Design Properties of Steels for Coal Conversion Vessels
Mechanical Properties of Materials

AP-1338
Research Project 627-1

Interim Report, January 1980

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ABSTRACT

The purpose of this report is to present a complete data log on the mechanical properties of the materials used in the present investigation. Weldments of SA387, SA542, and a type 347 stainless steel overlay were made by Chicago Bridge and Iron using base plates of typical commercial thickness and commercial welding practices. The results of preliminary mechanical property tests and microstructural examinations indicated that the material properties were sufficiently uniform and representative of conditions typical for production material properties to proceed with detailed testing. In SA387 and SA542, the microstructures were dominantly bainitic, with the average yield strengths respectively 345 MPa (50 ksi) and 496 MPa (72 ksi), due mostly to the selected tempering temperature. Average upper shelf Charpy toughness, was 180 Joules (133 ft-lbs) in both SA387 and SA542 base metals but 50% FATT transition temperatures were 294°K (70°F) and 244°K (-20°F), respectively. A temper embrittling treatment was tried which raised the 50% FATT of SA387 base metal and weld metal 67°K (120°F). Upper shelf fracture energy of the SA387 base metal was reduced 50 percent by the T.E. treatment.

Baseline data for the fracture mechanics type tests were developed in the form of da/dN versus ΔK_I, and fracture toughness in terms of J_{Ic}. Fatigue crack growth rate of SA387 was increased by a factor of 2 when comparing room temperature versus 727°K (850°F). Growth rate of SA542 was the same at 588°K (600°F) and room temperature. Fracture toughness by J_{Ic} showed the expected loss in upper shelf toughness with increased test temperature for SA387 base metal.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This interim report is the second in a series of reports to be issued under Research Project (RP) 627-1. This project is one step in providing the coal conversion industry with a rational design basis in terms of quantitative fracture mechanics parameters. Planned coal gasification techniques involve internal pressures ranging from 150 psi (low-Btu gas) to 1500 psi (high-Btu gas) at 450 to 650°F metal-wall temperatures, with 75 to 750 psi hydrogen partial pressure and up to 50 psi partial pressure of H_2S. Similarly, coal liquefaction processes specify pressures of up to 3500 psi total, of which hydrogen can account for about 3300 psi and H_2S for as much as 200 psi. Metal temperatures will be about 850°F, but local hot spots could be as high as 1000°F. In both conversion technologies, the product streams will contain various amounts of CO, CO_2, H_2O, and NH_3 as well. Under these conditions structural steels may be degraded by deleterious interactions between the steels and the environments. The only design basis available at present for pressure vessels operating in high-pressure, high-temperature hydrogenous environments is the empirical Nelson diagram approach used by the petrochemical industry. The present project was undertaken, therefore, to develop a quantitative fracture mechanics technology base for 2 1/4 Cr-1Mo steel with a variety of metallurgical and environmental conditions that may be typically encountered in coal liquefaction and gasification.

PROJECT OBJECTIVE

The principal objective of RP627 is to characterize the degradation of 2 1/4 Cr-1Mo steel and the American Iron and Steel Institute (AISI) Type-347 steel due to exposure in H_2-H_2S environments at room temperature and at elevated temperatures, in terms of quantitative fracture mechanics parameters.

PROJECT RESULTS

The project is now close to completion. The effects of H_2-H_2S atmospheres on the room temperature and on the elevated temperature (600 and 850°F) properties of the American Society for Testing and Materials (ASTM) A387 Class 2, ASTM A542 Class 3, and AISI Type-347 stainless steels have been fully characterized in terms of fracture mechanics parameters. In addition, the degradation of room temperature properties as a result of prolonged exposure under service conditions has also been characterized. One of the first tasks to be completed, however, was a detailed evaluation of the baseline properties of the various steels in air to ensure that the materials used in the study were truly representative of the material grade and that any inhomogeneity in properties as a function of location would be typical of the section sizes in which the plates would normally be used. These concerns have been satisfied as may be seen in the baseline data contained in this report.

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CONTENTS

Section Page

ILLUSTRATIONS

TABLES

SUMMARY

The recent emergence of coal conversion technologies into prominence has posed major challenges to the materials technologist. Planned coal conversion techniques call for internal pressures as high as 3500 psi and metal temperatures as high as 850°F in the pressure vessels. The materials of construction should also be able to withstand attack by hydrogenous environments. The only design basis available for pressure vessels operating in high pressure, high temperature hydrogenous atmospheres is the qualitative and empirical Nelson diagram approach used by the petrochemical industry. The present project was therefore undertaken to develop a more rational and quantitative design basis for coal conversion vessels in terms of fracture mechanics parameters. This purpose is now close to being achieved and a series of topical reports covering the various tasks are in the process of being issued. The present topical report is the second report in this series and describes the baseline data generated in air on the various materials, and will therefore serve as the foundation upon which the results of the more detailed environmental tests can build.

The materials covered in this study include two grades of 2¼ Cr-1 Mo steel, i.e., ASTM A387 Class 2 Grade 22, and ASTM A542 Class 3 and Type 347 stainless steel overlay material. The material conditions investigated include base metal, weld metal, heat-affected zone and temper-embrittled steel.

The baseline data reported clearly show that the materials utilized in this study are indeed typical of the material grade and that the inhomogeneities in properties are representative of the section sizes in which the materials are normally utilized. In SA 387 and SA 542 the microstructures were predominantly bainitic with average yield strengths of 345 MPa (50 ksi) and 496 MPa (72 ksi), respectively. Average upper shelf charpy toughness was 180 joules (133 ft-lbs.) in both grades of steel. Temper embrittlement treatments increased the 50% fracture appearance transition temperature of SA 387 from 294°K (70°F) to 361°K (190°F). Baseline data for fracture mechanics analysis were developed from fatigue crack

growth rate (da/dN VS K) and J_{IC}. Results show that the fatigue crack growth rate for SA 387 is increased by a factor of 2 at 727°K (850°F) compared to the room temperature data. Crack growth rate for SA 542 grade is the same at 588°K (600°F) as at room temperature.

Section 1

INTRODUCTION

An important part of any program for which extensive data development is planned is to completely characterize the material to be used and to establish that the metallurgical conditions provided are truly representative of the material grade. It is for this reason that a substantial effort has been devoted to routine material evaluation on the 2¼Cr-1Mo base materials and weldments received. The philosophy applied here was that once the suitability of the material has been established, it was then possible to proceed with the preparation of expensive fracture mechanics type specimens.

In this program, two grades of 2¼Cr-1Mo steel were chosen for testing; a normalized and tempered ASTM A387 Class 2, Grade 22 steel and a quenched and tempered ASTM A542 Class 3 steel.* These steels were supplied as submerged arc weldments of approximately 178 mm (7-inch) thickness. Pressure vessels for coal liquefaction processes are normally clad with an austenitic stainless steel; Type 347. This is usually applied to a SA387 base plate material in a welding overlay processes.

The plates of 2¼Cr-1Mo steel were manufactured by Lukens Steel Company and the weldments for this program were prepared by a major producer of welded pressure vessels, The Chicago Bridge and Iron Company, (CB&I). Five heats were used to fabricate all of the test pieces; two heats for the SA387 normalized and tempered weldment (Heat Nos. 3324 and 3596), two heats for the SA542 quenched and tempered weldment (Heat Nos. 7868 and 3707) and one heat of SA387 as vessel body material for the Type 347 SS overlay (Heat No. 4040). The chemistries for each of the base plates as supplied by Lukens are given in Table 1-1 along with the ASTM specifications for 2¼Cr-1Mo steel. As can be seen, each of the heats fall within the specified values for chemical composition. Tensile and Charpy "V" notch impact properties were conducted independently by Lukens on

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*Throughout this report the convention SA387 and SA542 will be used which indicates that this material is ASME Code approved for pressure vessel construction.

specimen blanks heat treated separately to assure the suitability of the materials, and these results are given in Table 1-2.

The weldments produced by CB&I were made according to commercial practice. A schematic of the weldment of SA387 Class 2, Grade 22 is shown in Figure 1-1, giving the dimensions. This weldment was fabricated from base plate Heats 3324 and 3596 using a submerged arc welding process with Linde 124 flux. The SA542 Class 3 weldment was fabricated from base plate Heats 7868 and 3707 using a submerged arc process with Linde 0091 flux. A schematic of this weldment is shown in Figure 1-2. The Type 347 stainless steel overlay was fabricated on an SA387 plate, Heat 4040, using a special geometry to allow for the preparation of fracture mechanics type test specimens, Figure 1-3. The first pass of the overlay was a Cb modified 309 SS which when diluted by 2¼Cr-1Mo during welding gives the aim composition for Type 347 SS. The subsequent passes were made with Type 347 SS filler material.

The preweld heat treatment of the base plates and post weld heat treatments for the SA387 and SA542 weldments are given in Table 1-3. The commercial practice on SA387 was normalize followed by an accelerated air fan cooling. This accelerated cooling is allowed by the ASTM standard (1) and is commonly used in commercial practice. However, it gives a microstructure which appears to be more like a quenched steel than a normalized steel. The SA387 has lower strength than the SA542, and this is achieved mainly by the difference in tempering temperatures, 964°K (1275°F) for the SA387 versus 936°K (1225°F) for the SA542. The fabrication steps and heat treatment for the 347 SS overlay simulation are also given in Table 1-3.

The weldments were inspected at CB&I by four different techniques. Details of these inspection techniques are given in Table 1-4. Additional ultrasonic inspection of the weldments was conducted at the Westinghouse R&D Center. The inspections revealed no defects in violation of the acceptance standards.

A section of the SA387 weld metal was subjected to a deliberate temper embrittlement treatment. This was done so that the cracking behavior of temper embrittled weld material in coal conversion environments could be compared to in air temper embrittlement. The heat treatment was a Westinghouse in-house step cooling process, given in Table 1-5.

Material characterization tests were conducted for all of the weldments. These tests included mechanical properties; tensile, Charpy V impact, and NDT drop weight tests, chemistries, micro examinations, and measurement of percent ferrite in the Type 347 SS overlay material. The scheme of the material characterization test plan is given in Table 1-6.

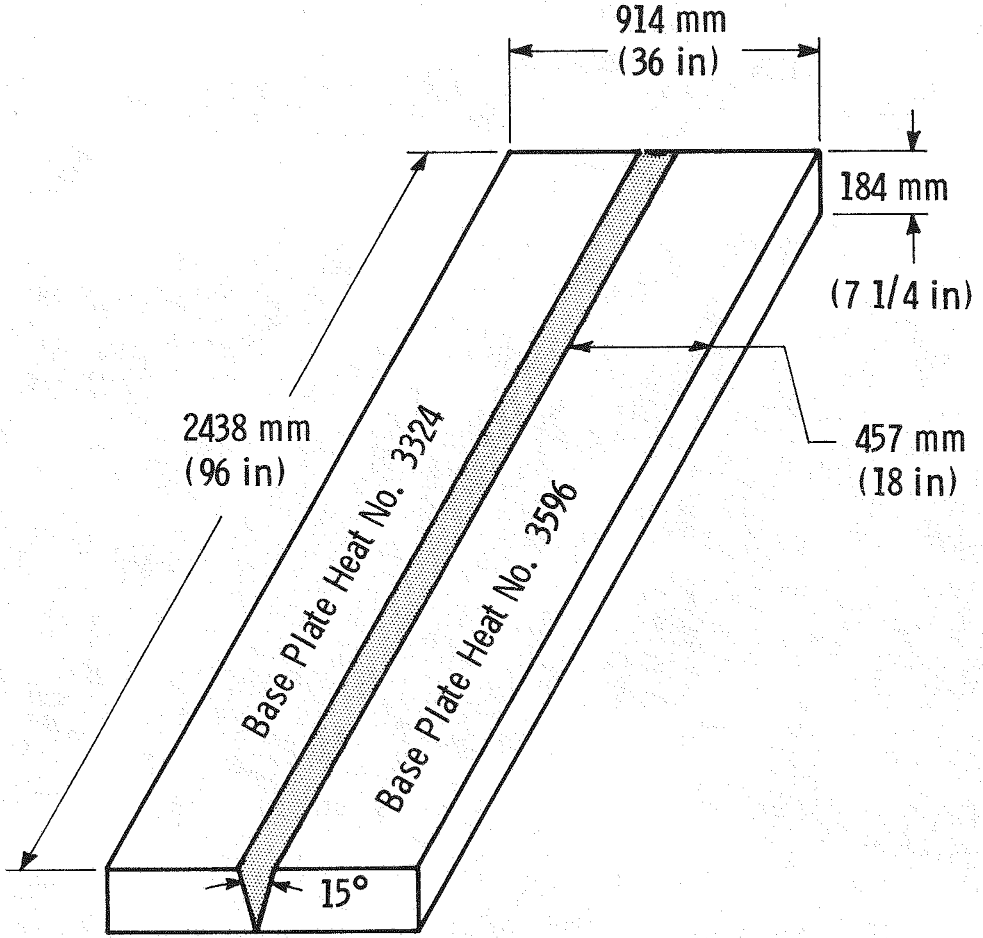

Fig. 1-1 – 2 1/4 Cr-1 Mo steel weldment normalized and tempered (ASTM A387 class 2, grade 22) Schematic of fabrication

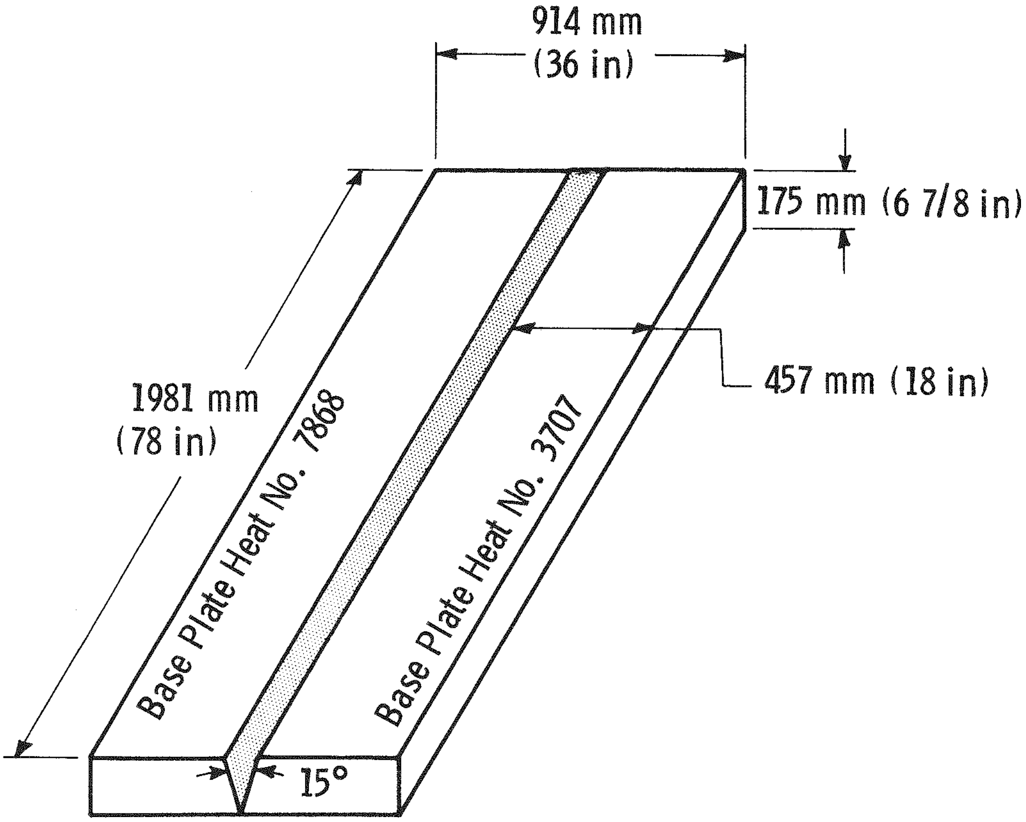

Fig. 1-2— 2 1/4 Cr-1 Mo steel weldment quenched and tempered (ASTM A542 Class 3) Schematic of fabrication

