently exempted in the codes reviewed.

The peak HAZ hardness for the 1B1L tests without preheat were 414HV, 404HV, and 412HV for ½", ¾", and 1½" thick plates and were all three located 0.010" from the weld fusion line. These peak HAZ values also correlate closely to the 388HV (39.6Rc) hardness at the $^{1}/_{16}$ mark on the Jominy bar (see Figure 3-2). The hardness values level out and reach the base material average of 191HV approximately 0.100" from the fusion line. The second 3B2L layer reduced the peak hardness by ~100HV points on the ½" and ¾" plates. The third 4B3L layer on the ½" and ¾" plates did not produce any appreciable amount of additional tempering of the base metal HAZ hardness. Interestingly, the second 3B2L layer on the 1½" thick plate increased the HAZ peak hardness by ~100HV at 0.060" from the fusion line. The third 4B3L layer increased the peak hardness by ~50HV at 0.040" from the fusion line. This increase in hardness with the second and third bead-on-plate layers is unexpected and cannot be explained from the test documentation.

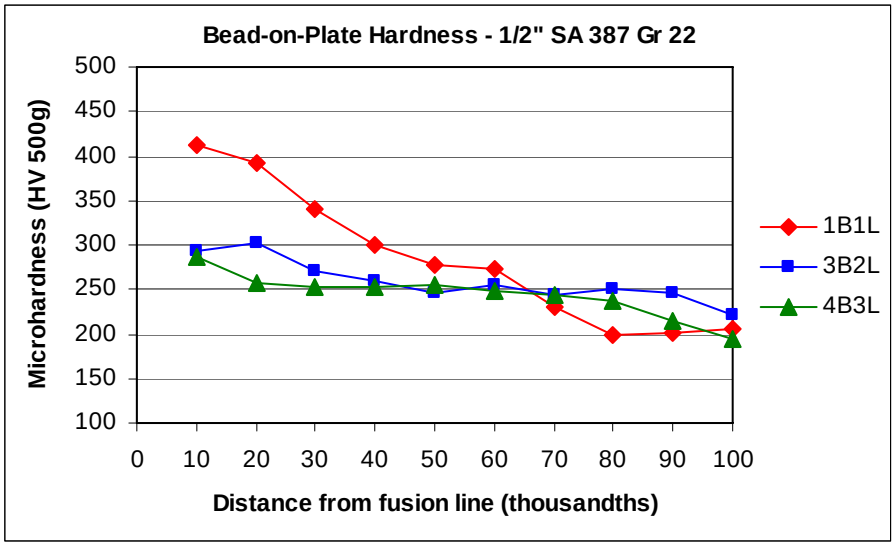


Figure 3-17:
SA-387-22 Bead-on-Plate Hardness Curves for ½" Plate

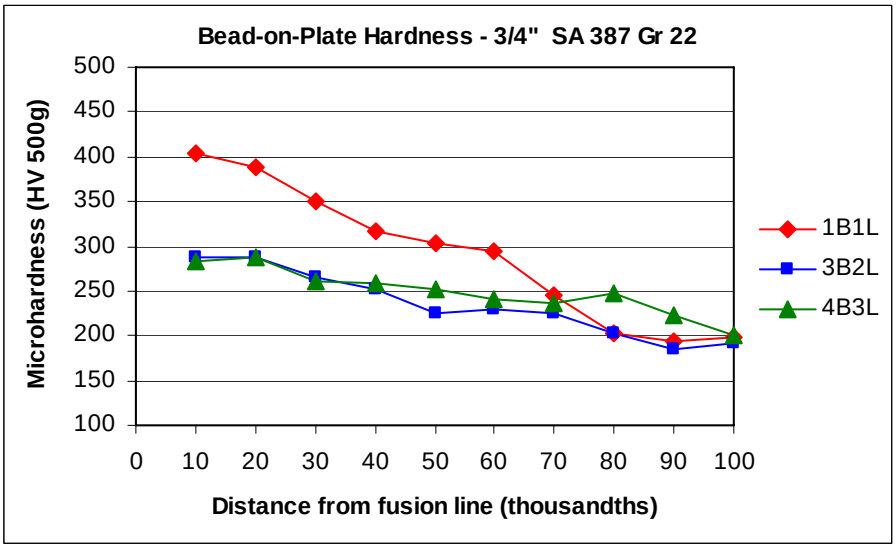


Figure 3-18:
SA-387-22 Bead-on-Plate Hardness Curves for ¾" Plate

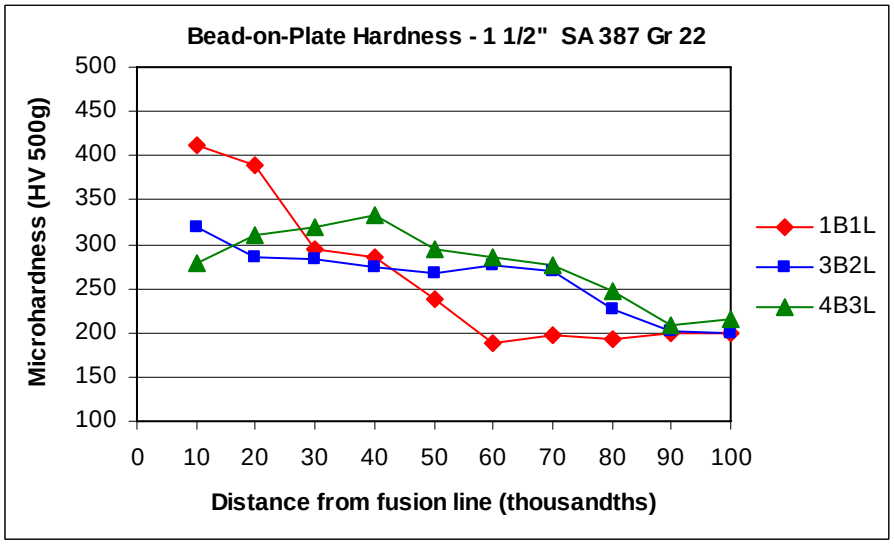


Figure 3-19:
SA-387-22 Bead-on-Plate Hardness Curves for 1½" Plate

3.2.6.2 Full Thickness Groove Welds

Figure 3-20 shows the average peak hardness curves for the ½", ¾" and 1½" SA-387-22 full thickness groove welds. The three curves trend closely together and there is little difference between the different thicknesses.

The peak HAZ hardness was 383 HV for the 1½" groove weld which is ~50HV to 60HV higher than the peak values measured for the multipass 3B2L and 4B3L bead-on-plate tests. Table 3-7 summarizes the peak hardness results of the bead-on-plate and full thickness welding.

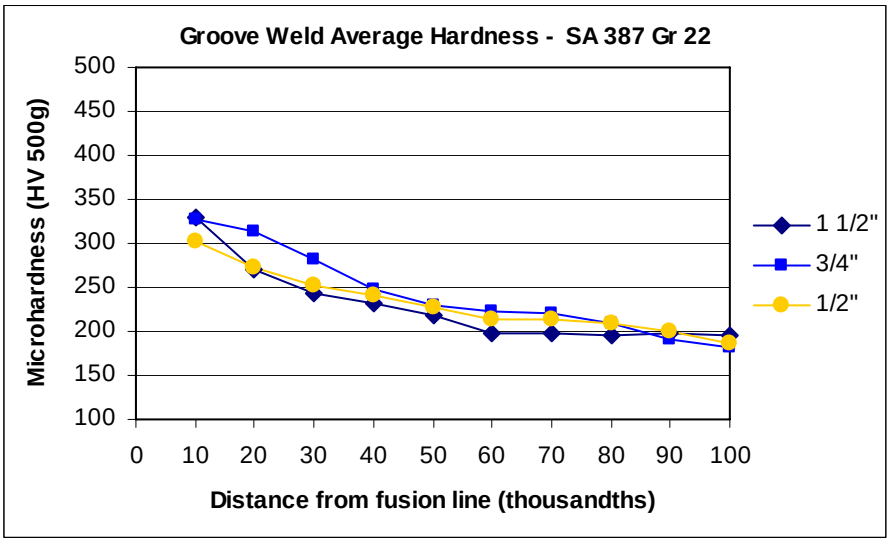


Figure 3-20
SA-387-22 Groove Weld Average Hardness Curves for ½", ¾" and 1 ½" Plate

Table 3-7:
SA-387-22 Peak Hardness Summary for Bead-on-Plate and Groove Welds

Specimen	Average Peak HAZ Hardness (2) (HV_{500})	Peak HAZ Hardness (HV_{500})	HAZ Width (Thousandths)
1B1L – ½"	—	413	110
3B2L – ½"	—	303	110
4B3L – ½"	—	285	110
1B1L - ¾"	—	404	110
3B2L – ¾"	—	287	110
4B3L – ¾"	—	287	110
1B1L – 1½"	—	412	110
3B2L – 1½"	—	320	110
4B3L – 1½"	—	333	110
Groove Weld – ½"	303	317 (midwall)	100
Groove Weld – ¾"	326	375 (root)	100
Groove Weld – 1½"	330	383 (midwall)	80-100

(1) The average unaffected base metal hardness was 191 HV_{500}
(2) Average of root, midwall, and face peak hardness

3.2.7 Hardness Results: P No. 5A – SA-335 Grade P22

3.2.7.1 Bead-on-Pipe Welds

Figures 3-21 and 3-22 show the hardness curves for bead-on-pipe welds on ⅝" and 1½" thick SA-335-P22 pipe material. The single pass 1B1L weld was made without preheat and with 300ºF preheat. The effect on hardness from subsequent beads and layers without preheat are shown by the 3B2L and 4B3L layers. The minimum thickness tested was ⅝" since this is the minimum thickness currently exempted from PWHT in the applicable codes reviewed (e.g., ASME Sections I and VIII).

The peak HAZ hardness values for the 1B1L tests without preheat were 415HV and 432HV for the ⅝" and 1½" thick pipes respectively. These peak hardness values were both at 0.030" distance away from the fusion line. For comparison the Jominy peak hardness was 377HV (38.5Rc) at the $^{1}/_{16}$ mark on the Jominy bar (see Figure 3-2). The 432HV peak HAZ hardness for the 1½" 1B1L test is actually higher than peak attainable hardness for 0.11wt% carbon content and is 55HV higher than the Jominy peak hardness. This indicates that the HAZ cooling rate in the ¾" 1B1L test without preheat was sufficiently rapid to obtain maximum attainable hardness in the moderately hardenable SA-335-P22 material.

Figures 3-21 and 3-22 show that the 1B1L test with 300°F preheat had only a slight effect on reducing the peak HAZ hardness. Elevated preheats normally will reduce HAZ hardness slightly by reducing the cooling rate. For this case however it appears the HAZ cooling rate on the 1B1L test with 300°F preheat was still sufficiently rapid to have little effect given the high hardenability of the SA-335-P22 material. This indicates that preheat may not be significantly effective in reducing HAZ hardness for materials with moderate to high hardenability.

The second 3B2L layer reduced the 1B1L peak HAZ hardness for both the ⅝" and 1½" thick pipe material reduced the peak HAZ hardness in varying degrees. Close to the fusion line the 3B2L layer had little effect but at 0.050" to 0.080" distance the HAZ hardness was reduced by up to 125HV. The third 4B3L layer did not provide any appreciable amount of additional tempering to the base metal HAZ hardness which indicates the majority of tempering occurred with the second layer.

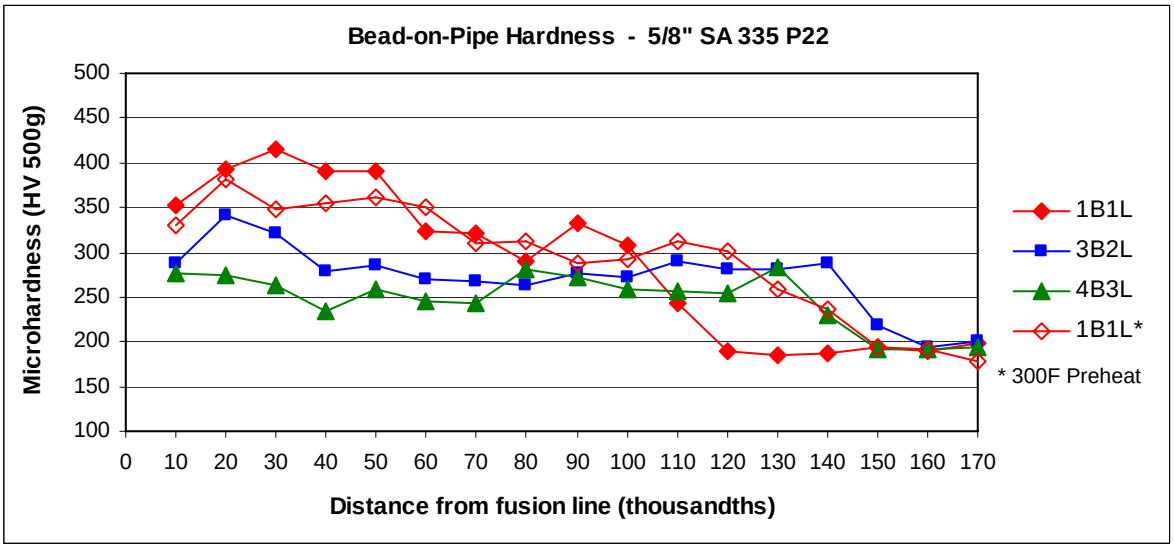


Figure 3-21
SA-335-P22 Bead-on-Pipe Hardness Curves for ⅝" Thick Pipe

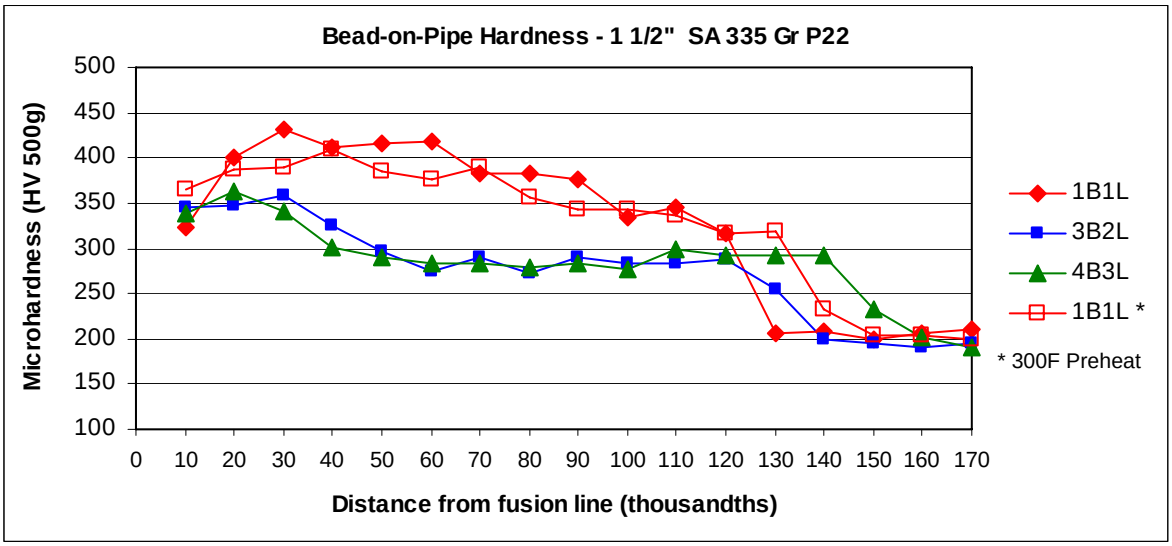


Figure 3-22:
SA-335-P22 Bead-on-Pipe Hardness Curves for 1½" Thick Pipe

Finally, each of the bead-on-plate hardness curves leveled out to the base metal hardness of 195HV at approximately 0.140" to 0.150" distance from the fusion line. This greater distance of heat affected length was first thought to be due to the high hardenability of SA-335-P22. However, the SA-387-22 has similar hardenability (see Figure 3-1) but does not exhibit similar extended heat affected length. Review of the SA-335-P11 hardness curves show a similar trend as the SA-335-P22. The FCAW weld process with higher heat input (see Table 2-4) was used to make the SA-335-P11 and SA-335-P22 test samples. The higher heat input of the FCAW process acts to decrease the cooling rate and also increase the weld heat affected zone depth.

3.2.7.2 Full Thickness Groove Welds

Figure 3-23 shows the average peak hardness curves for the SA-335-P22 ⅝"and 1½" full thickness groove weld tests. The three hardness curves trend closely together and there is little difference between the different thicknesses.

Table 3-8 summarizes the peak hardness results of the bead-on-plate tests and the full thickness groove welds. The average HAZ peak hardness values were 268HV, 276HV, and 292HV for the ⅝", ¾" and 1½" full thickness grooves welds respectively, which is the expected trend. The peak HAZ hardness was 310HV for the 1½" pipe. This is 50HV to 60HV lower than the 3B2L and 3B3L bead-on-pipe peak HAZ hardness values. This is somewhat of a surprise since it is opposite to the trends observed on the other tests.

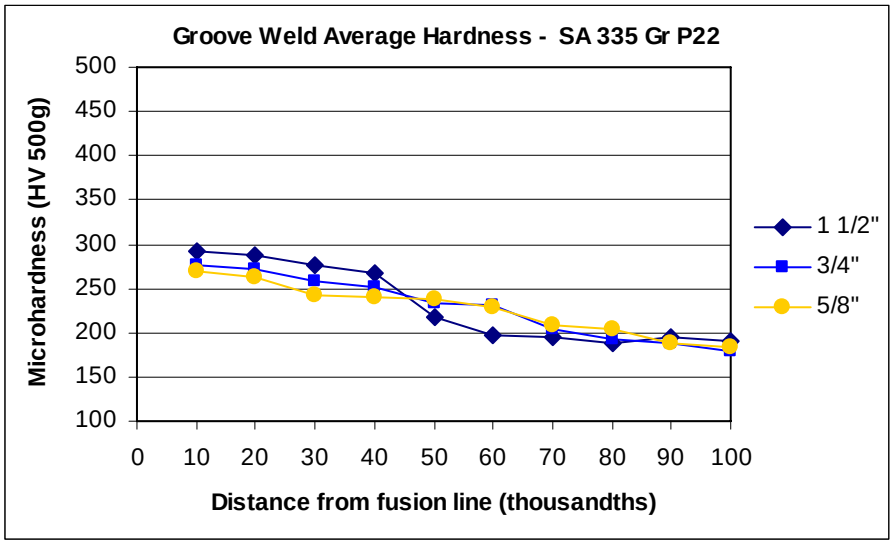


Figure 3-23
SA-335-P22 Groove Weld Average Hardness Curves for ⅝", ¾", and 1 ½" Thick Pipe

Table 3-8:
SA-335-P22 Peak Hardness Summary of Bead-on-Pipe and Groove Welds

Specimen	Average Peak HAZ Hardness [2] (HV_{500})	Peak HAZ Hardness (HV_{500})	HAZ Width (Thousandths)
1B1L – ⅝"	—	415	140-150
1B1L – ⅝" 300ºF preheat	—	381	140-150
3B2L – ⅝"	—	342	140-150
4B3L – ⅝"	—	277	140-150
1B1L – 1½"	—	432	130-150
1B1L – 1½" 300ºF preheat	—	409	130-150
3B2L – 1½"	—	359	130-150
4B3L – 1½"	—	364	130-150
Welded Pipe – ⅝"	268	288 (midwall)	60-80
Welded Pipe – ¾"	276	302 (face)	80
Welded Pipe – 1½"	292	310 (root)	60

(1) The average unaffected base metal hardness was 195 HV_{500}
(2) Average of root, midwall, and face peak hardness

3.2.8 Weld Metal Hardness

The hardness curve across the fusion line of the E9018-B3 filler metal and the SA-387-22 plate is unlike any of the other curves developed in the other weld metal/base metal combinations. For this combination the peak hardness values do not occur in the HAZ but in the weld metal although the peak HAZ hardness values are close to the weld metal hardness. Figure 3-24 shows the hardness curves for the weld metal up to and crossing the fusion line. The average weld metal hardness was 407HV for the 1B1L deposit, 345HV for the 3B2L deposit, and 388HV for the 4B3L deposit. This high hardness following successive layers of weld metal indicates that the alloy content of the weld filler is sufficiently high to maintain a high level of hardness. As a

result, weld metal hardness as the curve crosses the fusion line is higher than the base metal heat affected zone. This is indicative of the type of properties that can result when using matching filler metals in a non PWHT condition but which were designed to be used in the heat treated condition. However, the varying hardness values observed in the multiple pass welds in the weld metal show that some tempering has been achieved with subsequent passes. If this weldment had received a PWHT then it may have exhibited hardness characteristics which were more in line with the base metal. Currently accepted matching fillers may in fact be overmatching if the weld is being exempted from PWHT.