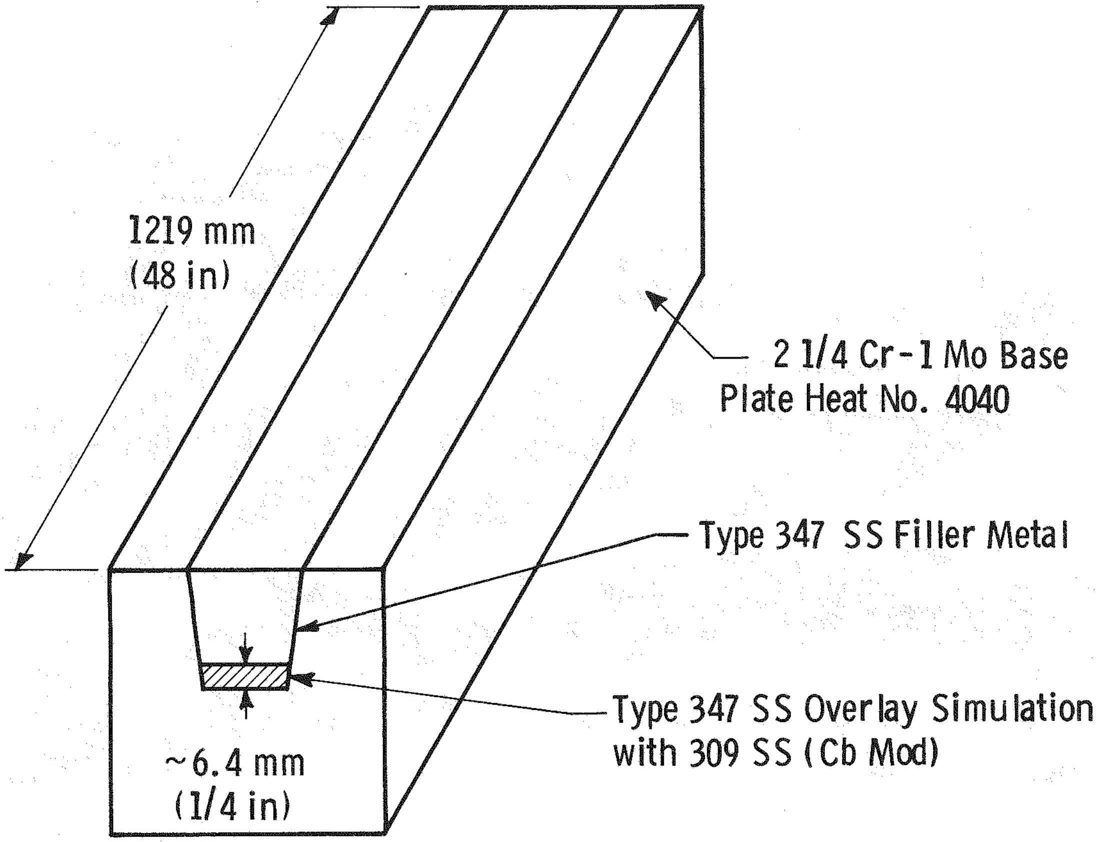

Fig. 1-3—Type 347 stainless steel overlay weldment simulating pressure vessel wall cladding

TABLE 1-1

BASE PLATE CHEMISTRIES FOR 2¼Cr-1Mo STEEL

(From Lukens Steel Company)

Heat No.	C	Mn	P	S	Cu	Si	Ni	Cr	Mo
3324	.13	.47	.016	.019	.08	.23	.07	2.36	1.08
3596	.12	.42	.013	.020	.16	.25	.14	2.48	1.06
7868	.12	.47	.010	.017	.12	.22	.22	2.26	.99
3707	.12	.45	.014	.015	.12	.21	.11	2.28	1.05
4040	.12	.45	.010	.025	.17	.23	.24	2.27	.99

ASTM Specification for 2¼Cr-1Mo Steel

min.		.27						1.88	.85
max.	.15	.63	.035	.035	--	0.50	--	2.62	1.15

TABLE 1-2

TENSILE AND IMPACT PROPERTIES FOR 2¼Cr-1Mo STEEL

(From Lukens Steel Company)

		Tensile Properties					Charpy V-Notch Impact		
Heat No.	Grade	Test Temp. °F (°K)	Yield Strength ksi (MPa)	Tensile Strength ksi (MPa)	% Elong. 2 in.	% RA	Test Temp. °F (°K)	Impact Energy ft-lb (J)	Fracture Appearance % Shear
3324	SA387	RT	69.2 (477)	85.7 (591)	27.5	75.4	50 (283)	142 (193)	80
							210 (372)	143 (194)	99
3596	SA387	RT	71.5 (493)	86.3 (595)	24.0	65.7	50 (283)	99 (134)	80
							210 (372)	134 (182)	99
7868	SA542	RT	67.8 (467)	81.8 (564)	20.5	73.1	50 (283)	126 (171)	99
		850 (727)	52.9 (365)	66.5 (459)	23.0	68.0			
3707	SA542	RT	69.8 (481)	86.4 (596)	25.0	73.4	50 (283)	98 (133)	70
		850 (727)	52.1 (359)	64.1 (442)	20.5	70.1			
4040	SA387	RT	69.5 (479)	86.7 (598)	22.0	68.5	50 (283)	98 (133)	70
		850 (727)	55.7 (384)	66.5 (459)	21.0	65.2			

Heat Treatment

a) 1227°K ± 14°K (1750°F ± 25°F) - .394 hr/cm soak time
Program cooled per CB&I cooling curve for full thickness plate

b) Temper 955°K (1260°F) - .394 hr/cm, air cool

c) Stress relieved
866°K (1100°F) - 15 hrs
922°K (1200°F) - 24 hrs
964°K (1275°F) - 15-18 hrs.

TABLE 1-3

HEAT TREATMENT FOR 2-1/4Cr-1Mo WELDMENTS

A. SA387 Class 2, Grade 22 Steel

Base Plate Heat Treatment

Normalize	1227°K	(1750°F)	5-1/2 hrs.	A.C.
Temper	964°K	(1275°F)	(1 hr/in.)	

Post Weld Heat Treatment

	866°K	(1100°F)	15 hrs.
	922°K	(1200°F)	22 hrs.
	964°K	(1275°F)	18 hrs.

B. SA542 Class 3 Steel

Base Plate Heat Treatment

Austenitize	1227°K	(1750°F)	5-1/2 hrs.	W.Q.
Temper	936°K	(1225°K)	(1 hr/in.)	

Post Weld Heat Treatment

	866°K	(1100°F)	15 hrs.
	922°K	(1200°F)	22 hrs.
	936°K	(1225°F)	18 hrs.

C. Type 347 SS Overlay Fabrication Process

Austenitize	1227°K	(1750°F)	5-1/2 hrs.
Temper	964°K	(1275°F)	7 hrs.
Temper	922°K	(1200°F)	15 hrs.
Weld first layer with 309 CB			
PWHT	866°K	(1100°F)	4 hrs.
Weld balance with type 347 SS			
PWHT	866°K	(1100°F)	11 hrs.
	964°K	(1275°F)	10 hrs.

TABLE 1-4

WELDMENT EXAMINATION PROCEDURE APPLIED TO EPRI COAL CONVERSION PROCESS PROGRAM BY CB&I

Method	References	Acceptance Standards	Repairs
Ultrasonic	1974 ASME, Section VIII, Appendix II 1974 ASME Section V, Article 5	3/4-inch Max flaw length.	Reexamine repairs.
Magnetic Particle	1974 ASME, Section VIII, Appendix VI 1974 ASME, Section V, Article 7	All linear discontinuities are unacceptable.	After repair, the area will be blend ground and reexamined.
Liquid Penetrant	1974 ASME, Section VIII, Appendix VIII 1974 ASME, Section V, Article 6	Reject relevant linear indications. Reject 4 or more rounded defects separated by 1/16 inch or less.	Prior to repair, remove defect. Blend grind after repair and reexamine.
Radiographic Examination	1974 ASME, Section VIII	All lack of fusion is repaired. Indications greater than 3/4-inch, or periodic in line indications with total accumulated length greater than T. Porosity in excess of that allowed in Section VIII, Appendix IV is repaired.	Location and identification of unacceptable defects are recorded. Repair and reexamination.

TABLE 1-5

STEP COOLING PROCESS FOR TEMPER EMBRITTLEMENT TREATMENT

Step	Temperature Step	Hold Time	Cooling Rate Between Steps
1.	886°K (1100°F)	1 hr.	56°K/hr (100°F/hr)
2.	811°K (1000°F)	5 hrs.	5.6 (10)
3.	797°K (975°F)	10 hrs.	5.6 (10)
4.	769°K (925°F)	50 hrs.	2.8 (5)
5.	741°K (875°F)	75 hrs.	2.8 (5)
6.	727°K (850°F)	100 hrs.	2.8 (5)
7.	672°K (750°F)	100 hrs.	Furnace Cool to 616°K (650°F) Air Cool

TABLE 1-6

MATERIAL CHARACTERIZATION PLAN

Tensile Tests	Room Temperature	Room Temp. to 727°K (850°F) @ ¼ Thickness
SA387	WM, BM	WM, BM
SA387 Temper Embrittled	WM	
SA542	WM, BM	WM, BM
Type 347 Overlay	HAZ*	WM
SA387 Under 347 Overlay	BM	BM

Charpy V Tests	Room Temperature	Transition Temp. Curve @ ¼ Thickness
SA387	WM, BM, HAZ	BM, WM
SA387 Temper Embrittled	WM	WM
SA542	WM, BM, HAZ	BM
Type 347 Overlay	WM, HAZ	
SA387 Under 347 Overlay	BM	BM

NDT Tests

SA387 - Base and Weld Metal
SA387 - Base Metal under 347 Overlay
SA542 - Base Metal

Micro Examinations	Examine at Surfaces, ¼T + Center
SA387	BM
SA542	BM
Type 347 Overlay	BM, WM, HAZ

Measure Percent Ferrite - A347 SS Overlay

WM - weld metal, 347 SS filler
HAZ - 1st layer of 309 Cb

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*347 HAZ is the first layer of 309 Cb stainless filler metal.

Section 2

MECHANICAL PROPERTIES

Material characterization was conducted in two steps; the first was the mechanical evaluation of through the thickness tensile properties of all base plates and weld metal and through the thickness Charpy impact property tests on base plates, weld metal, and heat affected zone, HAZ. This first step in the material characterization plan was conducted to see if the weldments were acceptable from a uniformity of mechanical properties standpoint and to select the base plates which were to be used for the fracture mechanics tests. The sampling plan for tensile and Charpy characterization is given in Figure 2-1.

Nine tensile specimens were tested through the thicknesses from the top surface to the bottom surface on both base plates and the weld metals in the SA387 and SA542 weldments. The base metal round tensile specimens were 9.0 mm (0.357 in.) diameter. The weld metal tensile specimens contained a reduced diameter of 6.4 mm (0.252 in.).

Nine Charpy V-notch impact specimens were tested at locations between 1/8-thickness and 7/8-thickness for base plates, weld metal and HAZ. The notch orientation is described as T-L according to the convention prescribed in ASTM standard E399 (2).

The samping plan for the 347 SS tensile and Charpy specimens is shown in Figure 2-2. The tensile specimens were reduced diameter 6.4 mm (0.252 in.) type and they were taken in the first pass section of the weldment labeled HAZ. Charpy specimens were taken from both the first pass section and filler section of the weldment, and for HAZ, the notch tip lies 3.8 mm (0.15 in.) from the fusion line as shown. The SA387 underlying vessel material was also fully tested for supplemental information purposes, Heat 4040.

EVALUATION FOR UNIFORMITY OF PROPERTIES-ROOM TEMPERATURE TESTS

Charpy

Results from the first step (all room temperature) in the material evaluation phase are averaged in Tables 2-1 through 2-3, and results are identified with respect to slab position in Figures 2-3 through 2-9.

In Figure 2-3 for SA387 base plates (Heat Nos. 3324 and 3596), one plate, 3596, showed fairly consistent CVN energies from surface to center, whereas base plate 3324 showed a tendancy toward reduced impact toughness properties at the surfaces. The Charpy impact properties for the SA387 weld metal and HAZ (taken on the 3596 side) indicated that the weakest link from the standpoint of toughness is the weld metal. See Figure 2-4. Judging from the percent brittle numbers in Table 2-1 and Figures 2-3 and 2-4, room temperature is slightly into the transition temperature range for these SA387 weld and base metals.

In Figure 2-5, Charpy impact properties for the two SA542 base plates (Heat Nos. 7868 and 3707) are given. These materials showed acceptable uniformity of toughness from surface to center. Charpy impact of weld metal and HAZ (on 7868 base plate side) are given in Figure 2-6. Again the weakest link with regard to impact toughness is the weld metal. These properties are averaged in Table 2-2. Note, however, that according to the % brittle indication, room temperature is in the transition temperature range for weld metal and into upper shelf behavior for both base metals and HAZ. Since the transition temperature for SA542 is below room temperature, these CVN energies cannot be fairly compared to the SA387 results that are in the transition range.

Tensile Tests

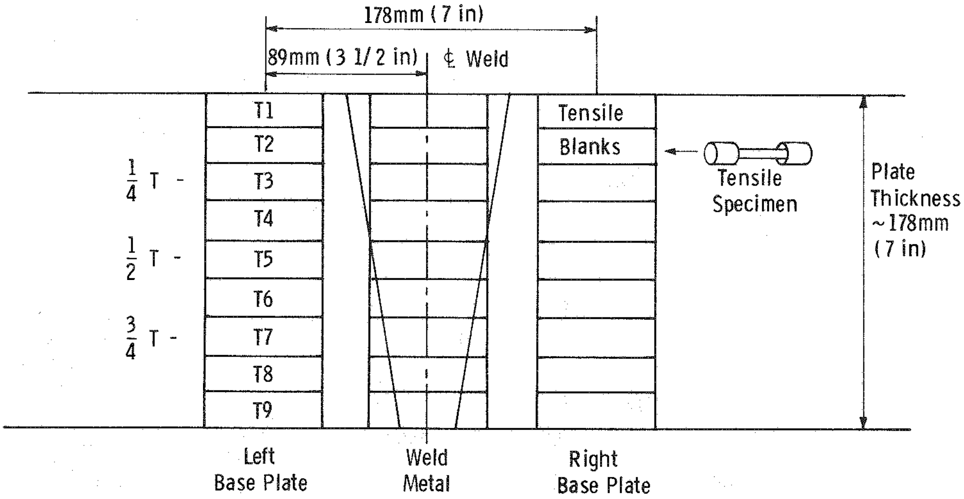
The tensile property values for the SA387 base plates are summarized in Table 2-1, and are plotted against position in Figure 2-7. The base plate, Heat No. 3596, shows the greatest variability in strength from surface to center, and hence would appear to be a second choice among the two for the extensive testing in fracture mechanics evaluations. However, the yield strength of the central part is more nearly the strength level representative of SA387. Also the CVN toughness was reasonably uniform throughout. Therefore Heat 3596 was chosen and the fracture mechanics type specimens were only taken between the 1/4 and 3/4 plate thickness positions.

Table 2-2 lists the averaged tensile properties of the SA542 plate materials and through thickness trends are plotted in Figure 2-8. Here the uniformity of through-thickness properties is excellent for both base plates. The choice was arbitrarily made on Heat No. 7868. The practice of obtaining fracture mechanics specimens from between 1/4 and 3/4 plate thickness positions was maintained here also despite the fact that this may have been unnecessary.

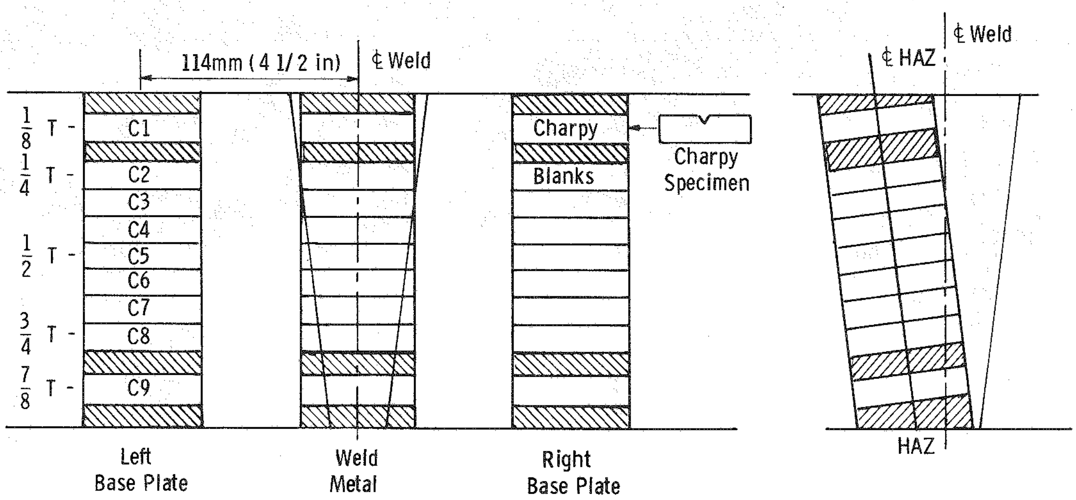
Tensile properties for weld metal from the SA387 and SA542 weldments are plotted in Figure 2-9. The strength difference obtained between the SA542 weld metal and SA387 weld metal is mainly due to PWHT at 936°K (1225°F) versus 964°K (1275°F).