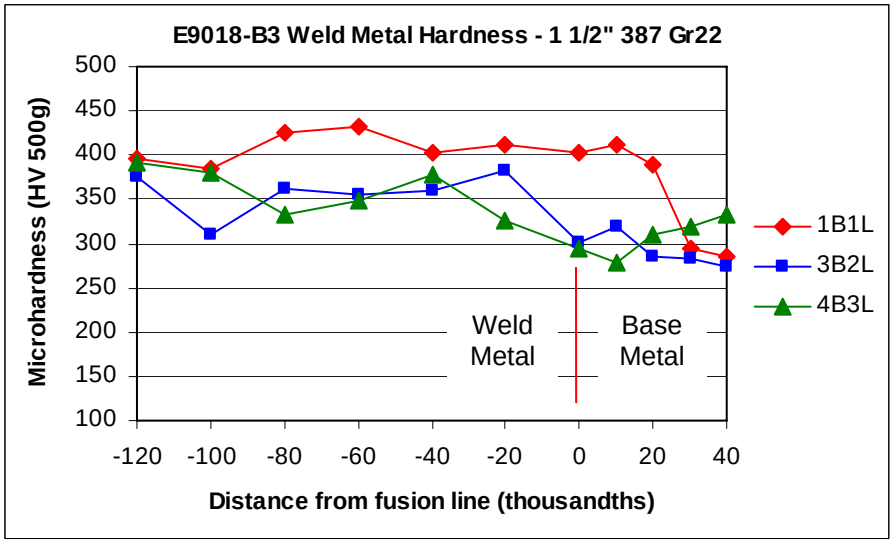


Figure 3-24
E9018-B3 Weld Metal Hardness Curves on 1½" Thick SA-387 Gr22 Plate

3.2.9 Summary and Discussion of Hardness Test Results

The hardness data clearly shows that the single pass 1B1L bead-on-plate deposit produces very high peak HAZ hardness for each thickness and type of material. In fact the data shows that the peak HAZ hardness that occurs with the single pass bead-on-plate with no preheat is close, to or even exceeds, the end quenched hardness of the Jominy test. In all cases the second 2B3L bead-on-plate layer substantially reduced the peak HAZ hardness on 1½" thick plates.

One premise for the Code PWHT exemption thickness limitations is that rapid weld cooling rates in heavy section weldments can result in excessively high cooling rates which increase the propensity for carbon and low alloy steels to form hard martensite with low ductility. This trend in increasing hardness with plate thickness up to 1½" was not generally observed with the bead-on-plate data or the full thickness groove weld data. For the single pass 1B1L bead-on-plate deposit with no preheat, the difference in peak HAZ hardness between the thinner ½", ⅝", ¾" plates that represent the PWHT exemption limit, and the thicker 1½" plate, that would currently require PWHT, ranged from no increase in hardness to a maximum of 38HV. This shows that the difference in HAZ cooling rate for plate thicknesses between ½" and 1½" is negligible in developing a significant increase in peak hardness. For the full thickness groove weld tests the maximum increase in hardness was 56HV and sometimes inconsistent. In two of the full thickness groove weld tests the thinner plates had higher average peak HAZ hardness with one ¾" plate having 33HV higher than the 1½" plate. These results demonstrate that multipass

welding of plates up to 1½" thick produces hardness properties not much different than welding on the thinner plates down to ½".

The hardness data shows that preheat applied with a single pass 1B1L bead-on-plate test only moderately reduces the peak HAZ hardness for low alloy steels. In contrast, the second 3B4L bead-on-plate layer was effective for all materials in substantially reducing the peak HAZ hardness. The 200ºF preheat effectively reduced the peak HAZ hardness for the P No. 1 SA-515-70 carbon steel. However, the second 3B4L bead-on-plate layer was more effective than preheat.

The beneficial tempering affects of subsequent layers on the peak HAZ hardness created with the single pass 1B1L deposit without preheat is clearly shown by the 3B2L and 4B3L hardness curves. In fact, the 3B2L hardness curves show that after just one additional weld layer the preexisting base metal HAZ receives a measurable degree of tempering from the heat input of the second layer for all plate thicknesses and base materials tested. This multipass tempering effect is the basic principle behind temperbead welding techniques where heat input and bead placement are controlled to achieve the required tempering in the base material. In practice, any multipass weld achieves some tempering, albeit with less consistency compared to a procedure where temperbead control parameters are followed.

The data for the full thickness groove welds trended similarly to the multiple layer bead-on-plate and bead-on-pipe tests. This again demonstrates the effect of multiple passes and layers on reducing peak HAZ hardness. Welding of the full thickness groove welds was not done using a temperbead like technique. Therefore it is likely that some bead placements would not show the same amount of tempering by successive beads as compared to the bead-on-plate tests. However, the full thickness groove welds exhibit hardness values well below the peak HAZ hardness of the single bead-on-plate welds, indicating there was a good amount of tempering by successive bead deposits even if the beads were not placed in controlled temperbead like fashion.

The ASME Section IX carbon equivalent equation, or CE number, is often used to predict the hardenability of a material and provide insight as to how readily the material will form martensite under rapid cooling conditions. There are numerous CE formulae that have been developed in an attempt to provide information relative to how a material will respond to rapid cooling cycles. A high CE number indicates a material can be substantially hardened by welding. The Jominy test is a much more effective method to evaluate the hardenability characteristics of a given carbon or low alloy steel. In fact, the Jominy data in this project show it is possible for a material with a higher CE number to actually have a lower hardenability than a material with a lower CE number. This demonstrates the limitations associated with using the ASME Section IX CE number to evaluate and compare the hardenability of various carbon and low alloy steels.

The maximum attainable hardness as a result of welding on each plate or pipe was revealed through the single bead-on-plate tests (i.e., the 1B1L hardness curves). The single bead-on-plate hardness values showed the strong effect of carbon on the peak hardness. The effect of carbon content on hardness is more pronounced with the Jominy test since the influence of the welding process and variable parameters are eliminated. The single pass 1B1L bead-on-plate peak hardness data did however correlate relatively closely to the Jominy hardness at the $^{1}/_{16}$" (end quench) hardness mark. The SA 515-70 with 0.26% C had the highest HAZ peak hardness. In contrast, the SA335-P11 with 0.11% C, exhibited the lowest HAZ peak hardness. This effect was not totally consistent in the weld test data due to variations in welding process, bead placement, etc. For example, preheat or an increase in welding heat input tends to reduce the quench rate in the HAZ region which may lower the peak HAZ hardness.

For full thickness groove welds on 1½" thick plates, the P No. 4 SA-387-11 and the P No. 5A SA-387-22 materials had the highest average HAZ peak hardness values of 348HV and 330HV. The P No. 5A SA-335-P22, P No. 4 SA-335- P11, and P No. 3 SA-204-C had moderate average HAZ peak hardness values of 292HV, 286HV, and 283HV. Finally, the P No. 1 SA-515-70 and P No. 1 SA-516-70 had the lowest peak average hardness of 251HV and 224HV respectively. This data shows that the ASME Section IX filler metal P No. groupings do not effectively categorize low alloy steels base materials in regard to hardenability or maximum as-weld hardness potential.

3.3 Tensile Testing Results

Full section tensile tests were conducted for each welded plate and pipe in accordance with the requirements of ASME Section IX, QW-462. This was done so that any effect on the tensile strength properties of the welded plate could be captured in the test. Ultimate tensile strength and failure location were recorded for each test. The testing was conducted at room temperature. Figure 3-25 shows the full thickness specimen used for the tensile testing. The test specimen gage section length was long enough to include the full weld with base metal on both sides of the weld.

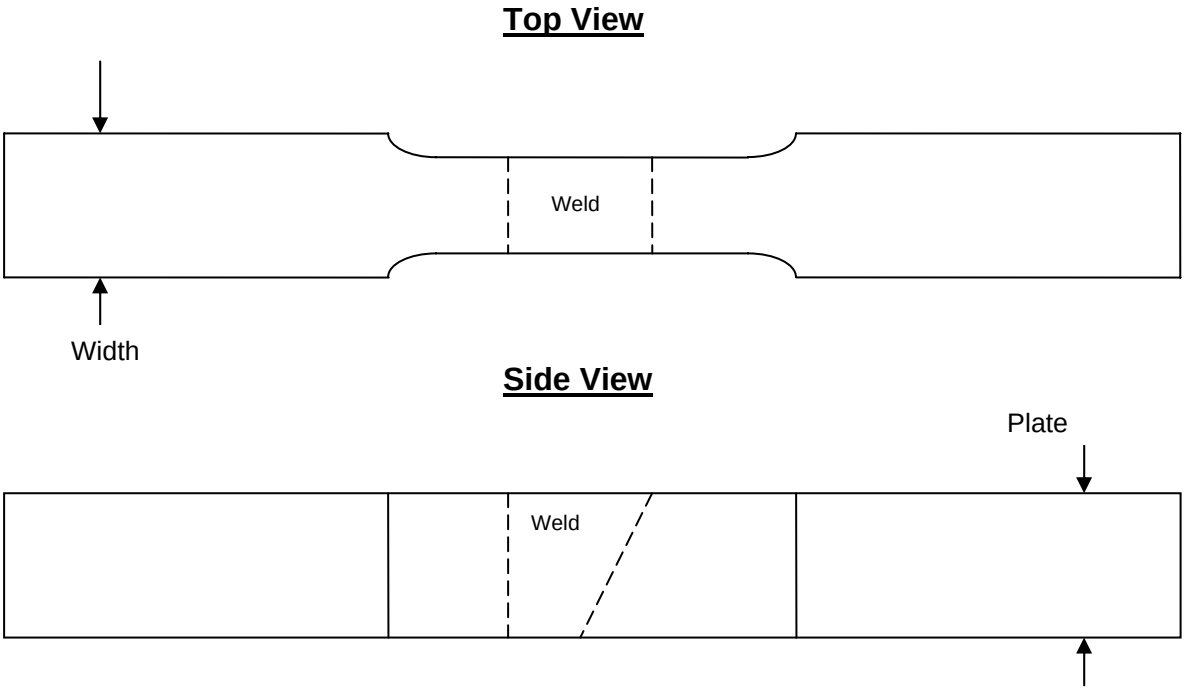


Figure 3-25:
Tensile Test Specimen Configuration

3.3.1 Tensile Testing Summary

The results listed in Table 3-9 show that in all cases the tensile strengths are acceptable and would pass qualification type requirements. None of the failures occurred in the HAZ or exhibited a brittle type fracture appearance. Elongation was not calculated for any of the tests but the tested samples all showed good signs of ductility in their fracture appearance. Figure 3-26 shows the tested tensile samples for the P No. 1 SA-516-70 ¾" and 1½" thick plate weldments. Figure 3-27 shows the tested tensile specimen for the 1½" thick P No. 5A SA-387-22 weldment. A sufficient amount of necking can be seen in both photographs of the tested samples indicating appreciable amounts of ductility associated with the base metal failures. The comparatively high strength of the E9018-B3 weld metal used for the SA-387-22 material forced the majority of the strain to occur in the adjacent base metal. Nevertheless the weldment exhibited enough mechanical strength to resist brittle failure from occurring in any of the P No. 5A weldments. The P No. 3 material exhibited the highest tensile strength while failing in the weld metal. Nevertheless the tensile test results passed the minimum specification requirement.

There were no indications that the tensile strengths of any of the materials were significantly degraded from welding the thicker sections and all tensile tests passed minimum required strength levels. The tensile strengths for the thinnest plate welded were not substantially different than the thickest plate welded for all specimens except the SA-335-P22 material, where the tensile strength measured was 6.6 ksi less in the 1½" thickness than in the ⅝" thickness. Even this material however, exceeded the minimum tensile strength required by 18.5 ksi. All tensile tests passed minimum required strength levels.

The location of the failure in the tensile tests and the hardness test results pointed out the importance of filler metal selection. The weld metal used for the SA-387 Grade 22 material (P No. 5A) was a similar composition as the base metal but did not respond to tempering from subsequent weld passes like that of the base metal HAZ. This resulted in a high relative strength and hardness in the weld that was not present in the base metal. The tensile test results on this material showed relatively no strain in the weld and forced the base metal to absorb the entire strain. Again the issue is the difference in the properties across the weldment. Selection of the appropriate filler materials when welding without subsequent PWHT is important to minimize the metallurgical notch affect of weldments.

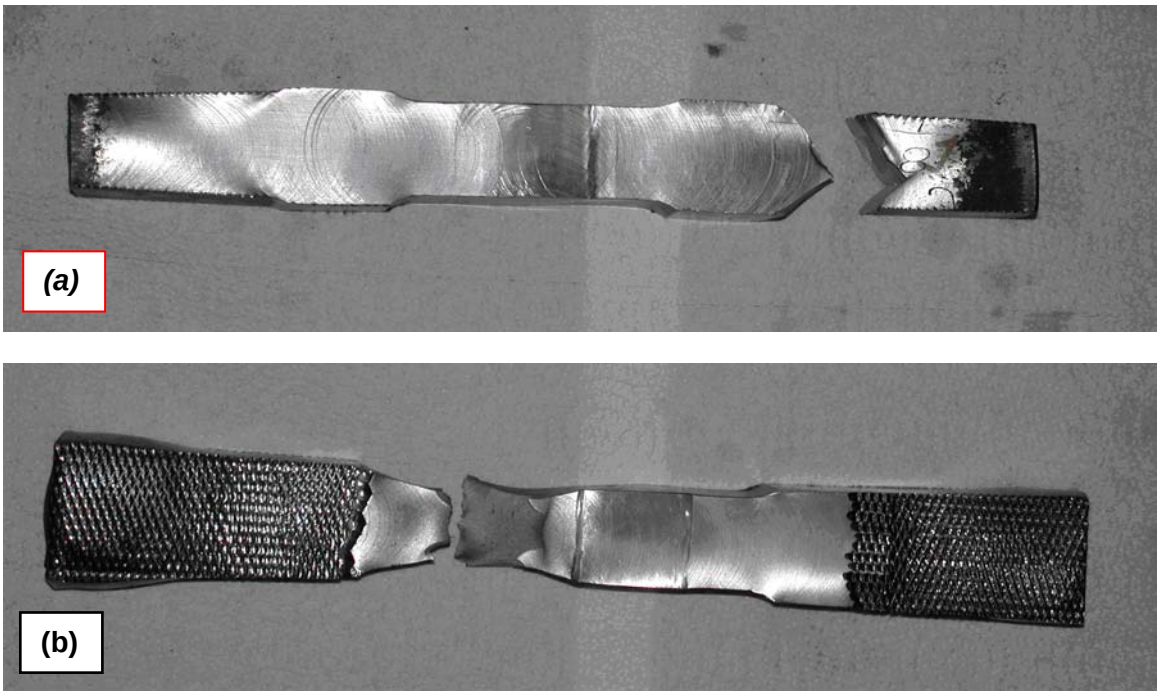


Figure 3-26:
SA-516-70 Tensile Test Weld Samples (a) 1½" Thick Plate (b) ¾" Thick Plate



Figure 3-27:
Tensile Test Sample for 1½" Thick Weld in SA-387-22 Class 1 Plate

Table 3-9:
Tensile Test Results

Material	Nominal Plate Thickness (inch)	Ultimate Tensile Strength (Ksi)	Failure Location	Test Results
P No.1/SA-516-70	¾	78.7	Base	Pass
	1½	76.7	Grip	Pass
Specification	—	70 to 90	—	—
CMTR Value	—	74.6	—	—
P No.1/SA-515-70	½	81.3	Base	Pass
	¾	83.7	Base	Pass
	1½	84.2	Base	Pass
Specification	—	70 - 90	—	—
CMTR Value	—	80.5	—	—
P No.3/SA-204-C	½	89.8	Weld	Pass
	¾	93.0	Weld	Pass
	1½	90.1	Weld	Pass
Specification	—	75 - 95	—	—
CMTR Value	—	81.1	—	—
P No.4/SA-387-11 Cl 2	½	80.8	Base	Pass
	¾	82.5	Base	Pass
	1½	81.7	Base	Pass
Specification	—	75 to 100	—	—
CMTR Value	—	80.0	—	—
P No.4/SA-335-P11	⅝	75.0	Base	Pass
	¾	73.7	Base	Pass
	1½	74.5	Base	Pass
Specification	—	60 min.	—	—
CMTR Value	—	68.7	—	—
P No.5A/SA-387-22 Cl 1	½	79.7	Base	Pass
	¾	80.3	Base	Pass
	1½	86.3	Base	Pass
Specification	—	60 to 85	—	—
CMTR Value	—	80.1	—	—
P No.5A/SA-335-P22	⅝	85.1	Base	Pass
	¾	81.8	Base	Pass
	1½	78.5	Base	Pass
Specification	—	60 min.	—	—
CMTR Value	—	84.1	—	—

3.4 Charpy Impact Testing Results

Charpy V Notch testing was done to determine if the welds could pass an ASME Section IX WPS qualification for toughness. Standard size (0.394" X 0.394") Charpy V Notch (CVN) impact specimens were removed from each base metal material. Base metal HAZ and weld metal CVN samples were removed for each plate and pipe thickness welded. The vertical fusion wall of the weld profile served to aid in CVN sample removal and accurate placement of the notch root in the HAZ of each weld plate. Figure 3-28 shows the removal location and notch placement for each HAZ CVN test specimen for each thickness weld plate. Similar specimen removal locations were also used for the pipe specimens except no weld metal CVN specimens were taken. For the weld metal CVN specimen, the notch was centered in the weld metal at the top of the weld plate in the same manner as the HAZ CVN specimens. Base metal CVN specimens were removed from each 1½" thick base material sample in the as received condition and in the same orientation near the top of the plate or pipe.