Charpy impact and tensile properties for the 347 SS weld overlay simulation are given in Table 2-3. Again, HAZ refers to the first layer of 309 Cb weld filler metal and weld metal is for the remaining 347 SS filler layers. The impact tests were made at 399°K (150°F) to be at a temperature for optimum basis of comparison. These materials had surprisingly low toughness, considering that the basic structure is high strength austenitic stainless. Only the higher toughness HAZ condition is being evaluated in the fracture mechanics part of the program.

After these materials (SA387, SA542 and 347 SS) were judged acceptable from the first step in this program, machining was begun for the fracture mechanics type specimens. The sampling plan is covered in the first annual report. The second step in the material characterization was then initiated. This step included tensile testing through the entire temperature range planned for the fracture mechanics testing, development of Charpy impact transition temperature curves, determination of the nil-ductility-temperature, NDT, and microstructural evaluations.

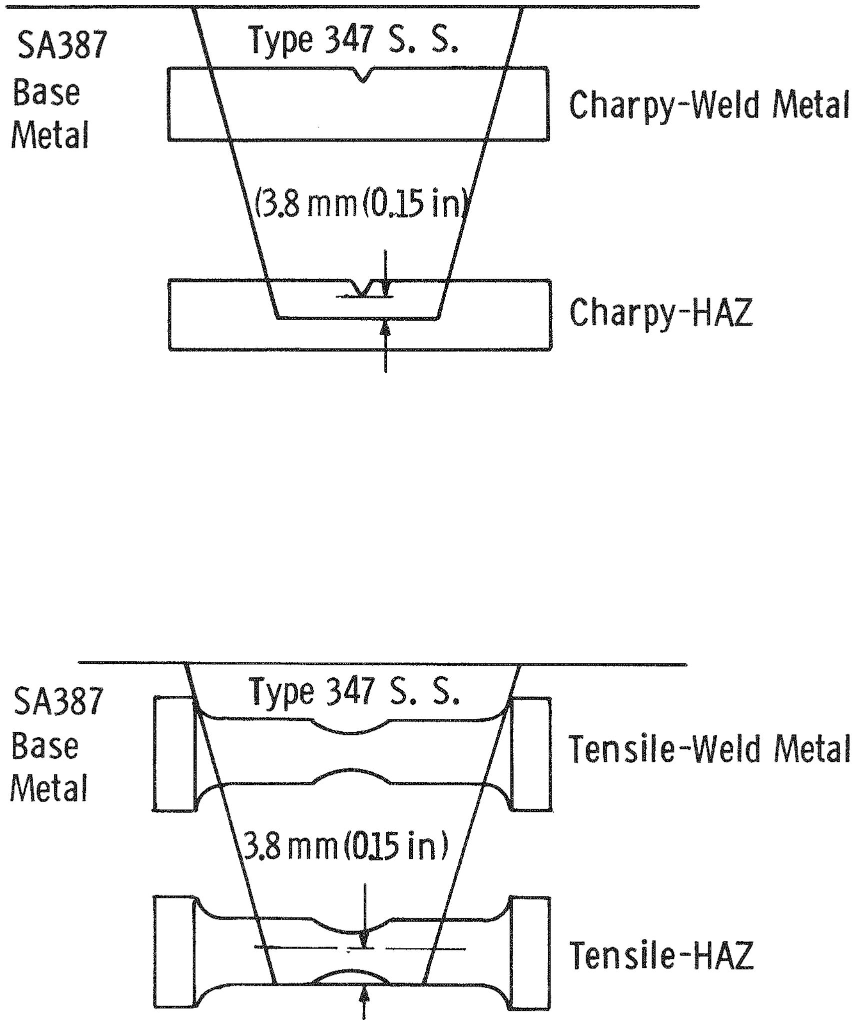


a) Schematic of Through Thickness Tensile Specimen Selection (Weld metal specimens contain a reduced parallel section with a 6.4mm (0.252 in) diameter over a 6.35mm (0.250) gage length)



b) Schematic of Through Thickness Charpy "V" Notch Specimen Selection (Notch direction is described as T-L according to ASTM E399 convention)

Fig. 2-1—Through plate thickness selection of tensile and Charpy "V" notch specimens for SA387 and SA542 weldments



Reduced Diameter and
Gage Length Tensiles
as per Fig. 5a

Fig.2-2—Tensile and Charpy "V" notch specimens for Type 347 SS overlay

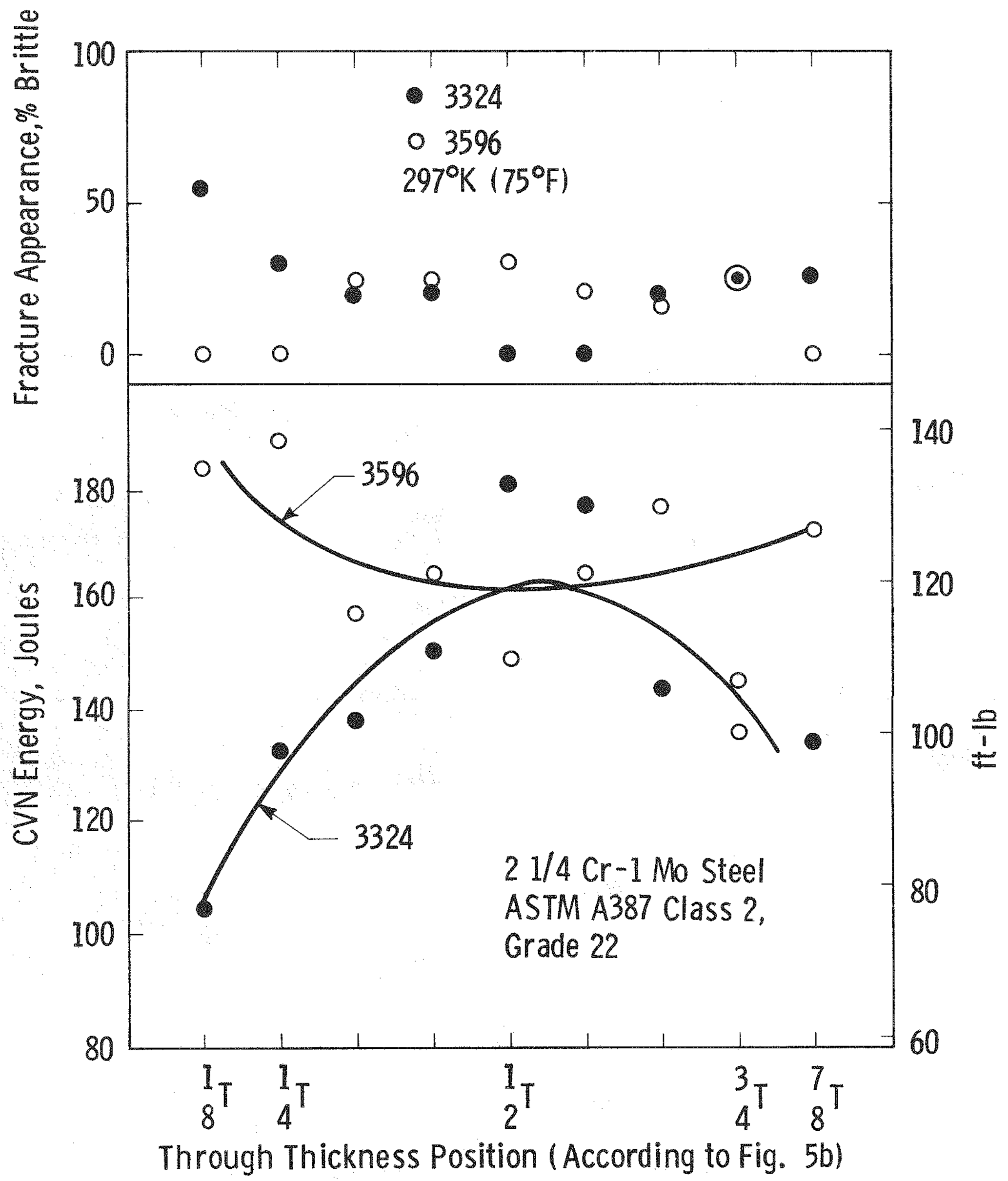


Fig.2-3— Through plate thickness charpy "V" notch impact tests for SA387 base plates (T-L Orientation)

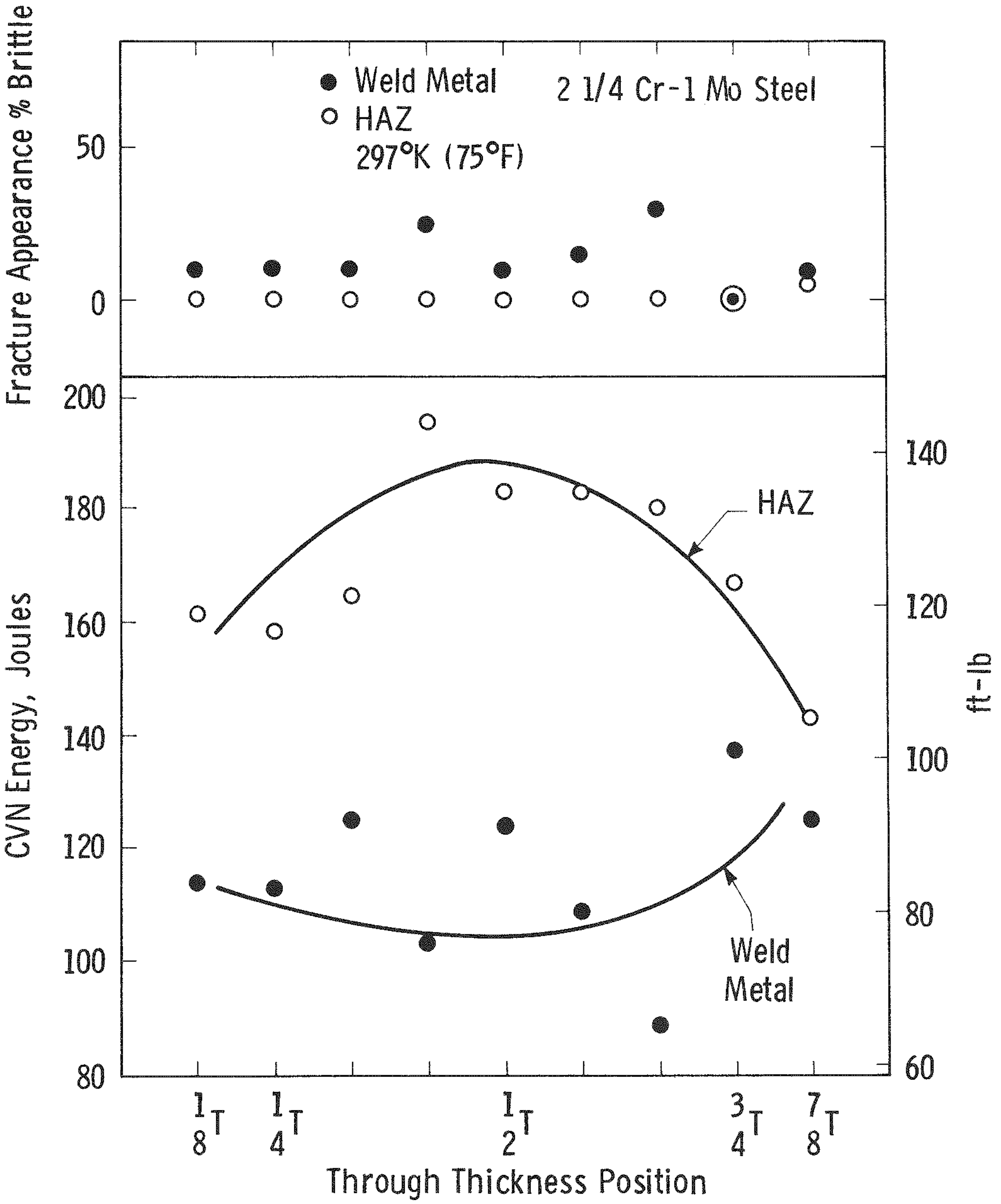


Fig. 2-4—Through plate thickness charpy "V" notch impact tests for SA387 weld metal and HAZ

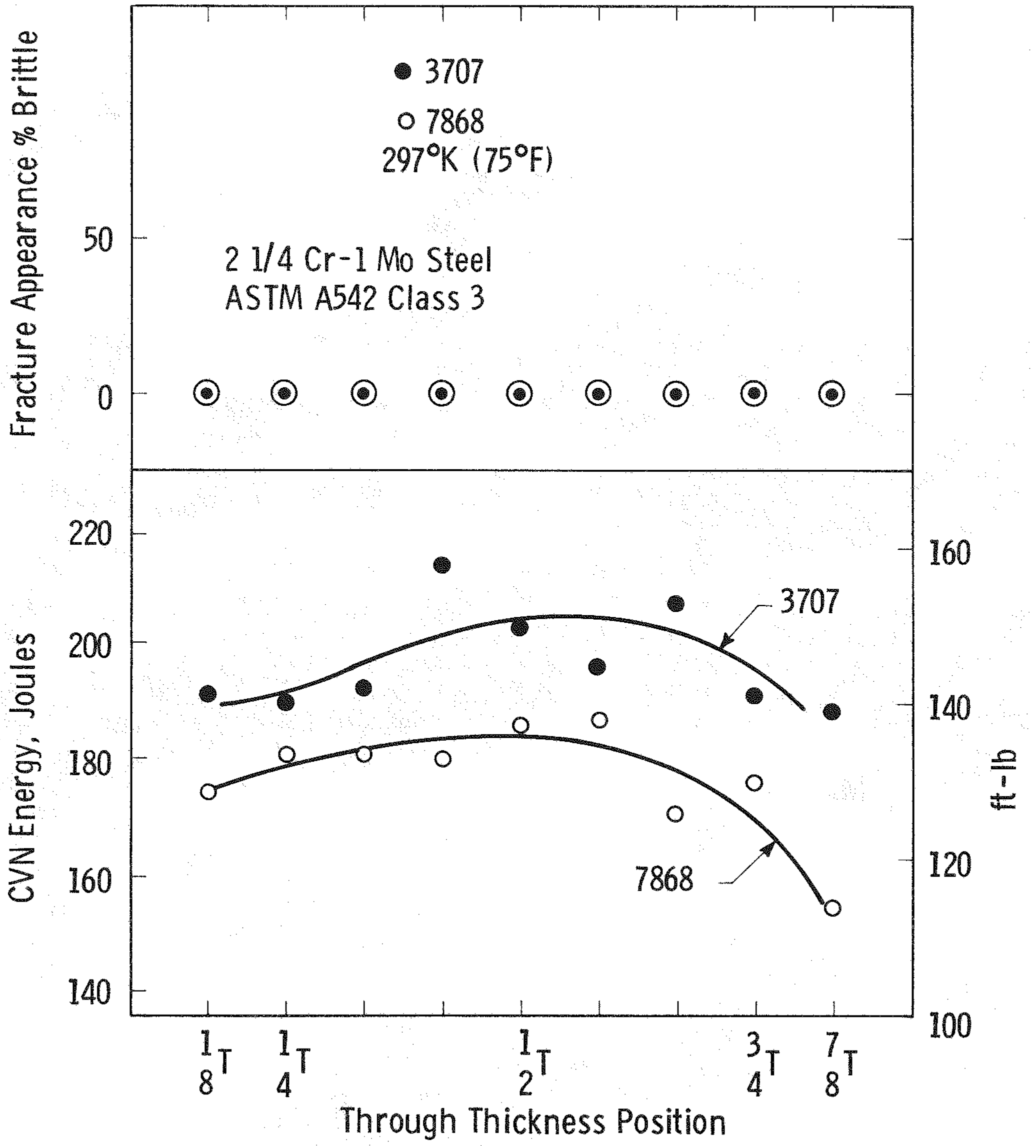


Fig. 2-5 —Through plate thickness charpy "V" notch impact tests for SA542 base plates (T-L Orientation)