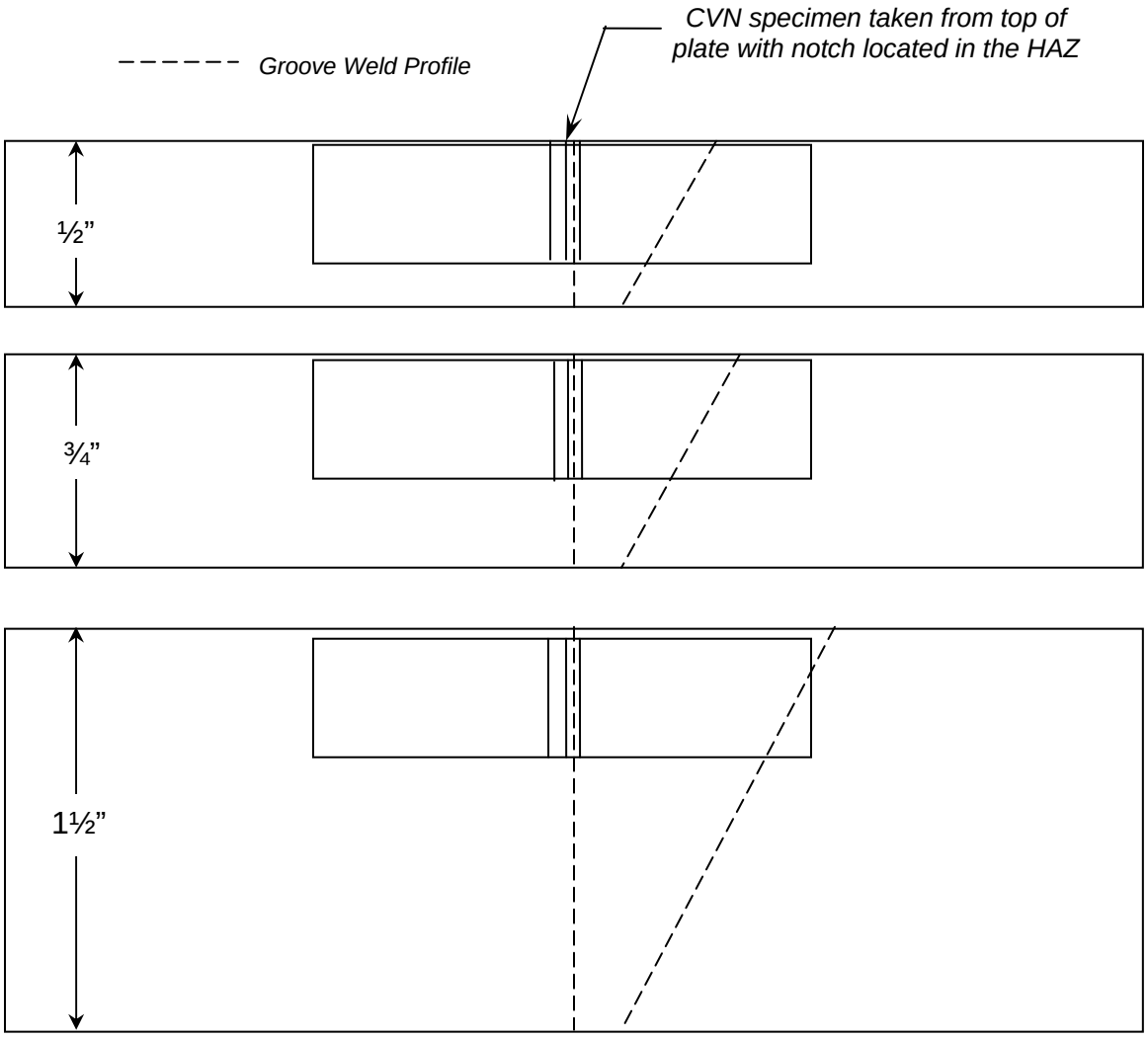


Figure 3-28:
Cross Section View of HAZ Charpy V-Notch Specimen Location

3.4.1 Charpy V-Notch (CVN) Testing Summary

Table 3-10 lists the results of the individual CVN tests for each test plate and pipe material thickness. The single values listed for each heading is the average of three CVN tests. All tests were conducted at room temperature using test requirements specified in Section IX and ASTM SA-370.

Table 3-10:
Room Temperature CVN test results (average of three tests)

Material	Nominal Thickness (in)	Base Metal CVN Impact (ft-lbs)	Base Metal HAZ CVN Impact (ft-lbs)	Weld Metal CVN Impact (ft-lbs)
P No.1 – SA-516-70	¾	—	178	201
	1½	149	167	181
P No.1 – SA-515-70	½	—	171.2	167.3
	¾	—	83 (1)	178.0
	1½	29.8	126.0	203.7
P No.3 – SA-204-C	½	—	234.7	167.3
	¾	—	167.7	195.5
	1½ "	59.2	171.7	215.0
P No.4 – SA-387-11 Cl 2	½	—	167	116
	¾	—	159	129
	1½	180	96.5	140
P No.4 – SA-335-P11	⅝	—	63.3	—
	¾	—	86.7	—
	1½	199	155.8	—
P No.5A – SA-387-22 Cl 1	½	—	152	72
	¾	—	154	64
	1½	209	149	47
P No.5A – SA-335-P22	⅝	—	183.5	—
	¾	—	185.3	—
	1½	240	192.5	—

(1) Average of only two samples

The average base metal CVN values listed for each 1½" thick plate or pipe are considered to be the same values for the other thicknesses since they were from the same heat of material. Depending on where the CVN samples were removed, the testing location from the thickness of each plate or pipe could reveal differences in the base metal impact results which is why the samples were removed from the top of each material when possible (done for the plate tests). Every attempt was made in the machining process to reduce the thicknesses of the test plates so that the top of the machined plate would still correspond to the top of the original 1½" plate. However, this was not done with the pipe materials due to the difficulty of machining the ID of

the pipes. The pipes were machined from the OD so the CVN samples were taken from different thickness locations relative to the original thicknesses. This was not expected to be the cause of any significant differences in the toughness results since the pipe materials were both normalized and tempered.

The ¾" thick SA-515-70 plate was the average of only two tests due to inadequate length for the correct placement of the HAZ notch in the test sample. The average value of 83 ft-lbs is based on the CVN results of 42 and 124 ft-lbs. The P No.4, 1½" thick weld plate showed a measurable drop in the impact energy as compared to the ½" and ¾" thick plate. The three values which were measured were (63, 83, 143.5 ft-lbs for an average of 96.5 ft-lbs). All toughness values were above the unaffected base metal energies for all thicknesses with the exception of the P No. 4 and 5A materials. Nonetheless the average energies revealed for the HAZ were considered acceptable for these two materials in all thicknesses for those applications where impact toughness is not a specific requirement of the Code. This would be true for most applications for these materials since their primary design metal temperatures are normally elevated where impact testing is not normally required.

Only Charpy V-Notch tests of the base metal, HAZ, and weld metal were done. These tests may not be conclusive of the overall toughness at lower temperatures since the impact energy absorbed is a function of both strength and ductility. The strength of the weld metal and of the HAZ exceeded the strength of the base metal for the P Nos. 4 and 5A materials since the tensile test failure location occurred in the base metal. However, the CVN results were lower for the weld metal and the HAZ. Additional mils lateral expansion (MLE) tests may offer additional information. However, none of the materials were of a strength level that required the MLE tests results so these tests were not done.

3.5 Side Bend Testing Results

Four side bend specimens were fabricated from each thickness of the welded plates and pipes. Table 3-11 shows the results of the side bend testing. All the bend tests passed the acceptance criteria necessary to qualify a welding procedure per ASME Section IX, QW-163.

Table 3-11:
Side bend test results

Material	Nominal Thickness (in)	Pass/Fail	Comments
P No.1 – SA-516-70	¾	Pass	—
	1½	Pass	—
P No.1 – SA-515-70	½	Pass	minor lack of fusion
	¾	Pass	—
	1½	Pass	—
P No.3 – SA-204-C	½	Pass	—
	¾	Pass	—
	½	Pass	—
P No.4 – SA-387-11 Cl 2	½	Pass	lack of penetration
	¾	Pass	—
	1½	Pass	—
P No.4 – SA-335 Gr P11	⅝	Pass	—
	¾	Pass	—
	1½	Pass	—
P No.5A – SA-387-22 Cl 1	½	Pass	—
	¾	Pass	—
	1½	Pass	—
P No.5A – SA-335 Gr P22	⅝	Pass	—
	¾	Pass	—
	1½	Pass	—

3.6 Low Cycle Fatigue Testing Results

Low Cycle Fatigue (LCF) cross weld test specimens were fabricated from welds removed from the ½" and 1½" thick plate welds and from the ⅝" and 1½" thick pipe welds. The weld HAZ was located in the LCF specimen gage section with weld metal on one side and base material on the other side. The HAZ is centrally location in the LCF specimen since this is the focus area of interest in this study. Figures 3-29, 3-30, and 3-31 show the typical configuration (after testing) of the cross weld LCF test specimens. LCF test specimens were also fabricated from only base material to establish a base line fatigue curve.

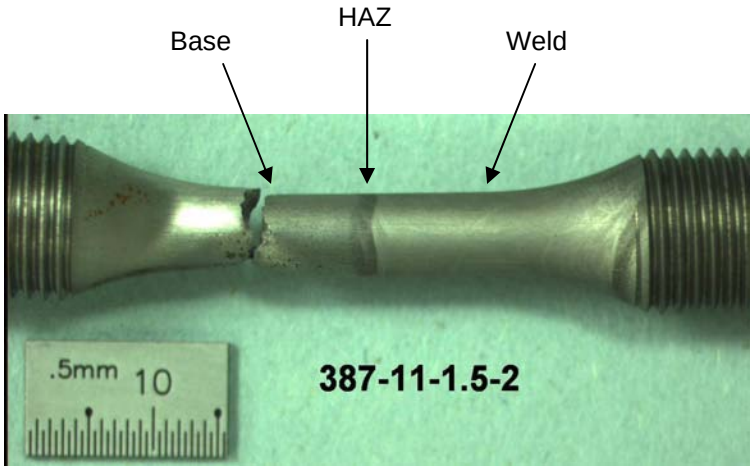


Figure 3-29:
Low Cycle Fatigue Specimen with Typical Base Metal Failure

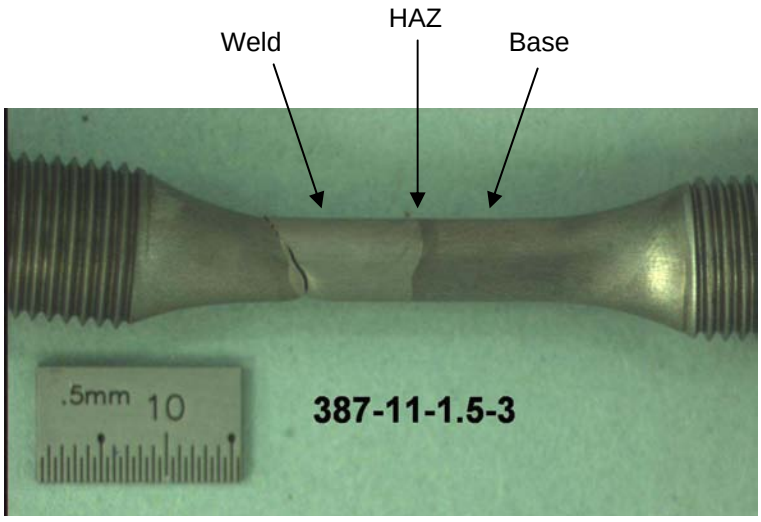


Figure 3-30:
Low Cycle Fatigue Specimen with Failure in Weld Metal Along Fusion Line

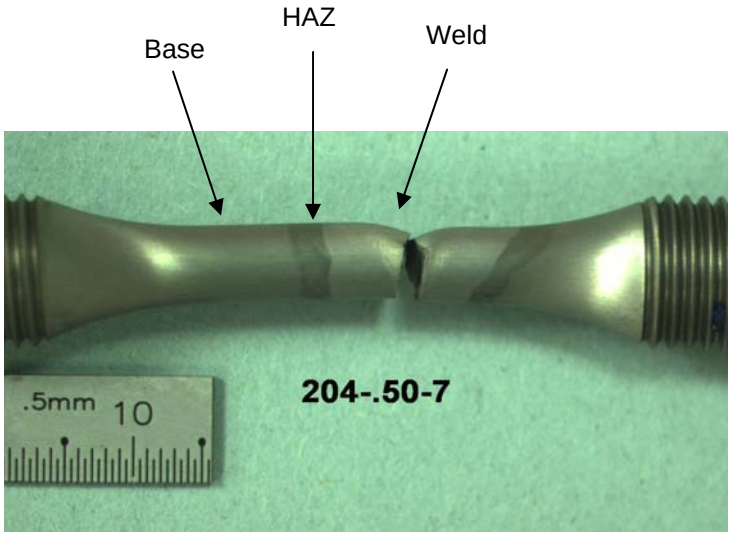


Figure 3-31:
Low Cycle Fatigue Specimen with Failure in Weld Metal

Fatigue testing was fully reversed cycle (R = - 1) under load control conditions. These loading conditions were kept constant for both the base metal specimens and the cross weld specimens. Comparison of the base metal and cross weld fatigue performance was conducted to reveal any adverse conditions resultant from welding which may have reduced the HAZ fatigue strength. The goal was to identify any shift in the region of the fatigue curve prior to reaching the endurance limit of the weldments. A post mortem examination of the test specimens was conducted to determine if HAZ failures were predominant in the testing.

Table 3-12 lists each material specification, the weld specimen thickness, fatigue loading conditions (stress amplitude), cycles to failure, and location of the fatigue failure with comments as necessary to describe the fatigue fracture surface. A number of fatigue failures occurred in vicinity of weld defects in the SA-204-C and SA-387-11 specimens. Figure 3-32 shows defects on the fatigue fracture surface of specimens removed from the ½" thick SA-387-11 weld samples. Similar weld defects were noted on the fracture surface of the SA-204-C specimens.

Figures 3-33 through 3-39 are plots of the low cycle fatigue data points for cross weld fatigue specimens removed from the ¾" and 1½" thick weld samples. The fatigue data points and fatigue (stress amplitude vs. cycles to failure) curve for the 1½" thick base material is also plotted for comparison.

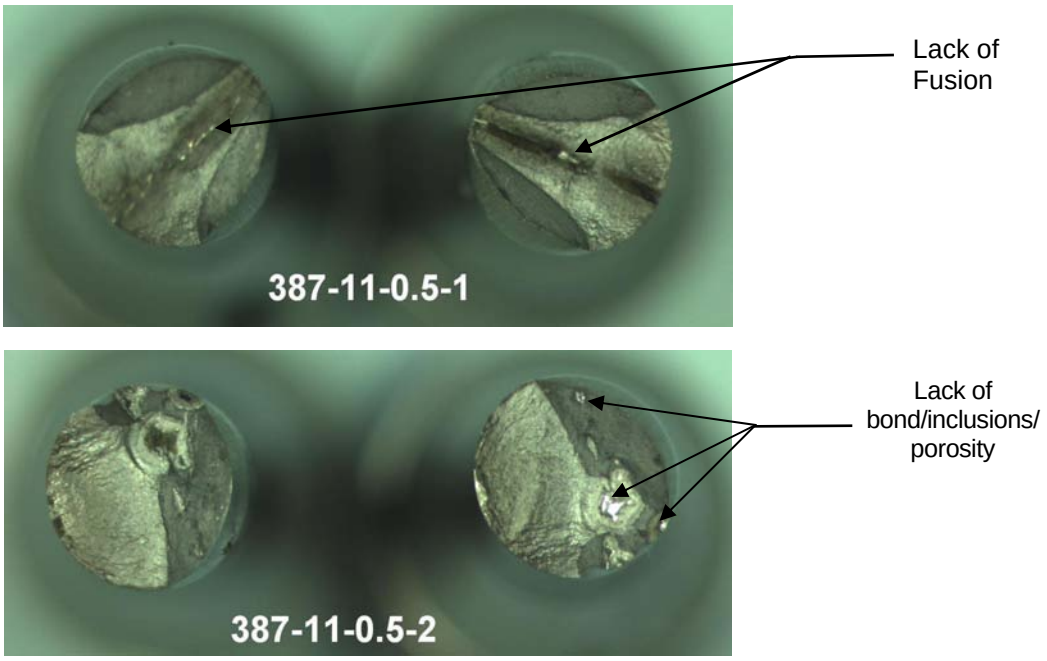


Figure 3-32
SA-387 Gr. 11 Premature Failure of Fatigue Specimens Due to Weld Defects

The results of the low cycle fatigue testing showed no significant detrimental fatigue strength effects of welding the thicker sections without PWHT compared to the currently exempted thicknesses. The only fatigue data points that were significantly below the base metal fatigue curve were the 1½" thick SA-204-C welded specimens. Review of the data for SA-204-C specimens in Table 3-12 show that these fatigue failures all occurred in the weld metal or were associated with a surface defect in the base material. There were also specimens that failed prematurely (farther to the left on the graph) as compared to the base metal trend line. The post testing examination found all of the samples which were located substantially to the left of the base metal fatigue curve were weld metal failures that had defects located at the fracture surface. Figure 3-33 shows photographic examples of the typical defects found on the fracture surface of the prematurely failed samples. This explains the premature failure of these specimens due to stress concentration sites which were exacerbated by the lower cross sectional area in the test gage section because the testing was run under load control. There were no indications that the failure location was concentrated in the base material HAZ due to detrimental conditions resulting from no PWHT. For the cross weld samples that failed in the base metal the fatigue data point trended closely with the fatigue curve developed from the base material fatigue data points.

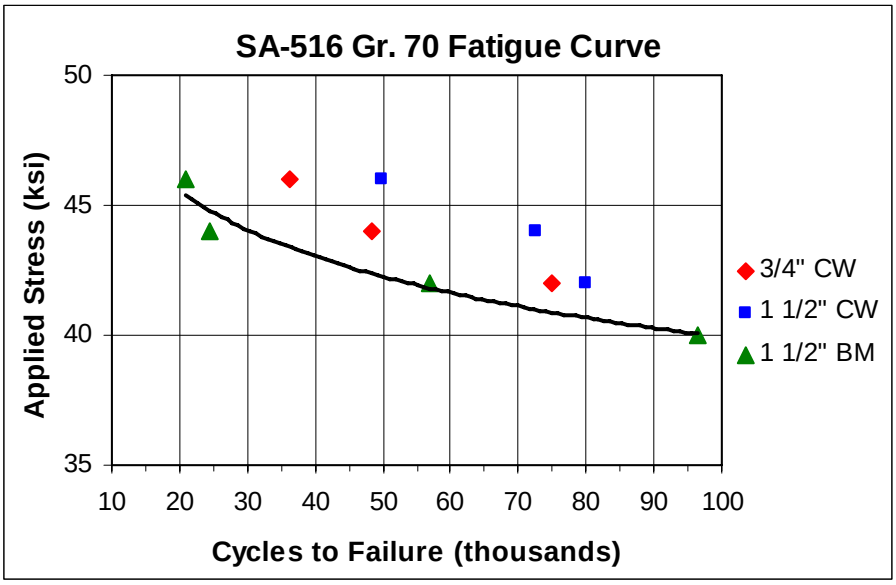


Figure 3-33:
SA-516-70 Fatigue (S/N) Curve for ¾" and 1½" Cross Weld and 1½" Base Material

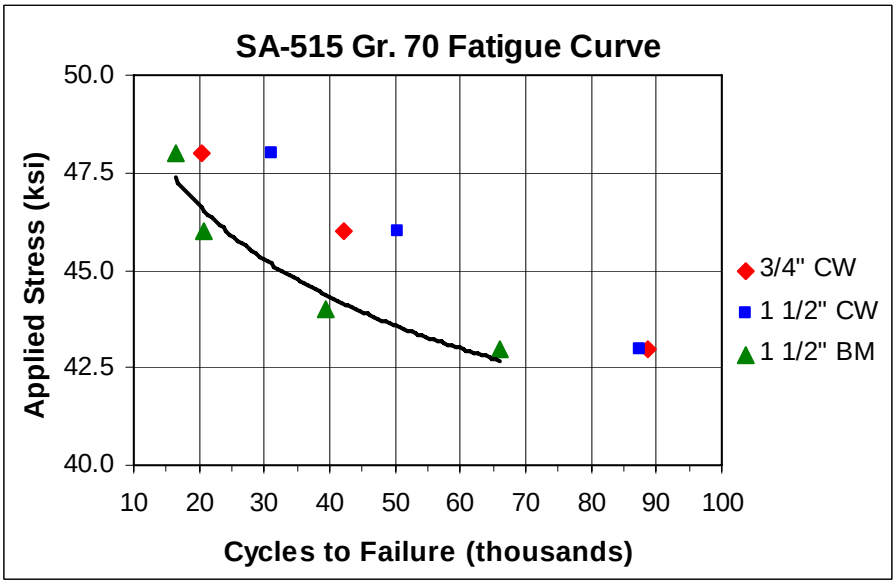


Figure 3-34
SA-515-70 Fatigue (S/N) Curve for ¾" and 1½" Cross Weld and 1½" Base Material

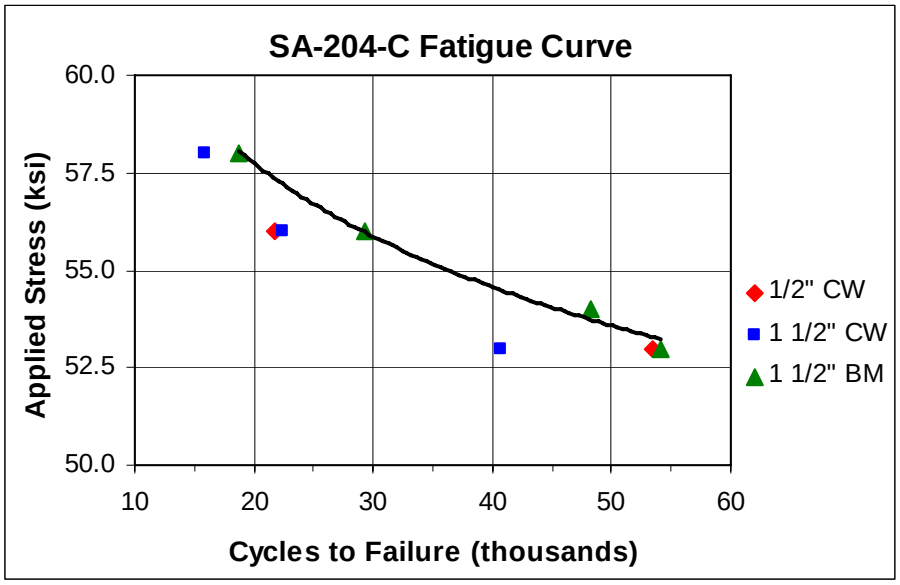


Figure 3-35
SA-204-C Fatigue (S/N) Curve for ½" and 1½" Cross Weld and 1½" Base Material