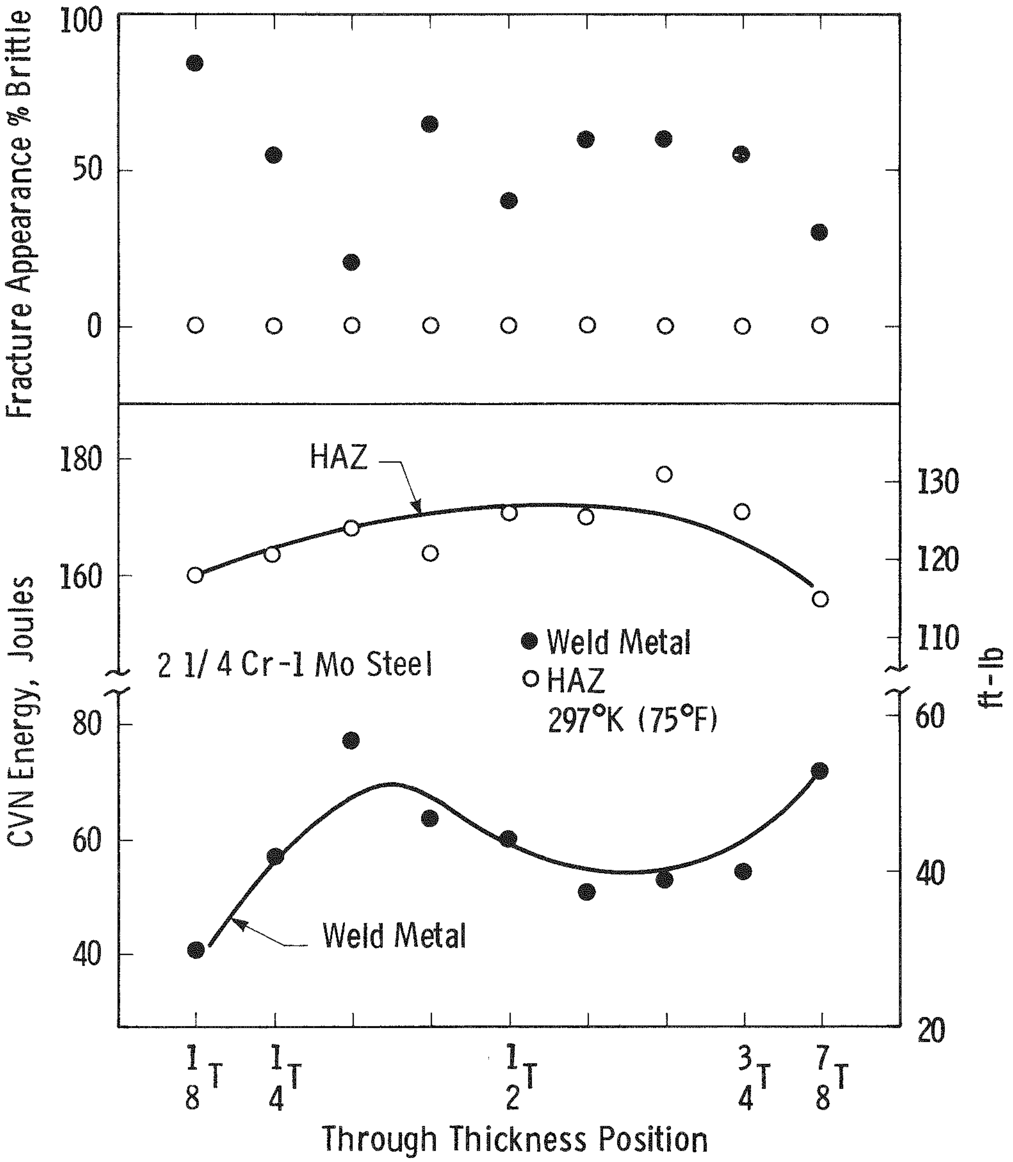


Fig. 2-6— Through plate thickness charpy "V" notch impact tests for SA542 weld metal and HAZ

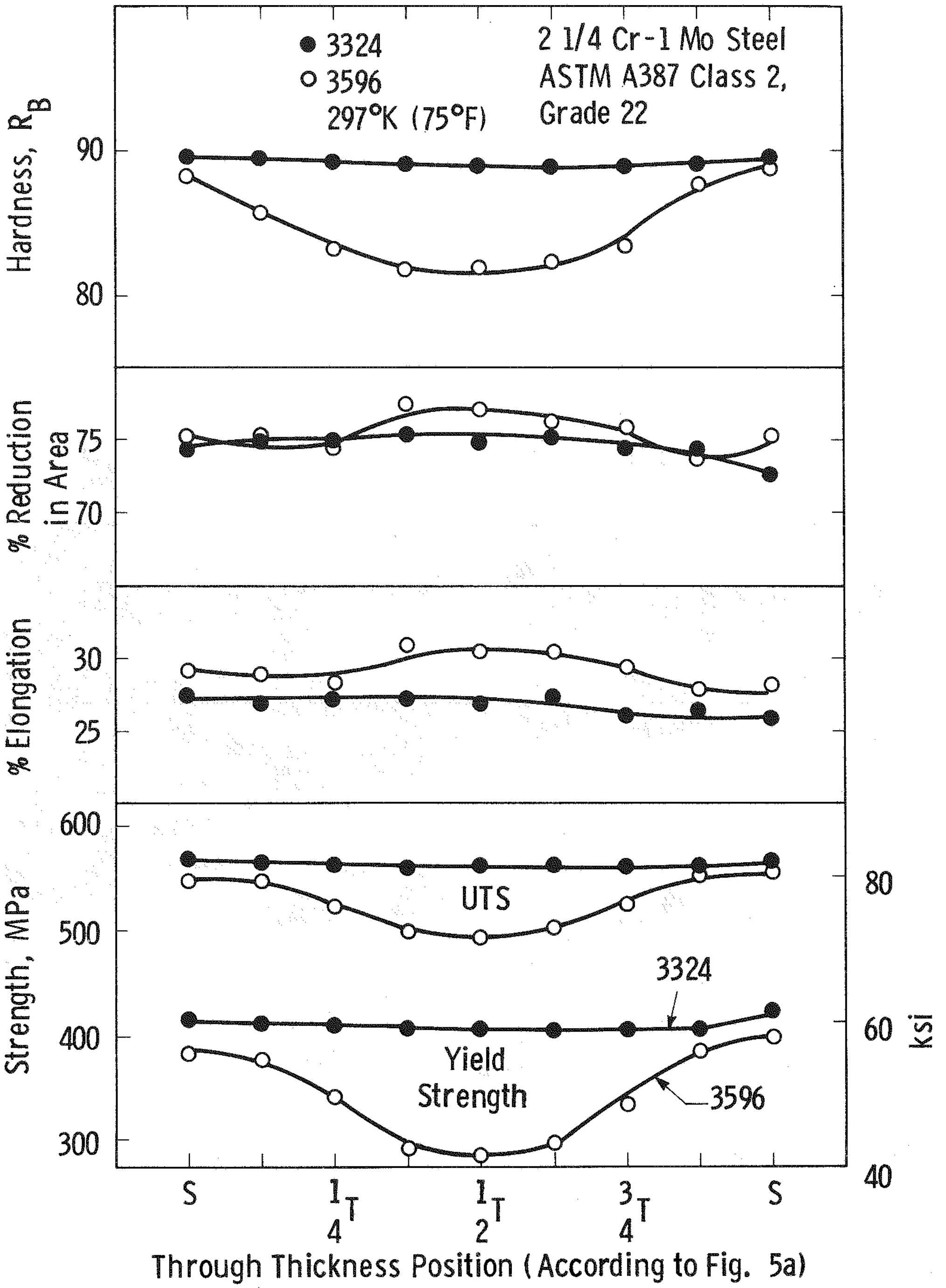


Fig. 2-7— Through plate thickness tensile properties and hardness for SA387 base plates

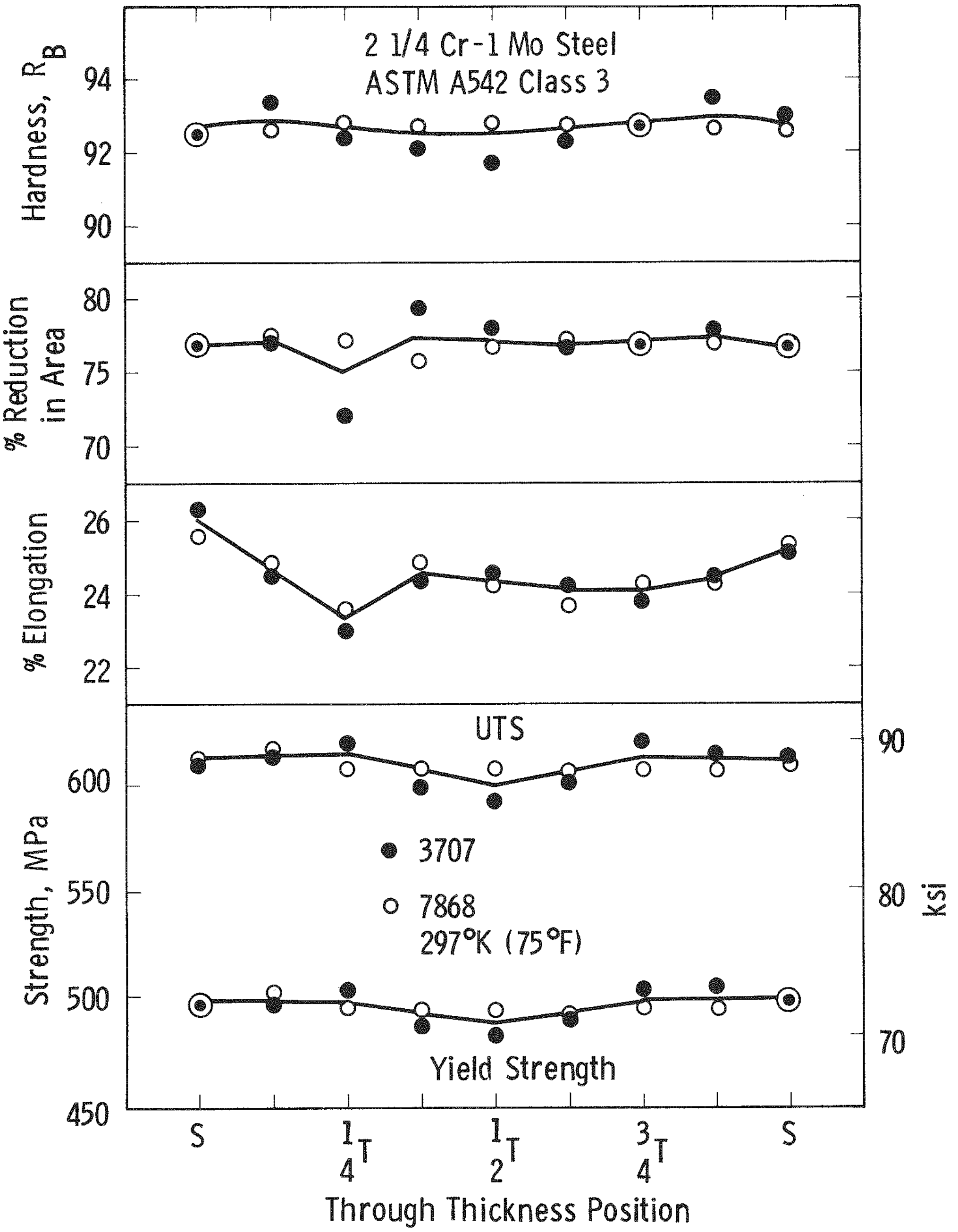


Fig. 2-8— Through plate thickness tensile properties and hardness for SA542 base plates

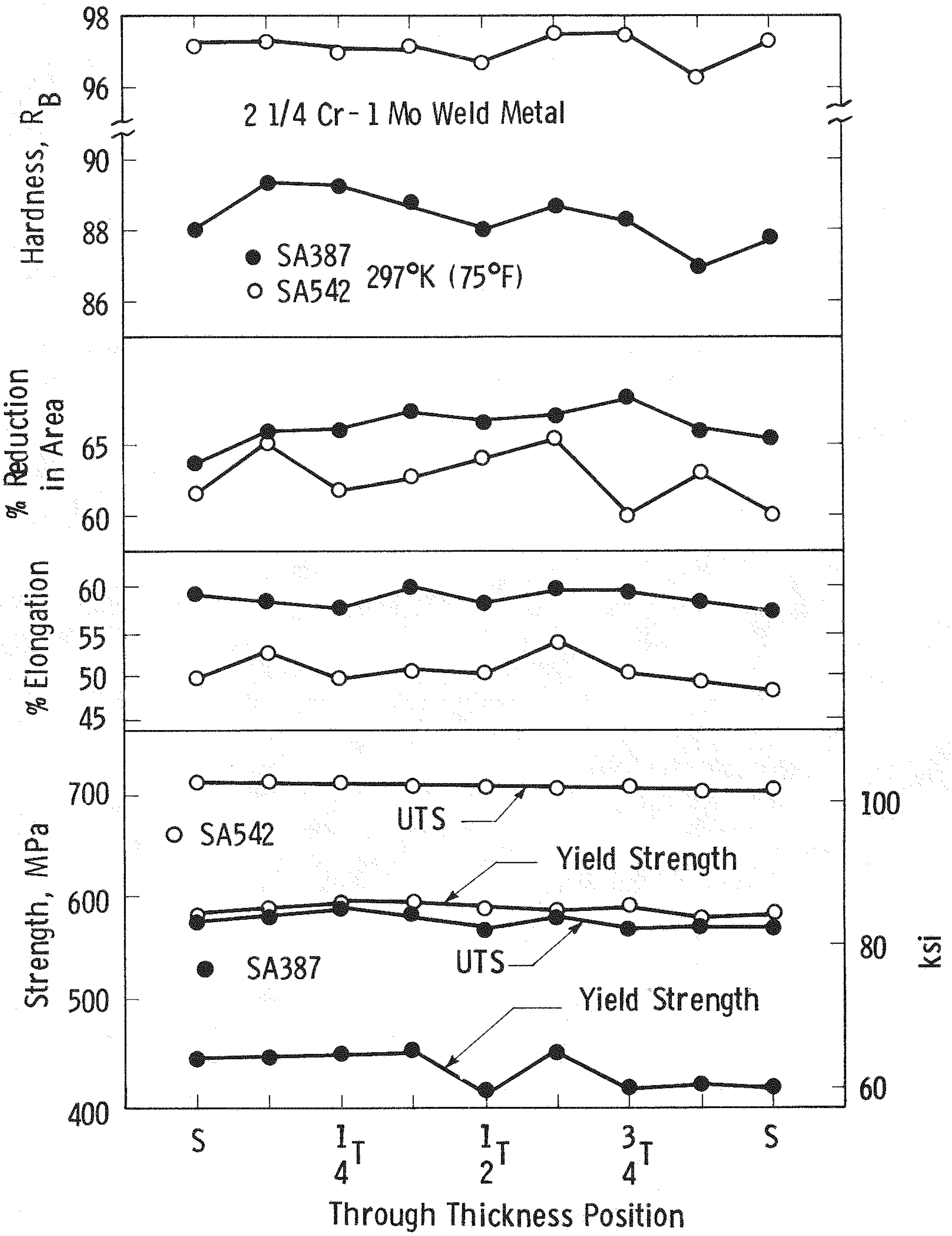


Fig.2-9 — Through plate thickness tensile properties and hardness for SA387 and SA542 weld metal

TABLE 2-1

SUMMARY OF THROUGH PLATE THICKNESS MECHANICAL PROPERTIES FOR SA387 WELDMENT AT 297°K (75°F)

Mechanical Property	Plate 3596	Plate 3324	Weld Metal	Temper Embrittled Weld Metal	HAZ	SA387 Class 2, Grade 22 Code Minimum
Charpy Impact:						
Energy - Joules	165 ± 23*	144 + 39	115 ± 27	29	171 + 27	
(ft-lb)	(122 ± 17)	(106 ± 29)	(85 ± 20)	(21.5)	(126 ± 20)	
% Brittle	16 ± 16	23 ± 34	14 ± 18	90	0 ± 0	
Lateral Expansion - mm	2.36 ± 0.25	2.06 ± 0.41	1.98 ± 0.48	.56	2.41 ± 0.18	
(mils)	(93 ± 10)	(81 ± 16)	(78 ± 19)	(22)	(95 ± 7)	
Tensile:						
Yield Strength - MPA	345 ± 57	411 ± 14	423 ± 10	435		310
(ksi)	(50.1 ± 8.3)	(59.7 ± 2.0)	(61.4 ± 1.4)	(63)		(45)
UTS - MPa	528 ± 33	563 ± 4	575 ± 12	578		517-690
(ksi)	(76.6 ± 4.8)	(81.7 ± 0.6)	(83.4 ± 1.8)	(82.7)		(75-100)
% Elongation†	29.4 ± 1.4	26.9 ± 1.1	58.7 ± 1.5	59.3		18
% RA	75.7 ± 1.9	74.5 ± 1.9	66.2 ± 2.5	67.2		45
Hardness - R_B	84.8 ± 3.9	89.2 ± 0.5	88.3 ± 1.3	--		

*Average of nine tests ± maximum variation from the average.

†% Elongation is measured over a 44 mm (1.75 in.) G.L. for base metal specimens and over a 6.4 mm (0.25 in.) G.L. for weld metal specimens.