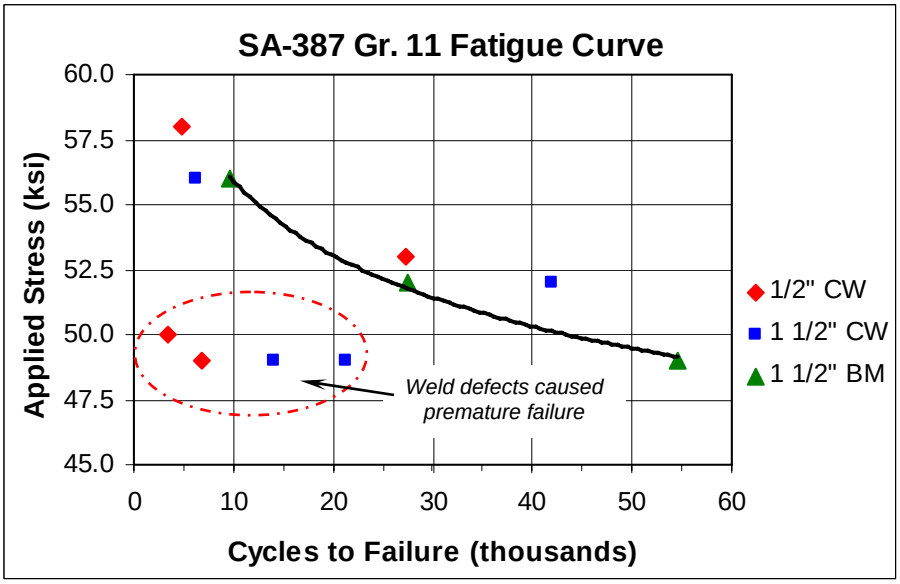


Figure 3-36
SA-387-11 Fatigue (S/N) Curve for ½" and 1½" Cross Weld and 1½" Base Material

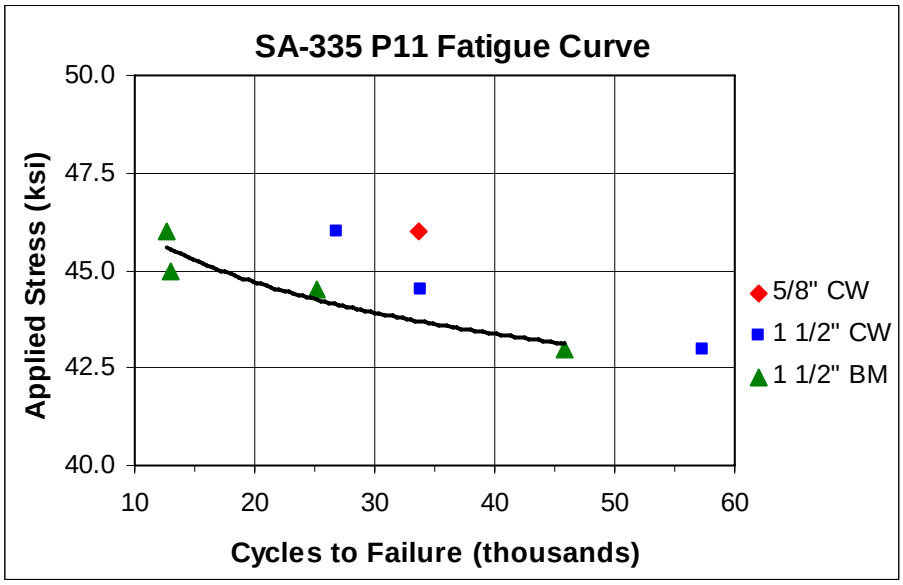


Figure 3-37:
SA-335-P11 Fatigue (S/N) Curve for ⅝" and 1½" Cross Weld and 1½" Base Material

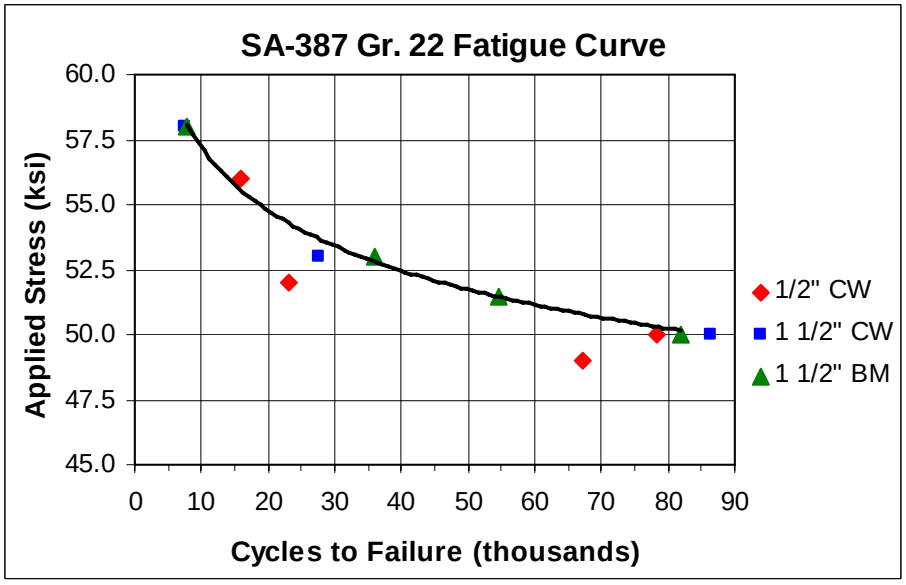


Figure 3-38:
SA-387-22 Fatigue (S/N) Curve for ½" and 1½" Cross Weld and 1½" Base Material

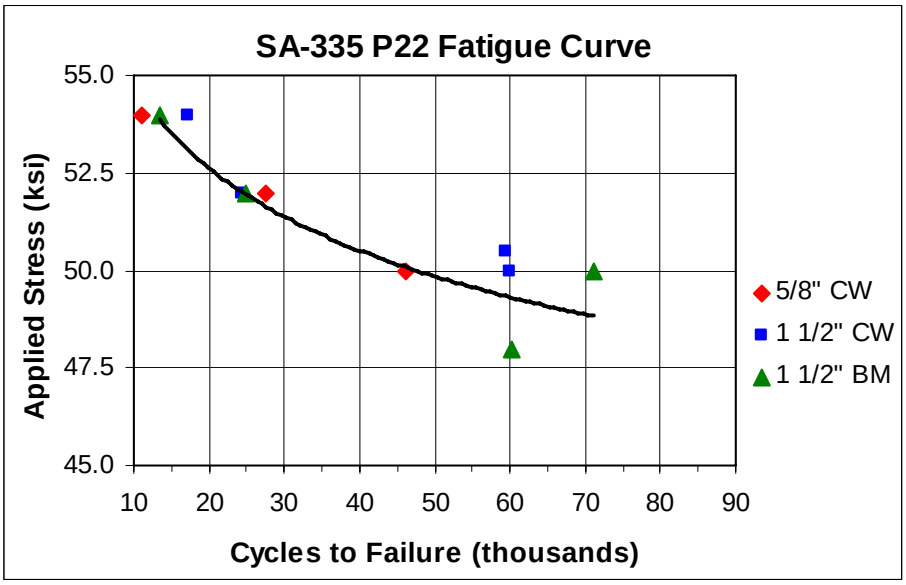


Figure 3-39:
SA-335-P22 Fatigue (S/N) Curve for ⅝" and 1½" Cross Weld and 1½" Base Material

Table 3-12:
Low cycle fatigue test data

P No.	Material	Weld Sample Thickness (inch)	Loading Condition (+/- ksi)	Cycles to Failure	Failure Location	Comments
1	SA-516-70 Cross Weld	¾	46.0	36,355	BM	—
			44.0	48,488	BM	—
			42.0	75,001	Removed	—
		1½	46.0	49,965	BM	—
			44.0	72,569	BM	—
			42.0	79,935	Removed	—
	SA-516-70 Base Metal	1½	46.0	20,985	BM	—
			44.0	24,509	BM	—
			42.0	56,998	BM	—
			40.0	96,407	BM	—
1	SA-515-70 Cross Weld	¾	48	20,480	BM	—
			46	42,282	BM	—
			43	88,526	Removed	—
		1½	48	31,004	BM	—
			46	50,487	BM	—
			43	87,424	Removed	—
	SA-515-70 Base Metal	1½	48	16,322	BM	—
			46	20,639	BM	—
			44	39,250	BM	—
			43	66,046	BM	—
3	SA-204-C Cross Weld	½	*58*	*9,651*	*WM*	*Defects on FS*
			56	*21,718*	*WM*	*Defects on FS*
			53	*1,277*	*WM @ FL*	*Large Defects*
			53	53,507	BM	—
		1½	58	15,848	WM	—
			56	22,367	WM	—
			53	40,727	BM	Surface Defects

P No.	Material	Weld Sample Thickness (inch)	Loading Condition (+/- ksi)	Cycles to Failure	Failure Location	Comments
	SA-204-C Base Metal	1½	53	54,091	BM	—
			56	29,237	BM	—
			58	18,795	BM	—
			54	48,250	BM	—
4	SA-387-11 Cross Weld	½	58.0	4,796	WM near FL	Large Defects
			53.0	27,390	WM @ FL	Large Defects
			50.0	*3,390*	*WM near FL*	*Large Defects*
			49.0	*6,858*	*WM near FL*	*Large Defects*
		1½	56.0	6,147	WM near FL	Large defects
			52.0	41,841	BM	—
			49.0	*13,978*	*WM near FL*	*Large Defects*
			49.0	*21,223*	*WM near FL*	*Large Defects*
	SA-387-11 Base Metal	1½	56.0	9,586	BM	—
			52.0	27,534	BM	—
			49.0	54,652	BM	—
4	SA-335-P11 Cross Weld	⅝	46.0	33,682	BM	Surface Defect
			44.5	72,870	BM	—
			43.0	186,789	BM	—
		1½	46.0	26,849	BM	—
			44.5	33,869	BM	—
			43.0	57,375	BM	—
	SA-335-P11 Base Metal	1½	46.0	12,643	BM	—
			45.0	13,046	BM	—
			44.5	25,161	BM	—
			43.0	45,852	BM	—

P No.	Material	Weld Sample Thickness (inch)	Loading Condition (+/- ksi)	Cycles to Failure	Failure Location	Comments
5A	SA-387-22 Cross Weld	½	56.0	15,904	BM	—
			52.0	*23,027*	*BM*	*OD Surf Defect*
			50.0	78,211	FL	Defects on FS
			49.0	67,222	WM/BM	—
		1½	58.0	7,445	BM	—
			53.0	27,632	BM	—
			50.0	86,375	Removed	—
	SA-387-22 Base Metal	1½	58.0	7,840	BM	—
			53.0	35,967	BM	—
			51.5	54,685	BM	—
			50.0	81,825	BM	—
5A	SA-335-P22 Cross Weld	⅝	54.0	11,154	BM	—
			52.0	27,422	BM	—
			50.0	46,063	BM	—
		1½	54.0	17,276	BM	—
			52.0	24,354	BM	—
			50.5	59,394	BM	—
			50.0	60,046	BM	—
	SA-335-P22 Base Metal	1½	54.0	13,409	BM	—
			52.0	24,762	BM	—
			50.0	71,031	BM	—
			48.0	60,210	BM	—

(1) "Removed" indicates the testing was terminated prior to specimen failure.
(2) Failure Locations = WM (Weld Metal), FL (Fusion Line), BM (base Metal)
(3) Shaded entries in italics are not plotted due to weld flaws that resulted in unreasonable values

4
CONCLUSIONS

4.1 Hardness, Hardenability, and Mechanical Testing

It is the intent of this document to provide data with which technical justifications can be made to support any increases in the current exemption thickness limits set forth by various ASME codes. Ideally, the goal is to make a weldment (e.g., base material, weld metal, and HAZ) with uniform composition and mechanical properties. While this is not realistic, the goal is to determine to what thickness a material can be successfully welded without PWHT and expected to provide safe and reliable service.

While local peak hardness values associated with components without PWHT may be higher than components with PWHT, the effect on the overall mechanical behavior of the welded component is what is in question. The results of the mechanical testing show that weldments with higher peak hardness, within limits, does not necessarily mean that the material has been degraded and is not fit for service. For example, high hardness does not always correlate to low toughness or a loss of fatigue strength.

Hardenability properties which have been estimated by the use of CE formulas do not appear to provide enough information in the materials investigated (P Nos.1, 3, 4 and 5A) to correlate with the outcome of the HAZ properties. Hardness measurements across the fusion line through the HAZ do not reveal a consistent trend which would prohibit welding these materials in thicker sections. While some of the materials tested showed an increase in the average peak hardness within the HAZ as the greater thicknesses of the materials were welded, this increase was relatively small and often inconsistent.

Carbon content is a strong indicator that affects the maximum level of hardness particularly within the first 100 to 200 thousandths of the base metal heat affected zone for the single bead-on-plate tests of the P Nos.1, 3, 4 and 5A materials. The hardness values developed near the quenched end of the Jominy test bar were not apparent in the full welded plate as a result of tempering between weld passes in the weld plate.

The hardness test data show that multipass welding is an effective method for reducing the local HAZ peak hardness that is in range of the maximum attainable Jominy end quench hardness for the based materials tested. Single bead-on-plate welds installed without preheat are effectively tempered by a second layer. The test data also indicate that for the low alloy steels tested the multipass weld technique and more effective at reducing the HAZ hardness than elevated preheats.

The tensile and bend test results were all satisfactory and showed that adequate tensile strength and ductility can be achieved in thicker section welds without PWHT for the materials tested.

The toughness tests showed that substantial toughness can be achieved relative to the hardness levels that were created from welding. The testing was conducted at room temperature for this study. Transition curve behavior would not be expected to suffer as a result of welding on these materials. All of the tested materials had adequate toughness in the HAZ near the fusion line.

The low cycle fatigue tests were satisfactory and showed no significant detrimental fatigue strength effects of welding the thicker sections without PWHT for the materials tested.

4.1.1 Welding of Thicker Sections - Summary

Tables 4-1 and 4-2 below show the results of the hardness examinations and the CVN impact strengths for welding thicker sections of each material. Typical welding process parameters and multipass techniques were used to make the welds. No detrimental effects are observed by welding on plate thicknesses that are greater than the currently exempted PWHT thickness limits set forth by the Codes. The tensile tests, side bend tests and the fatigue testing all showed satisfactory results for thicker weldments in the as-welded condition.

Table 4-1:
Room Temperature CVN Impact Energies for Differing Thickness

Material	Carbon Equivalent	Carbon wt%	Thickness (inch)	Base Metal (ft-lbs)	HAZ (ft-lbs)
SA-516 Gr. 70 P No.1 Group 1	0.46	0.20	¾ (1)	149.0	178.0
			1½		167.0
SA-515 Gr. 70 P No.1 Group 2	0.48	0.26	½	29.8	171.2
			¾ (1)		83.5 (3)
			1½		126.0
SA-204 Gr. C P No.3 Group 2	0.54	0.20	½ (1)	59.2	234.7
			¾		167.7
			1½		171.7
SA-387 Gr, 11, Cl.1 P No.4 Group 1	0.66	0.15	½ (1)	180.0	167.0
			¾		159.0
			1½		97.0
SA-335 Gr. P11 P No.4 Group 1	0.65	0.11	⅝ (2)	199.0	63.3
			¾		86.7
			1½		155.8
SA-387 Gr. 22, Cl.1 P No.5A Group 1	0.88	0.12	½ (1)	209.0	152.0
			¾		154.0
			1		149.0
SA-335 Gr. P22 P No.5A Group 1	0.89	0.11	⅝ (2)	240.0	183.5
			¾		185.3
			1½		192.5

Notes:

(1) Minimum code exemption thickness
(2) Code exemption thickness for ASME Sections I & VIII
(3) Average of two CVN specimens instead of three

Table 4-2:
Full Thickness Groove Welds Hardness Values and Carbon Equivalents

Material	Carbon Equivalent	Carbon wt%	Thickness (in)	Average Peak Hardness (HV)	Peak Hardness (HV)
SA-516 Gr. 70 P No.1 Group 1	0.46	0.20	¾ (1)	207	226
			1½	251	263
SA-515 Gr. 70 P No.1 Group 2	0.48	0.26	½	220	240
			¾ (1)	263	303
			1½	224	238
SA-204 Gr. C P No.3 Group 2	0.54	0.20	½ (1)	287	323
			¾	315	340
			1½	283	304
SA-387 Grade 11, Cl.1 P No.4 Group 1	0.66	0.15	½ (1)	292	306
			¾	294	335
			1½	348	385
SA-335 Grade P11 P No.4 Group 1	0.65	0.11	⅝ (2)	260	272
			¾	259	270
			1½	286	299
SA-387 Grade 22, Cl.1 P No.5A Group 1	0.88	0.12	½ (1)	303	317
			¾	326	375
			1½	330	383
SA-335 Grade P22 P No.5A Group 1	0.89	0.11	⅝ (2)	268	288
			¾	276	302
			1½	292	310

(1) Minimum code exemption thickness
(2) Code exemption thickness for ASME Sections I & VIII

4.2 Criteria for PWHT Exemption Thickness

As stated previously, the purpose of PWHT is to reduce weld residual stress to an acceptable level and to temper hardened microstructures of the weldment and base metal HAZ. The justification for increasing the PWHT thickness limitations for carbon and low alloy steels in the various Codes should show that adequate properties are maintained in the weld, HAZ, and the base metal properties without PWHT. There has always been a concern for as-welded peak hardness, particularly at the HAZ close to the weld fusion line. The results of the testing in this project to date show that this may not be a major concern when limited heat input multipass welding techniques are applied. The use of controlled placement of weld passes with specific heat input (i.e., temperbead welding) is one approach that justifies welding without subsequent PWHT although these techniques do require specific WPS qualification. Another approach for carbon steels that may be of value are increased preheat temperatures. Finally, the use of

specifically engineered filler metals would also contribute to minimizing differences in the properties of the weldments.

Reducing and minimization of weld residual stress and tempering of the weld and HAZ microstructures can be very important to the level of corrosion resistance of the weldment. It may not be advisable to eliminate PWHT in particularly severe corrosive environments. The corrosion resistance criteria for PWHT are only generally addressed in the current Code rules. Current Code rules for PWHT are based primarily on tempering to reduce peak hardness caused by welding. Caution may be warranted in Code rules to warn users that elimination of PWHT may potentially lower corrosion resistance.

5
FUTURE WORK

5.1 Additional Testing and Research

Additional testing and evaluation would be very beneficial to move this work forward in the ASME Code Committees. Testing and investigation on the following issues would further this issue. Testing on wider range of commonly used carbon and low alloy steels, testing of thicker plates, low alloy piping with ½" wall thickness, and investigation of influence of higher heat input welding processes. Also, research and investigation of other carbon equivalent equations or other methods to categorize the hardenability of carbon and low alloy steels used in the power generation industry is needed. Testing of full thickness groove welds without preheat to investigate effectiveness of typical multipass welding techniques on maintenance and control of peak hardness in the HAZ. Investigation of bead placement techniques for control of peak hardness without resorting to overly restrictive temperbead type controls.

5.2 Code Support

A white paper justifying appropriate PWHT exemption thickness limits for P Nos. 1, 3, 4, and 5A will be developed for code review. EPRI staff and contractors will be responsible for championing technical items necessary for implementing the proposed criteria for the PWHT exemption thickness.

6
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