TABLE 2-2

SUMMARY OF THROUGH PLATE THICKNESS MECHANICAL PROPERTIES FOR SA542 WELDMENT AT 297°K (75°F)

Mechanical Property	Plate 7868	Plate 3707	Weld Metal	HAZ	SA542 Class 3 Code Minimum
Charpy Impact:					
Energy - Joules	176 ± 22*	197 ± 18	58 ± 19	167 ± 11	
(ft-lb)	(130 ± 16)	(145 ± 13)	(43 ± 14)	(123 ± 8)	
% Brittle	0 ± 0	0 ± 0	54 ± 32	0 ± 0	
Lateral Expansion - mm	2.39 ± 0.22	2.36 ± 0.10	0.99 ± 0.25	2.31 ± 0.13	
(mils)	(94 ± 9)	(93 ± 4)	(39 ± 10)	(91 ± 5)	
Tensile:					
Yield Strength - MPa	497 ± 7	496 ± 8	586 ± 14		517
(ksi)	(72 ± 1.0)	(71.9 ± 1.2)	(85 ± 2.0)		(75)
UTS - MPa	610 ± 6	610 ± 17	705 ± 5		655-793
(ksi)	(88.4 ± 0.9)	(88.4 ± 2.4)	(102.3 ± 0.7)		(95-115)
% Elongation†	24.5 ± 1.1	24.5 ± 1.8	50.7 ± 3.1		20
% RA	76.9 ± 1.0	76.8 ± 6.8	62.6 ± 2.9		
Hardness - R_B	92.7 ± 0.2	92.6 ± 0.9	97.1 ± 0.4		

*Average of nine tests ± maximum variation from the average

†% Elongation is measured over a 44 mm (1.75 in.) G.L. for base metal specimens and over a 6.4 mm (0.25 in.) G.L. for weld metal specimens

TABLE 2-3

SUMMARY OF MECHANICAL PROPERTIES FOR TYPE 347 STAINLESS STEEL OVERLAY

Mechanical Property	Weld Metal	HAZ
Charpy Impact: 339°K (150°F)		
Energy - Joules	30 ± 3*	77 ± 15
(ft-lb)	(22 ± 2)	(58 ± 11)
Laterial Expansion - mm	0.43 ± 0.05	1.37 ± 0.15
(mils)	(17 ± 2)	(54 ± 6)
Tensile: 297°K (75°F)		
Yield Strength - MPa		590 ± 7
(ksi)		(85.6 ± 1.0)
UTS - MPa		800 ± 11
(ksi)		(116 ± 1.6)
% Elongation†		37.2 ± 1.6
% RA		35.9 ± 4.8

*Average of three tests ± maximum variation from the average.

†6.4 mm (0.25 in.) G.L.

Section 3

TRANSITION TEMPERATURE EVALUATION

CHARPY & NDT

Charpy transition temperature curves were developed mostly on the materials that were slated for fracture mechanics testing. These were: SA387 Heat 3596 and SA387 weld metal in the as received condition and as temper embrittled. The SA387 used in connection with the 347 SS overlay simulation (Heat No. 4040) and the SA542, Heat 7868 base materials were also similarly characterized. Specimens for base metal evaluation were all taken at the 1/4 thickness location. The transition temperatures are listed in Table 3-1 and the test curves are shown in Figures 3-1 through 3-4. These curves indicate that the transition temperature for SA387 is very nearly at room temperature and that SA542 has slightly better toughness, having a transition temperature below room temperature. When both grades of base plate are evaluated at upper shelf, the impact energies and lateral expansion, L.E., indicate no difference.

The nil ductility test was performed on these same materials according to ASTM standard method E209 (3). See Table 3-1. Specimens of P3 size were used. It is of interest to observe that there evidently is no correlation between the Charpy 50% FATT and NDT temperature. This might have been anticipated since NDT sometimes tends to be an unreliable transition temperature indicator for heat treated grades of steels.

TEMPER EMBRITTLEMENT

A section of the SA387 weldment was given a step cooling temper embrittlement treatment according to Table 1-5. The extent of embrittlement is typically evaluated in terms of the shift in Charpy transition temperature and this is shown in Figures 3-5 and 3-6. See also Table 3-1. The step cooling treatment increased the 50% FATT temperature by about 67°K (120°F) in both cases which is typical for this grade of $2\frac{1}{4}$Cr-1Mo. The drastic loss in upper shelf toughness of the SA387 base material, however, is a disturbing observation that deserves careful consideration for design. The significance of this toughness loss is better evaluated by fracture mechanics tests which will be covered in other reports.

HIGH TEMPERATURE TENSILE PROPERTIES

The results of the tensile properties versus temperature are given in Tables 3-2, 3-3 and 3-4, and in Figures 3-7, 3-8 and 3-9. Except for the 347 SS overlay where duplicate specimens were tested, these tensile results are for single specimens. The temperature range covered is the same as that slated for fracture mechanics testing. It is evident that material strength is retained suitably at all temperatures up to 727°K (850°F) in all materials. There generally is slight loss in strength and a corresponding slight loss in ductility. The simulated 347 SS overlay suffered the greatest decrease in yield strength, and mostly above 616°K (650°F). This is better illustrated in Figure 3-10 which is a summary plot of the yield strengths for all the materials versus test temperatures.

The comparison of ductility for different materials is better made from percent reduction in area rather than the percent elongation. The percent elongation for base metal specimens is made relative to a 44 mm (1.75 in.) gage length and the tensile specimens for the weld metal contained a reduced section diameter 6.4 mm (.252 in.) over a 6.4 mm (0.25 in.) gage length. Consequently, the percent elongation is referenced to this reduced gage length which results in artifically higher percent elongation for weld metal specimens.

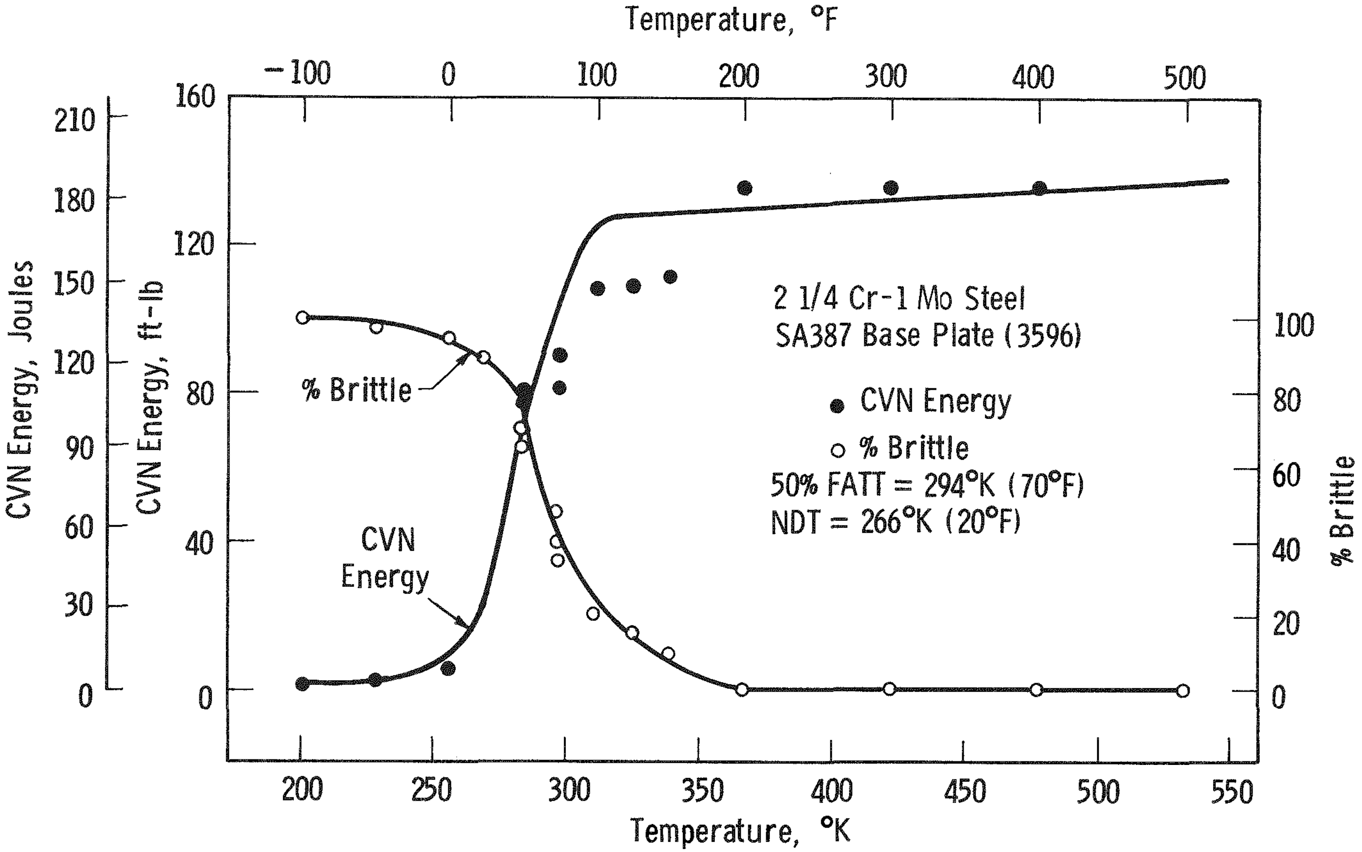


Fig. 3-1 — Charpy "V" notch impact properties of SA387 base plate versus temperature at 1/4 plate thickness (Heat 3596) (T-L Orientation)

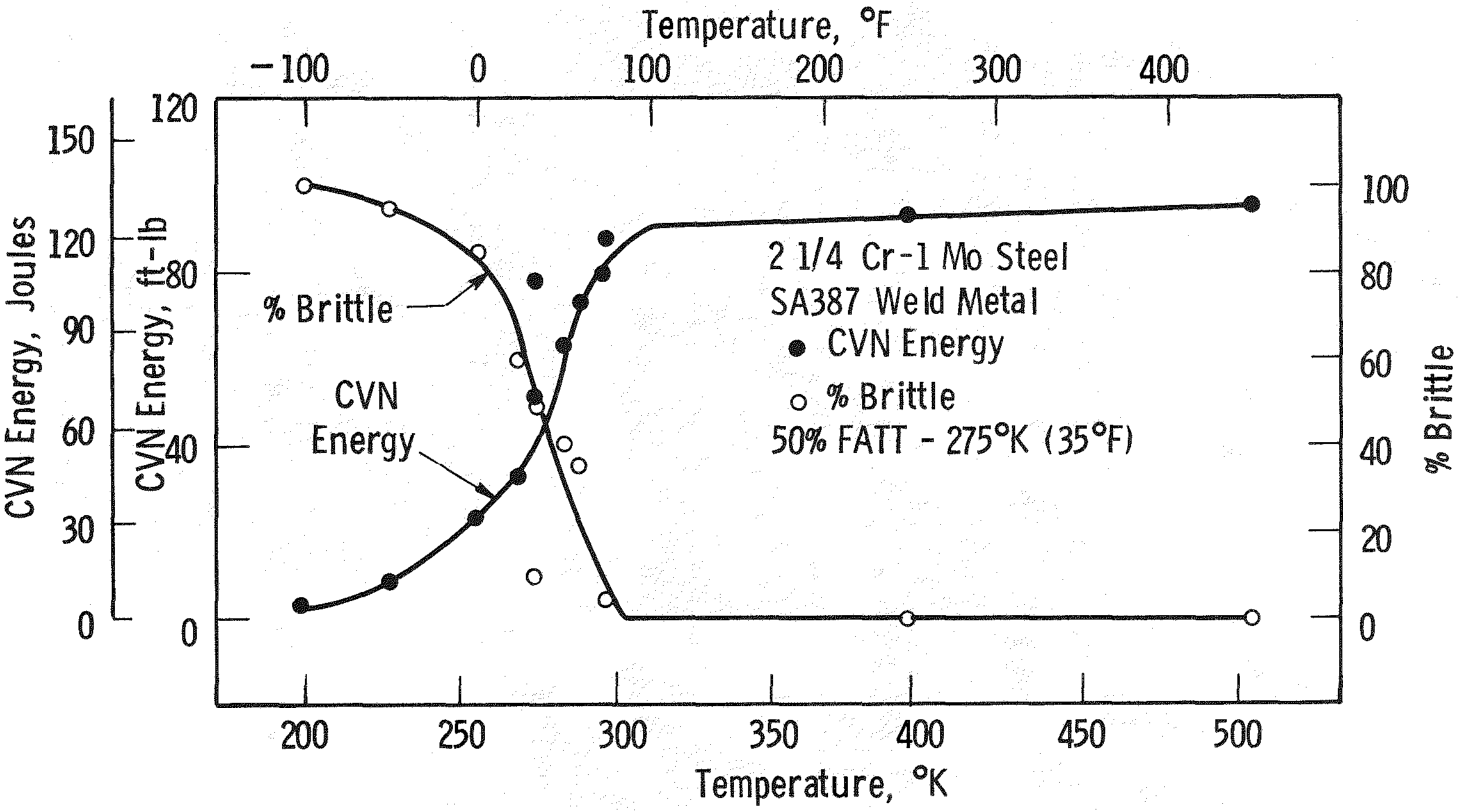


Fig. 3-2— Charpy "V" notch impact properties of SA387 weld metal versus temperature

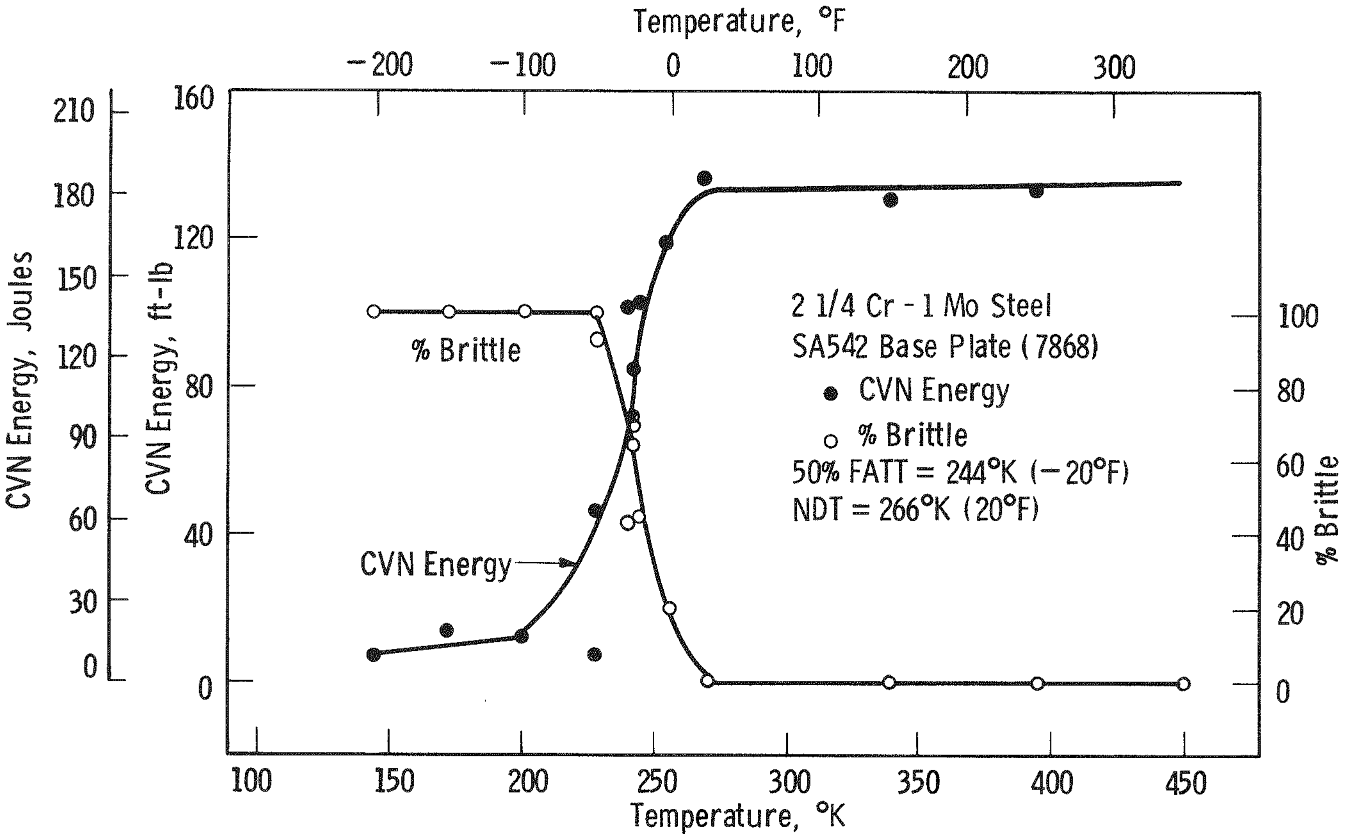


Fig. 3-3— Charpy "V" notch impact properties of SA542 base plate versus temperature at 1/4 plate thickness (Heat 7868) (T-L Orientation)

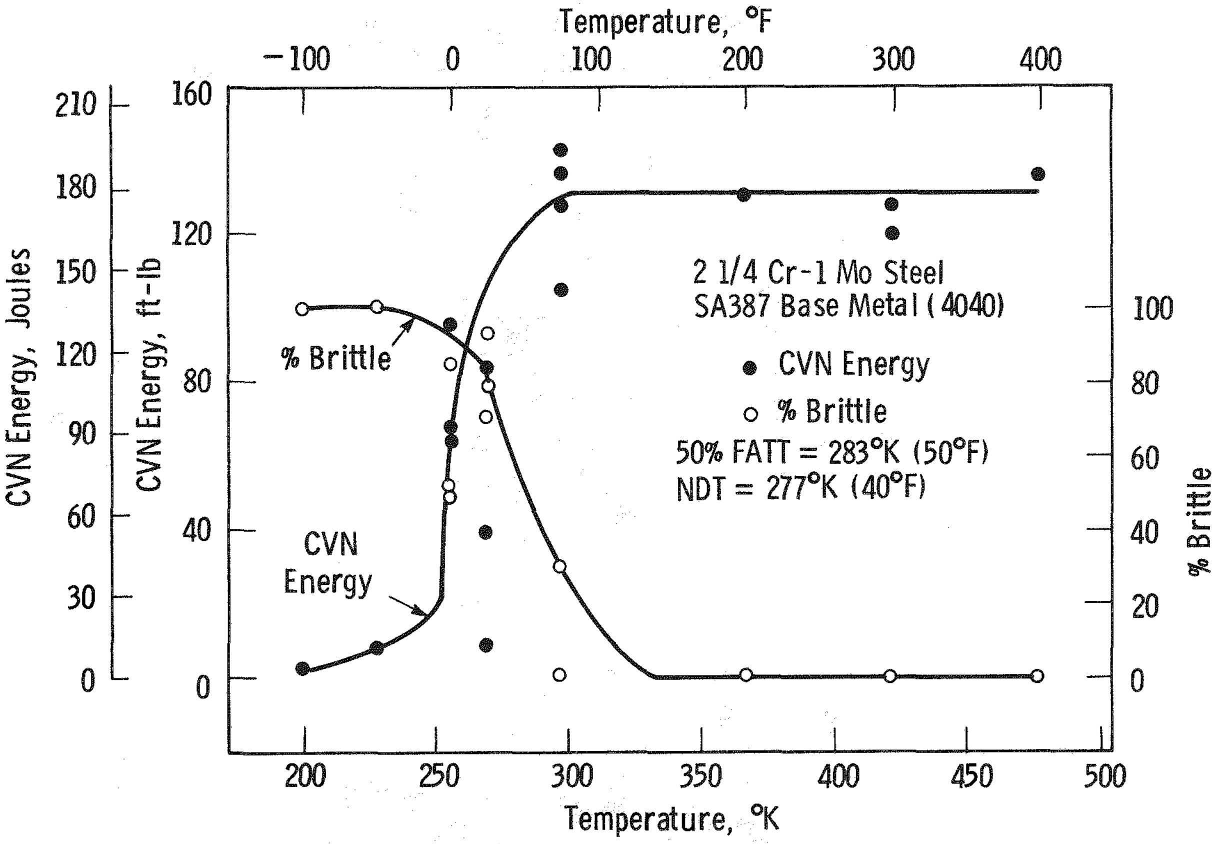


Fig. 3-4— Charpy "V" notch impact properties of SA387 base plate from the Type 347 S. S. overlay weldment (Heat 4040) versus temperature (T-L Orientation)

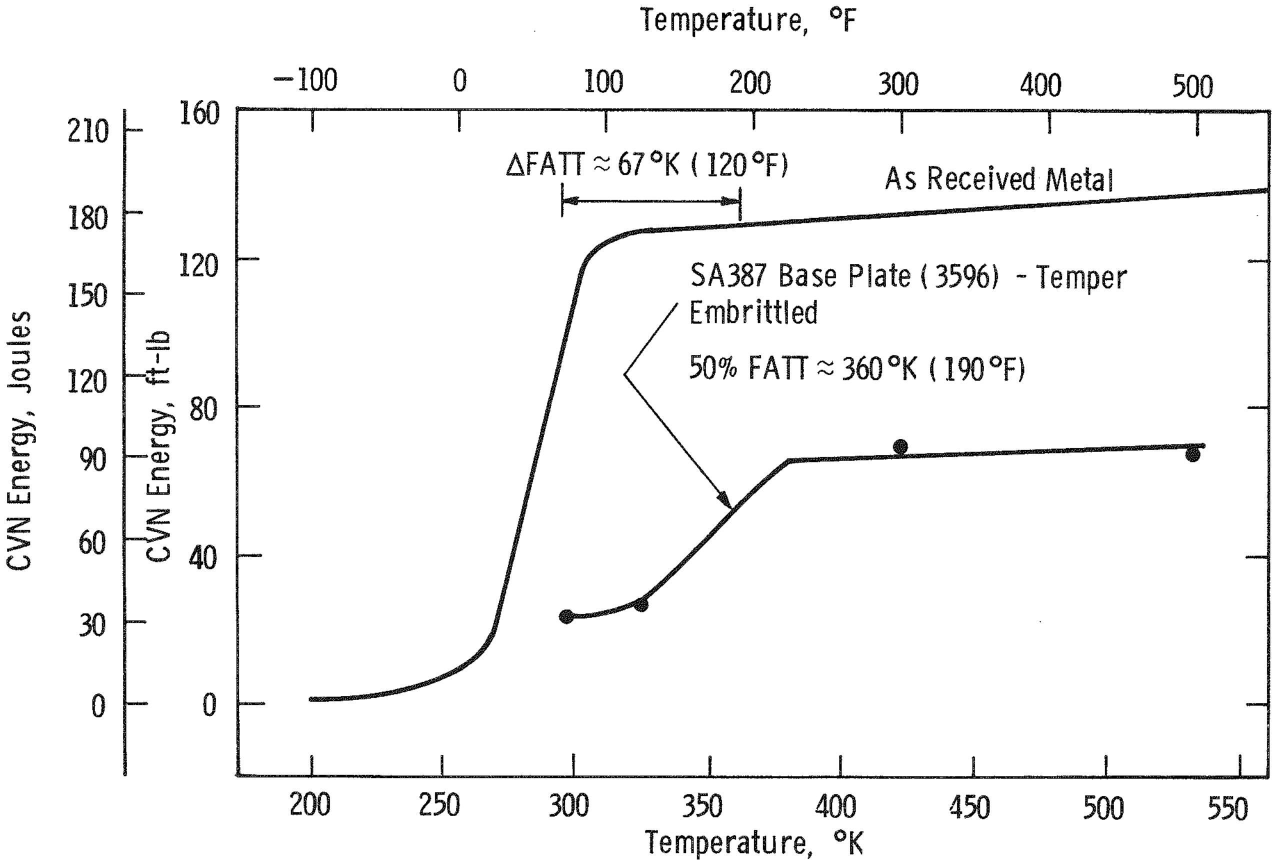


Fig. 3-5—Charpy "V" notch impact properties of temper embrittled SA387 base plate versus temperature (Heat 3596)

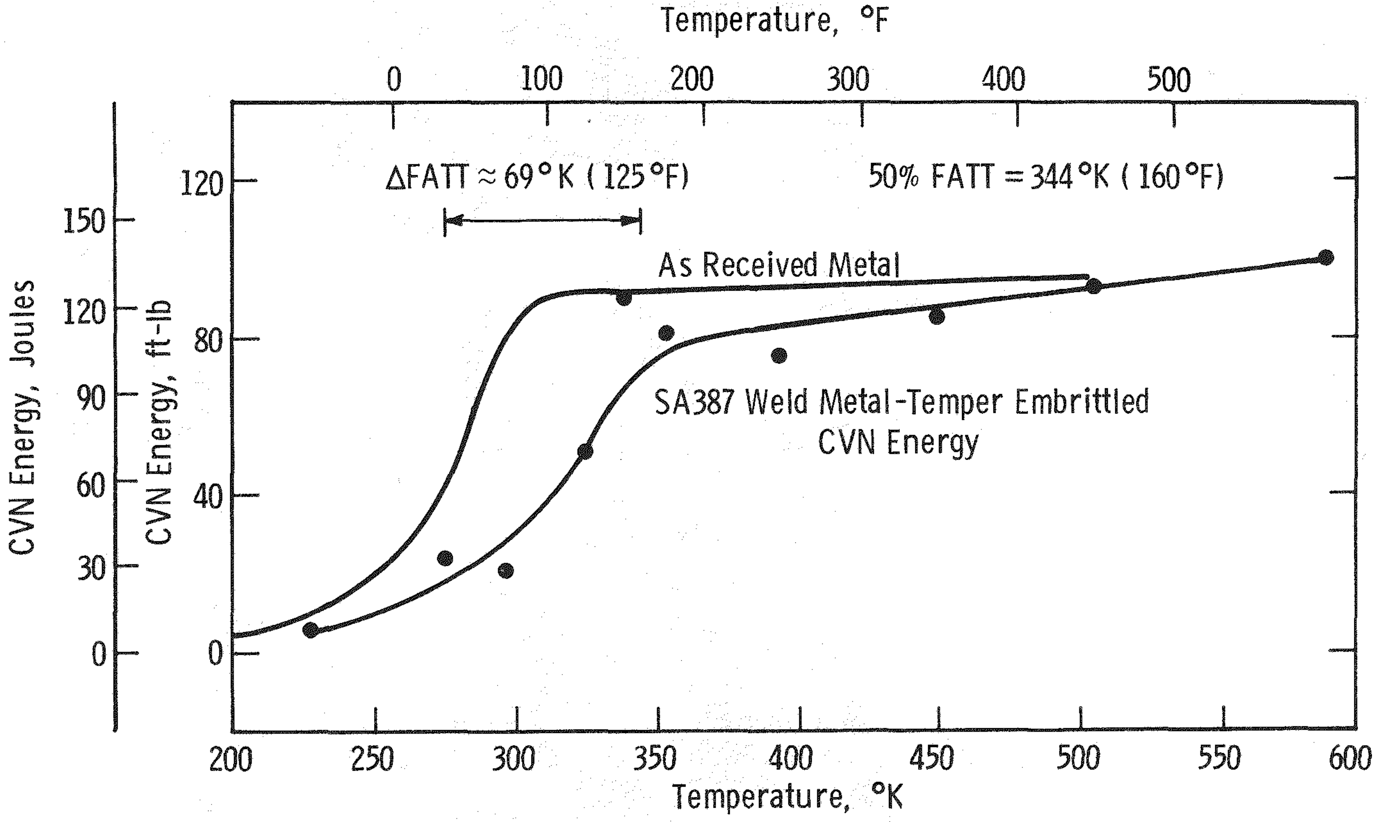


Fig. 3-6—Charpy "V" notch impact properties of temper embrittled SA387 weld metal versus temperature

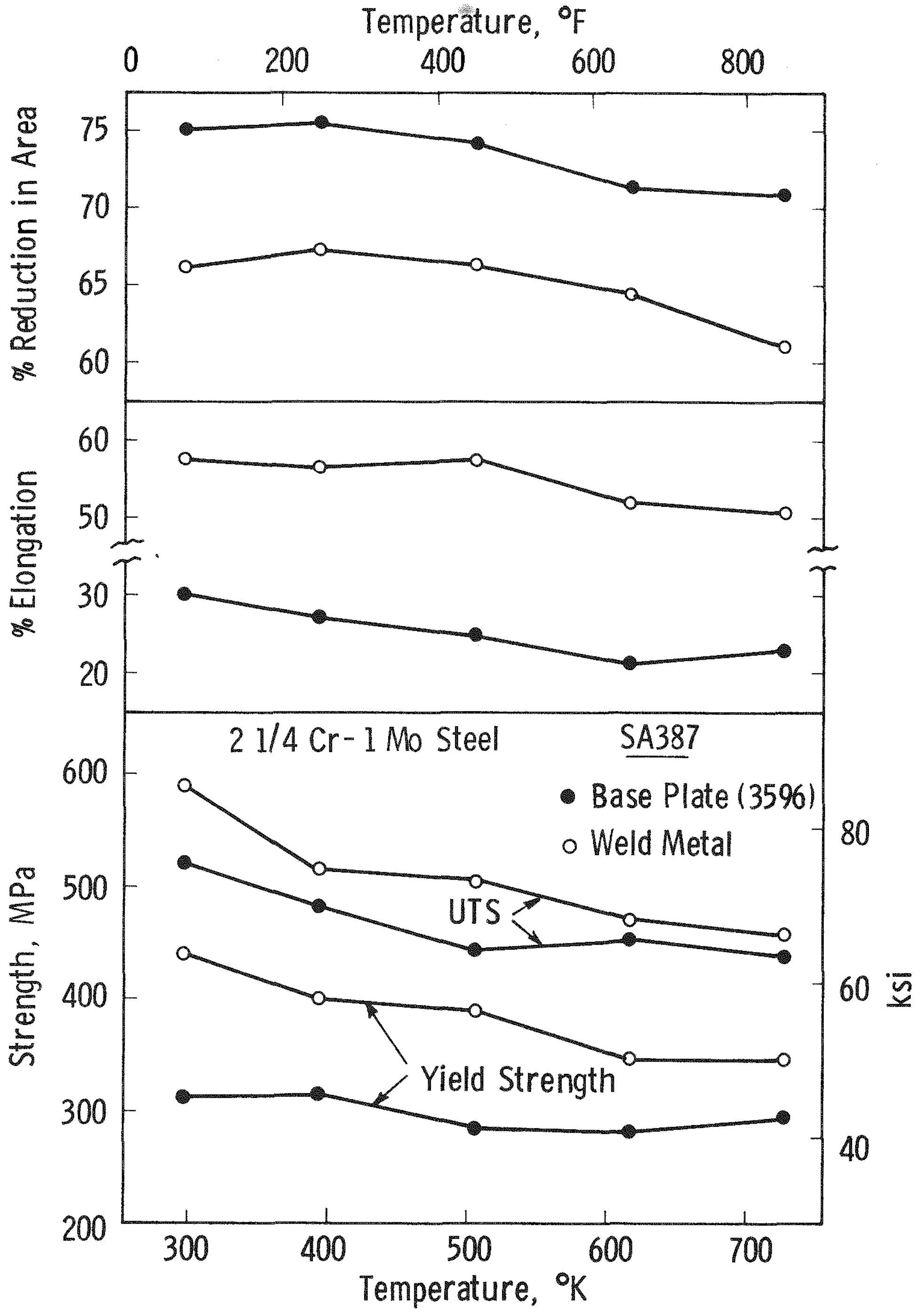


Fig. 3-7 – Tensile properties versus temperature for SA387 weld metal and base plate (Heat 3596)

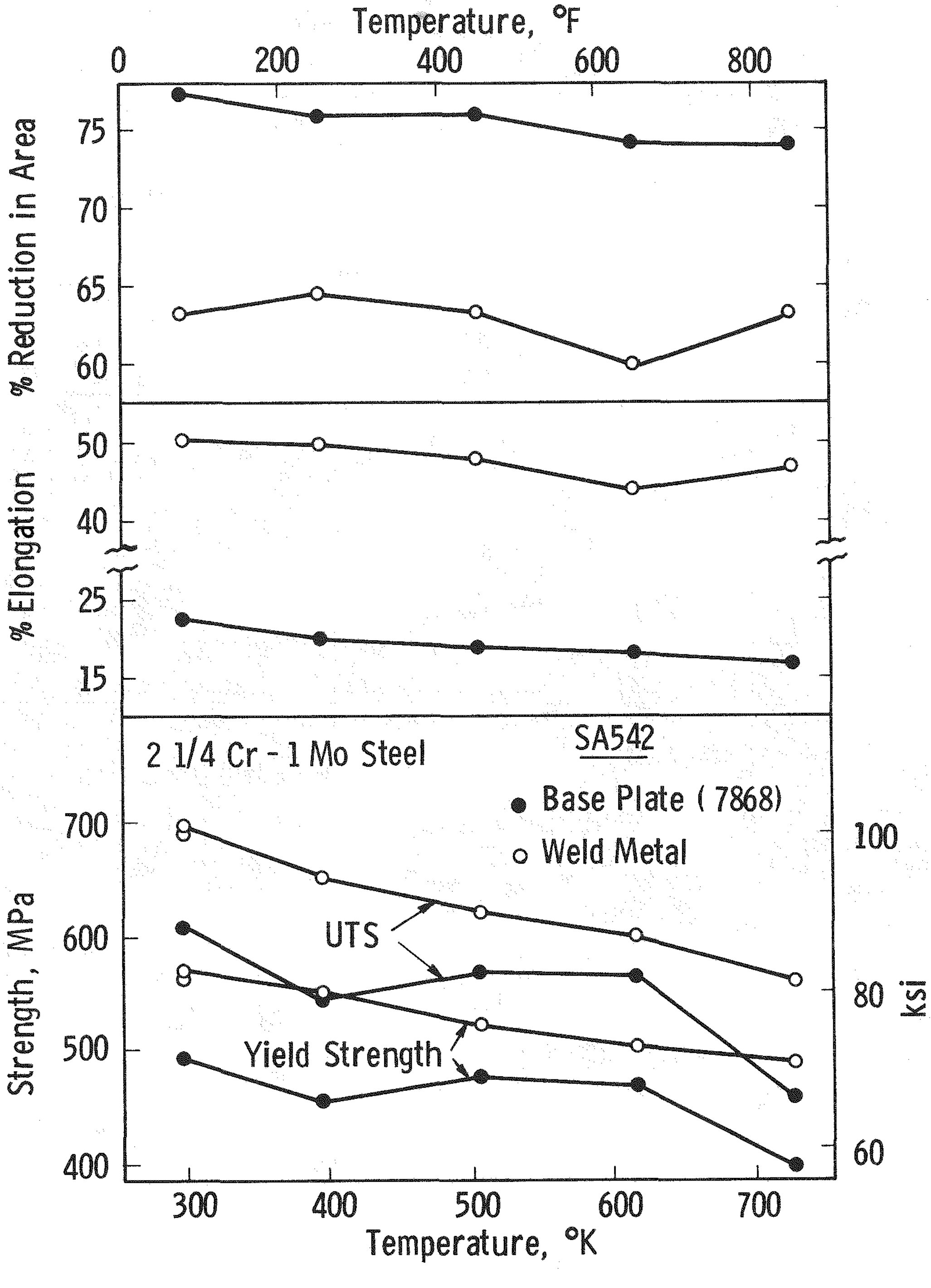


Fig. 3-8— Tensile properties versus temperature for SA542 weld metal and base plate (Heat 7868)

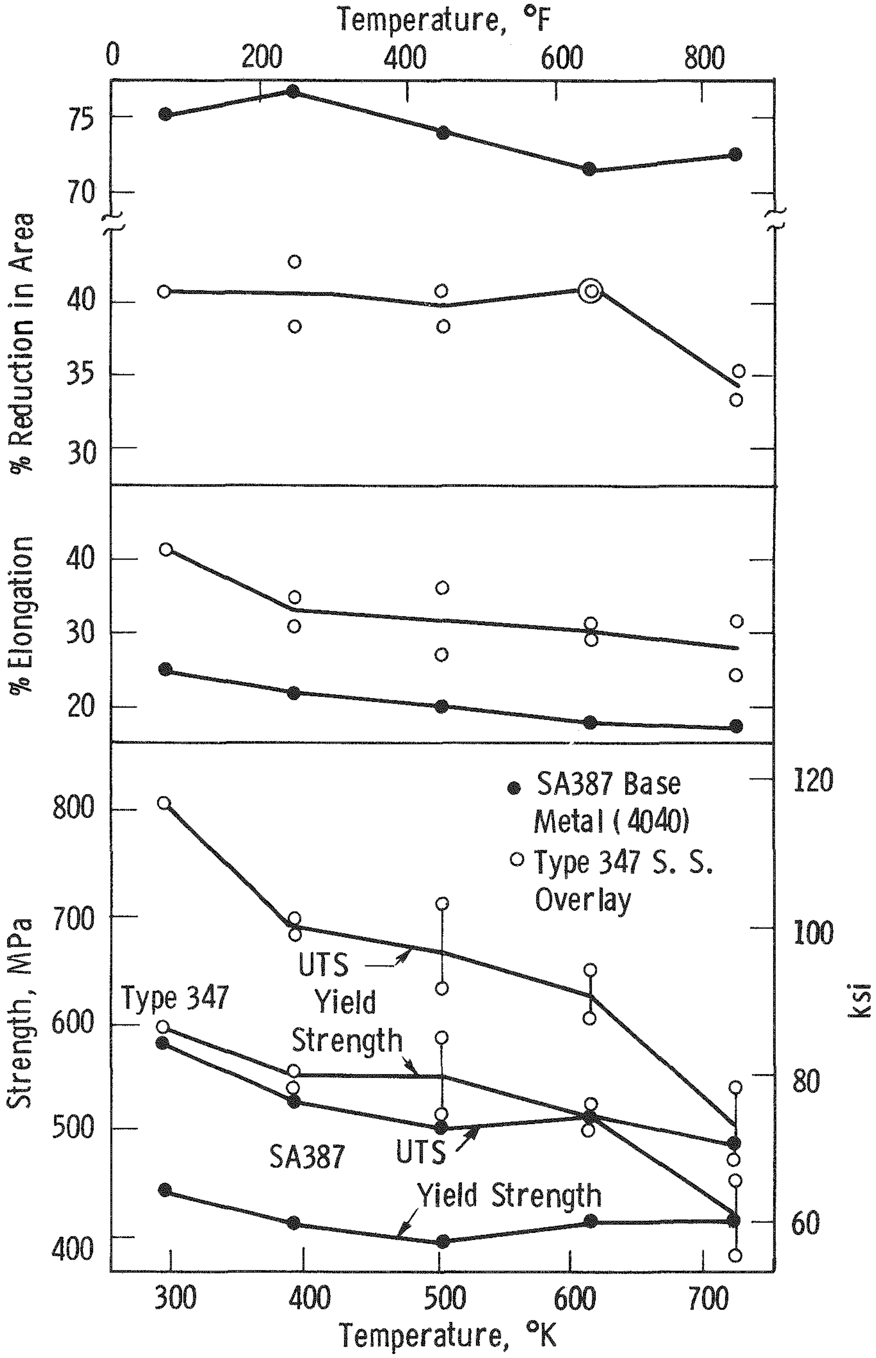


Fig. 3-9 —Tensile properties versus temperature for SA387 base metal (Heat 4040) and Type 347 S. S. overlay

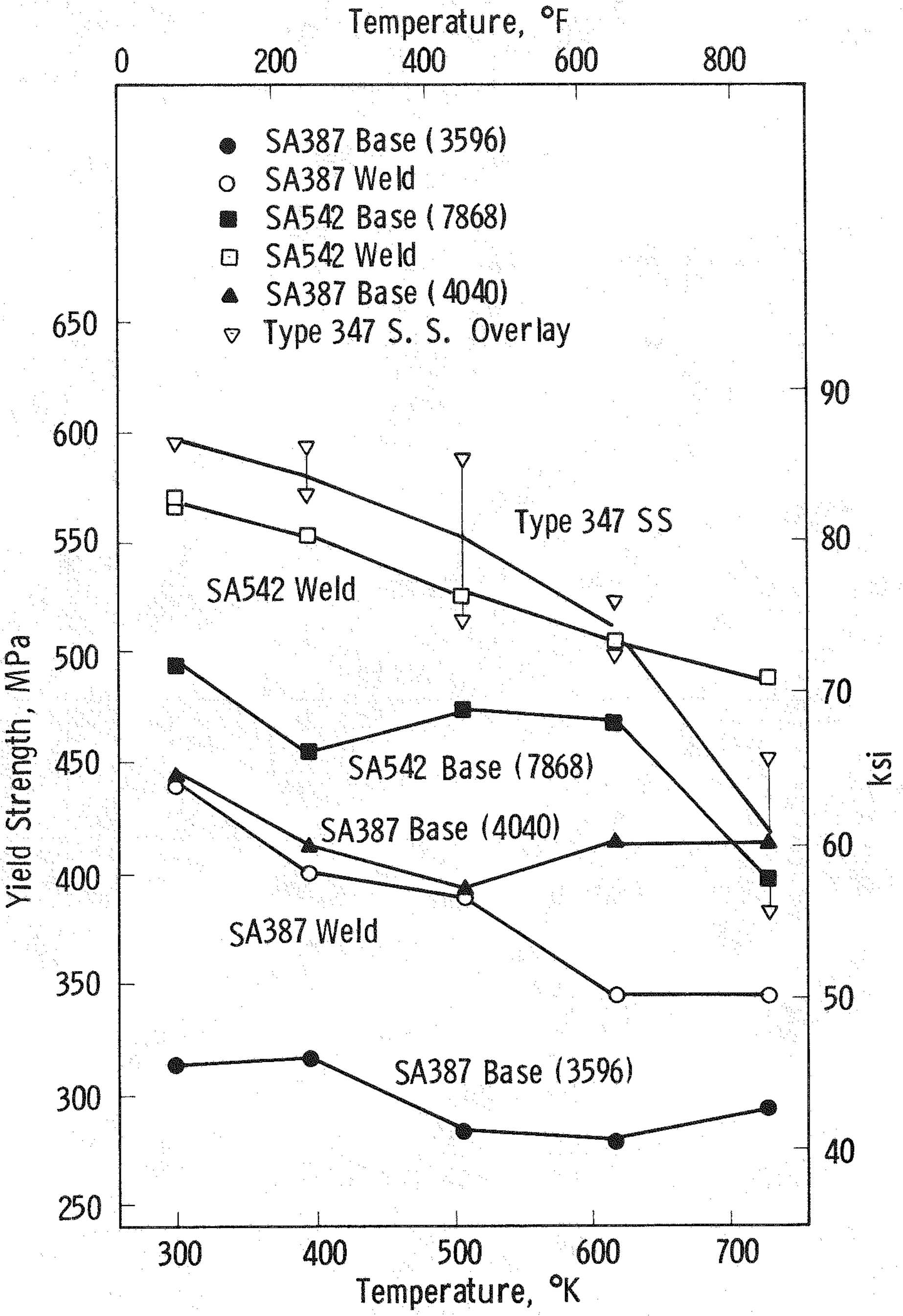


Fig. 3-10—Yield strength versus temperature for base plates and weld metals

TABLE 3-1

SUMMARY OF IMPACT TRANSITION PROPERTIES

			Upper Shelf	
Material	50% FATT Temp.*	NDT Temp.†	Av. Energy	Av. L.E.
SA387 Base Plate (Heat 3596)	294°K (70°F)	266°K (20°F)	183 Joules (135 ft-lb)	2.44 mm (96 mils)
SA387 Base (Under Type 347 Overlay - Heat 4040)	283°K (50°F)	277°K (40°F)	183 Joules (135 ft-lb)	2.21 mm (87 mils)
SA387 Weld Metal	275°K (35°F)	244°K (-20°F)	117 Joules (86 ft-lb)	1.98 mm (78 mils)
SA387 Weld Metal Temper Embrittled	344°K (160°F)		127 Joules (93 ft-lb)	2.13 mm (84 mils)
SA387 Base Metal (Heat 3596) Temper Embrittled	360°K (190°F)		96 Joules (70 ft-lb)	1.68 mm (66 mils)
SA542 Base Plate (Heat 7868)	244°K (-20°F)	266°K (20°F)	180 Joules (133 ft-lb)	2.18 mm (86 mils)

*50% Shear Fracture Appearance Transition Temperature

†Nil Ductility Temperature

TABLE 3-2

TENSILE PROPERTIES VERSUS TEMPERATURE FOR SA387 BASE PLATE AND WELD METAL

Material	Test Temperature	Yield Strength	UTS	% Elongation	% RA
SA387 Base Metal (Heat 3596) 1/4 Thickness	297°K (75°F)	313 MPa (45.4 ksi)	521 MPa (75.5 ksi)	30.1[*]	75.1
	394°K (250°F)	316 MPa (45.9 ksi)	481 MPa (69.8 ksi)	27.0	75.7
	505°K (450°F)	284 MPa (41.2 ksi)	430 MPa (62.4 ksi)	24.8	74.3
	616°K (650°F)	279 MPa (40.4 ksi)	454 MPa (65.9 ksi)	21.3	71.3
	727°K (850°F)	295 MPa (42.8 ksi)	437 MPa (63.4 ksi)	22.8	71.0
SA387 Weld Metal	297°K (75°F)	440 MPa (63.8 ksi)	589 MPa (85.4 ksi)	57.7[†]	66.2
	394°K (250°F)	401 MPa (58.1 ksi)	514 MPa (74.5 ksi)	56.9	67.3
	505°K (450°F)	390 MPa (56.5 ksi)	505 MPa (73.3 ksi)	57.5	66.5
	616°K (650°F)	345 MPa (50.1 ksi)	470 MPa (68.1 ksi)	52.0	64.5
	727°K (850°F)	345 MPa (50.1 ksi)	456 MPa (66.1 ksi)	50.6	61.1

[*] 44 mm (1.75 in.) G.L.

[†] 6.4 mm (0.25 in.) G.L.

TABLE 3-3

TENSILE PROPERTIES VERSUS TEMPERATURE FOR SA542 BASE PLATE AND WELD METAL

Material	Test Temperature	Yield Strength	UTS	% Elongation	% RA
SA542 Base Metal (Heat 7868) 1/4 Thickness	297°K (75°F)	495 MPa (71.8 ksi)	608 MPa (88.2 ksi)	23.6[*]	77.3
	394°K (250°F)	455 MPa (66.0 ksi)	547 MPa (79.3 ksi)	20.1	75.7
	505°K (450°F)	475 MPa (68.9 ksi)	569 MPa (82.5 ksi)	18.7	76.0
	616°K (650°F)	469 MPa (68.0 ksi)	565 MPa (82.0 ksi)	18.1	74.0
	727°K (850°F)	398 MPa (57.7 ksi)	459 MPa (66.5 ksi)	16.6	74.0
SA542 Weld Metal	297°K (75°F)	569 MPa (82.5 ksi)	696 MPa (100.9 ksi)	50.2[†]	63.3
	394°K (250°F)	552 MPa (80.1 ksi)	650 MPa (94.2 ksi)	49.8	64.5
	505°K (450°F)	525 MPa (76.1 ksi)	620 MPa (89.9 ksi)	48.0	63.3
	616°K (650°F)	505 MPa (73.3 ksi)	601 MPa (87.1 ksi)	44.0	59.7
	727°K (850°F)	489 MPa (70.9 ksi)	561 MPa (81.3 ksi)	47.0	61.7

[*] 44 mm (1.75 in.) G.L.

[†] 6.4 mm (0.25 in.) G.L.

TABLE 3-4

TENSILE PROPERTIES VERSUS TEMPERATURE FOR TYPE 347 S.S. OVERLAY AND SA387 BASE METAL

Material	Test Temperature	Yield Strength	UTS	% Elongation	% RA
Type 347 SS Overlay	297°K (75°F)	596 MPa (86.4 ksi)	807 MPa (117 ksi)	41.4[*]	40.7
	394°K (250°F)	547 MPa (79.4 ksi)	690 MPa (100.1 ksi)	32.8	40.5
	505°K (450°F)	551 MPa (79.9 ksi)	672 MPa (97.5 ksi)	31.8	39.5
	616°K (650°F)	512 MPa (74.2 ksi)	627 MPa (91.0 ksi)	30.3	40.7
	727°K (850°F)	419 MPa (60.7 ksi)	505 MPa (73.2 ksi)	27.8	34.3
SA387 Base Metal Under A347 (Heat 4040)	297°K (75°F)	443 MPa (64.2 ksi)	582 MPa (84.4 ksi)	25.1[†]	75.1
	394°K (250°F)	412 MPa (59.7 ksi)	525 MPa (76.2 ksi)	21.7	76.8
	505°K (450°F)	394 MPa (57.2 ksi)	501 MPa (72.6 ksi)	20.0	74.0
	616°K (650°F)	414 MPa (60.0 ksi)	516 MPa (74.8 ksi)	17.8	71.6
	727°K (850°F)	414 MPa (60.0 ksi)	485 MPa (70.3 ksi)	17.3	72.5

[*] 6.4 mm (0.25 in.) G.L.

[†] 44 mm (1.75 in.) G.L.

Section 4.0

MICROSTRUCTURES

SA387 & SA542

Photomicrographs were taken for both base plates of SA387 and SA542. The microstructures at the center of the SA387 base plates are shown in Figures 4-1 and 4-2 at 500X, and similar microstructures at the center of the SA542 base plates are shown in Figures 4-3 and 4-4. Although the strength levels and hardness of the two grades of 2¼Cr-1Mo steel are somewhat different, the microstructures are very similar, appearing to be lower bainite. This was initially considered to be somewhat unexpected since a ferrite-pearlite microstructure would be expected for the normalized and tempered condition representative of SA387. It was postulated that the accelerated fan cooling after anneal results in a microstructure which appears more like a quenched steel than a normalized steel. In subsequent communication with CB&I personnel they expressed the opinion that the similarities in microstructure are not unusual. At the center of thick plates such as the two in this program, the cooling rates for water quenching versus air cooling are not too much different. Air cooling may produce upper bainite whereas water quenching may produce lower bainite; and it is difficult to distinguish between these two microstructures (3).

To further examine typical microstructures for a normalized 2¼Cr-1Mo, a sample piece of SA387 Heat No. 3596 was laboratory normalized and given a cooling rate simulating a 184 mm (7¼ in.) thick plate. See Figure 4-5. Although the resulting hardness was the same, the microstructures are quite different as is apparent in Figures 4-6 and 4-7. The microstructure for the laboratory normalized piece looks similar to that reported by Fetterolf and Hurth (5) for normalized 2¼Cr-1Mo steel.

TYPE 347 SS OVERLAY EVALUATION

In commerical weld overlay practice, the first layer is usually made with Type 309 stainless steel filler wire or as in the present case, a columbium modified Type 309. The reason for this is that base metal mixing during deposit of the first layer causes dilution of chromium and nickel content, requiring an enriched weld metal to achieve the aim 347 composition. The composition corresponding to 347 is a balanced chemistry such that with typical weldment cooling rates, the resulting microstructure will be austenitic containing between 5 to 10 percent delta ferrite. This aim microstructure is sought for reduced hot cracking tendancy in the as cast weldment microstructure (6). This desirable feature of the hot cracking resistance is offset by a tendency for sigma phase to develop from transformation of delta ferrite during post weld heat treatments, typically made at 1275°F (7). Here, there will be partial embrittlement of weld metal, the extent of which depends upon the initial ferrite content and this calls for the setting of upper limits on delta ferrite of nominally 10 percent. The 347 weldment of the present project, therefore, was evaluated for ferrite and sigma phase content to determine if the microstructure is representative of the aim levels sought in commercial practice. Figure 4-8 shows the fracture mechanics specimen with the built up type 347 stainless weld metal and the location of delta ferrite and sigma phase determination. The welding practice and post weld heat treatments were reported in Table 1-3.

The following table lists the results of the microstructural evaluation:

Position by Fig. 4-8	Material	Metallographic (ΔFe + σ)%	Analysis %	Magnagage FN*
1	347			4
2	347	5.6	0.8	5
3	347			4
4	309	4.3	0.2	3

---

*FN - Ferrite Number - Reportedly is directly convertable to percent ferrite with numerical values below 18.

The metallographic evaluations were made by first etching with a 10% NaCN solution to reveal sigma phase. A second etch with 20% NaOH is then used to bring out sigma and delta ferrite. See Figures 4-9 to 4-12. The quantitative metallograph was used, scanning 100 fields to determine percentage of second phase, and the averaged results are reported in the above table. Percent ferrite by Magnagage essentially confirms the results of the metallographic work.

The percent ferrite in the 309 Cb weld pass is determined to be slightly low, suggesting that the base metal mixing resulted in a lean Type 347 composition. Considering the entire weldment, the delta ferrite content is acceptable but somewhat leaner than aim levels. Sigma phase is almost non-existent and the cracking resistance properties in H_2S-H_2 gas environment should be optimum for the grade of cladding material.

Fig. 4-1 — Microstructure at the center of A387 base plate, Ht. 3324, 500x Villella's etchant, CVN = 133 ft-lbs, R_B = 89.

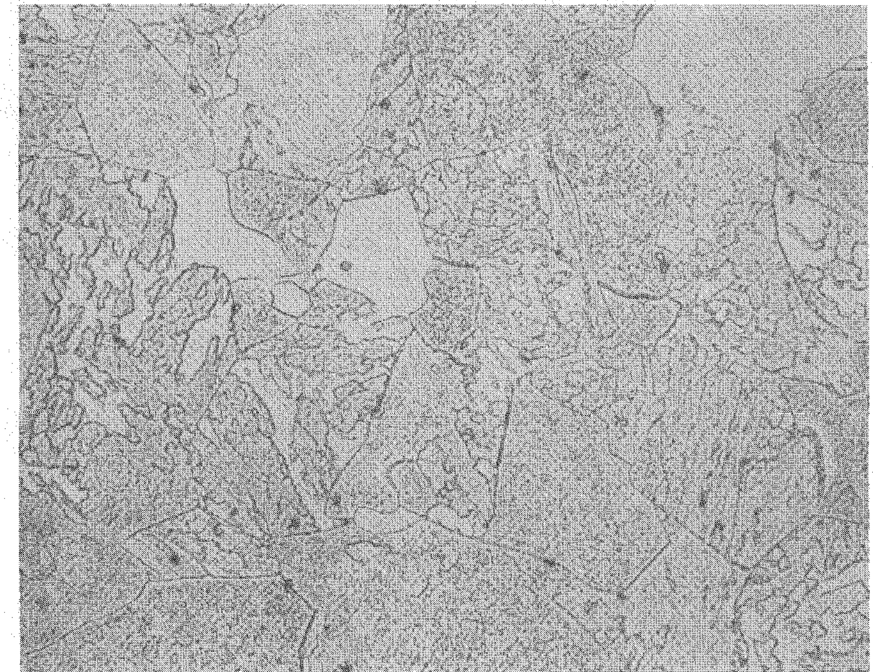


Fig. 4-2 — Microstructure at the center of A387 base plate, Ht. 3596, 500x, Villella's etchant, CVN = 110 ft-lbs, R_B = 82.

Fig. 4-3 — Microstructure at the center of A542 base plate, Ht. 7868, 500x, Villella's etchant, CVN = 137.5, $R_B = 93$

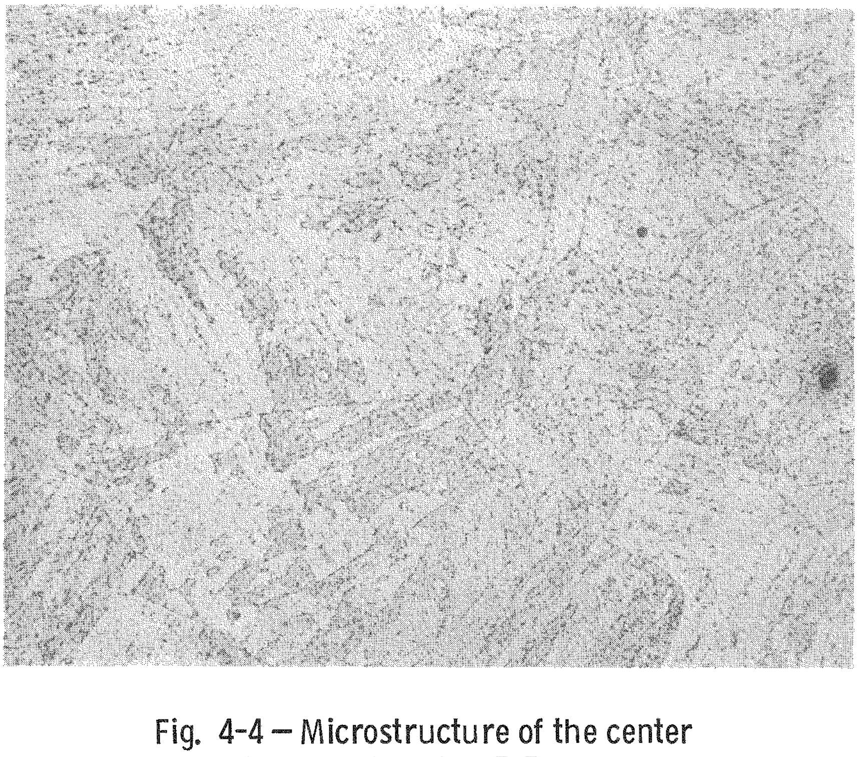


Fig. 4-4 — Microstructure of the center of A542 base plate, Ht. 3707, 500x, Villella's etchant, CVN = 150 ft-lbs, $R_B = 92$.

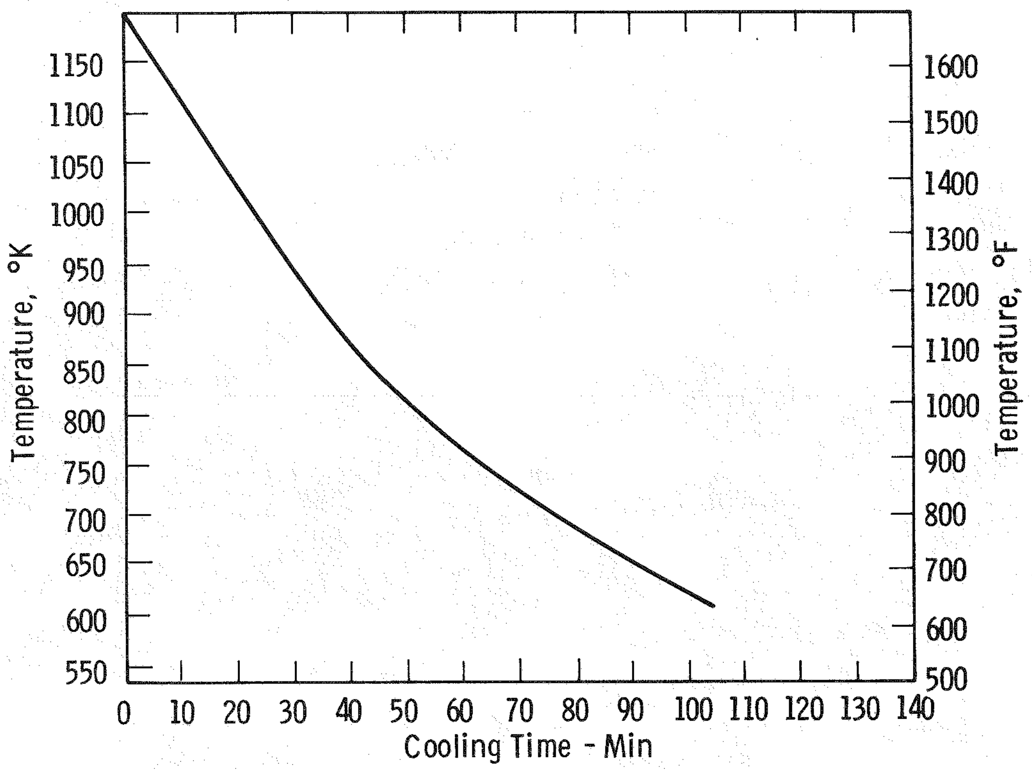


Fig. 4-5 — Simulation cooling curve for normalization of a 7-1/4" thick plate

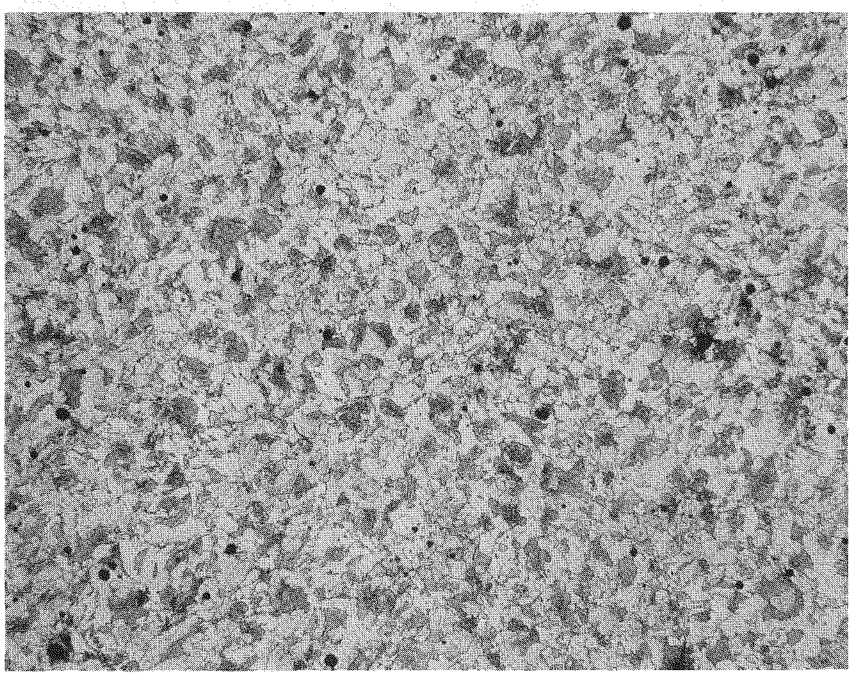


Fig. 4-6 — Microstructure of laboratory normalized A387 100x Picral etchant, $R_B = 82$.

Fig. 4-7 — Microstructure of as received A387, Ht. 3596 100x Picral etchant, $R_B = 82$.

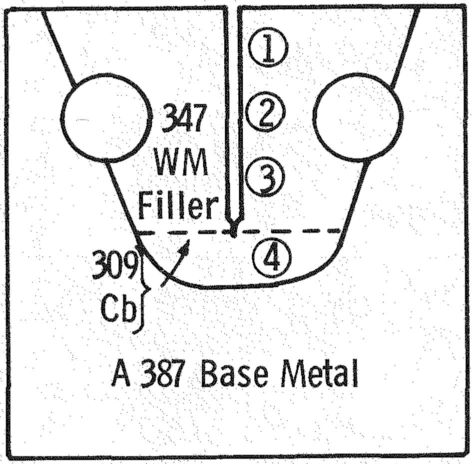


Fig. 4-8—Composite weld metal - Base metal specimen for weld overlay material evaluation

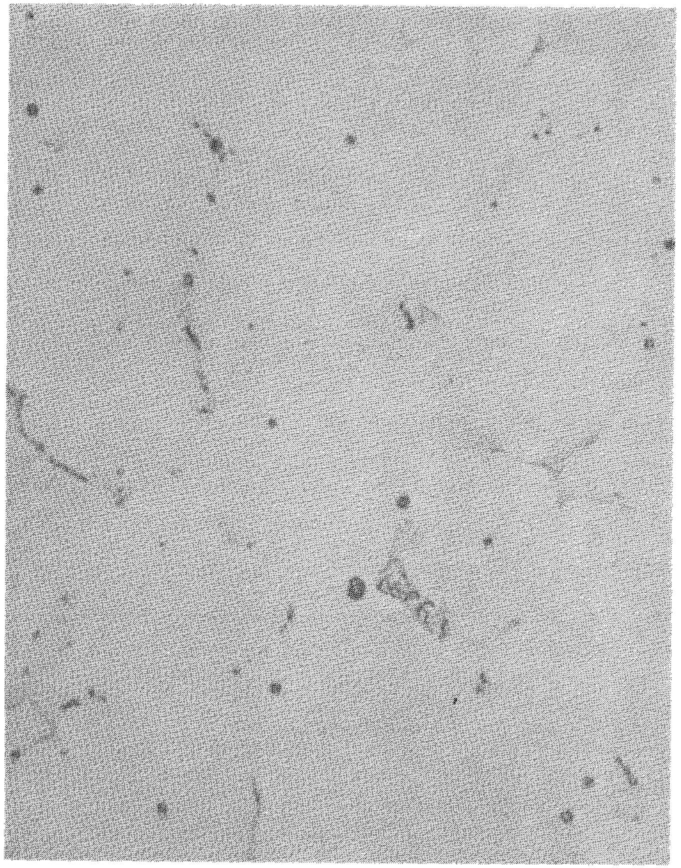


Fig. 4-9 — Type 347 weld filler metal. Sigma phase. 2000X, 10% NaCN electrolytic etch

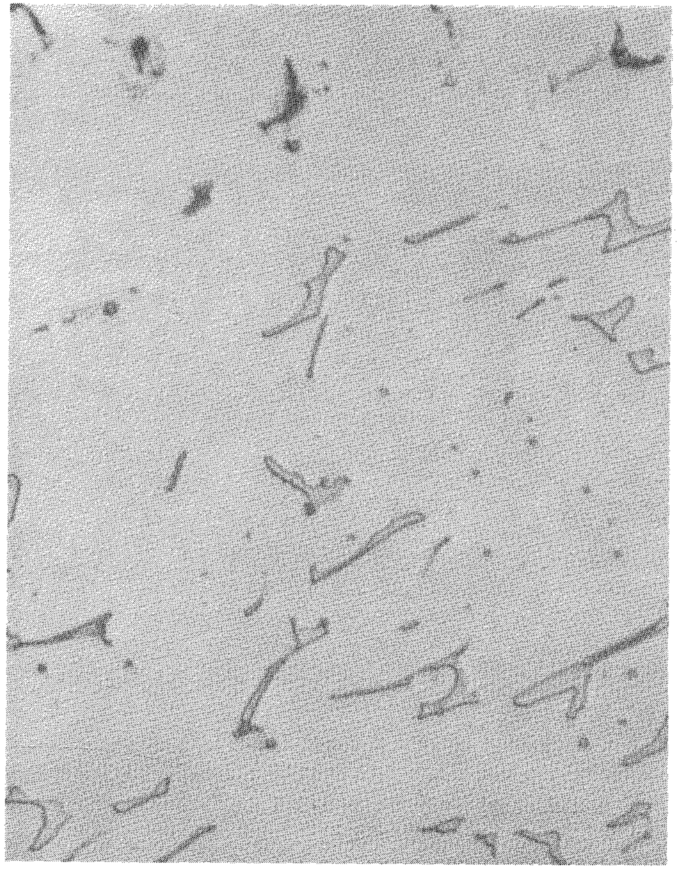


Fig. 4-10 — Type 347 weld filler metal. Delta ferrite plus sigma phase. 2000X 20% NaOH electrolytic etch

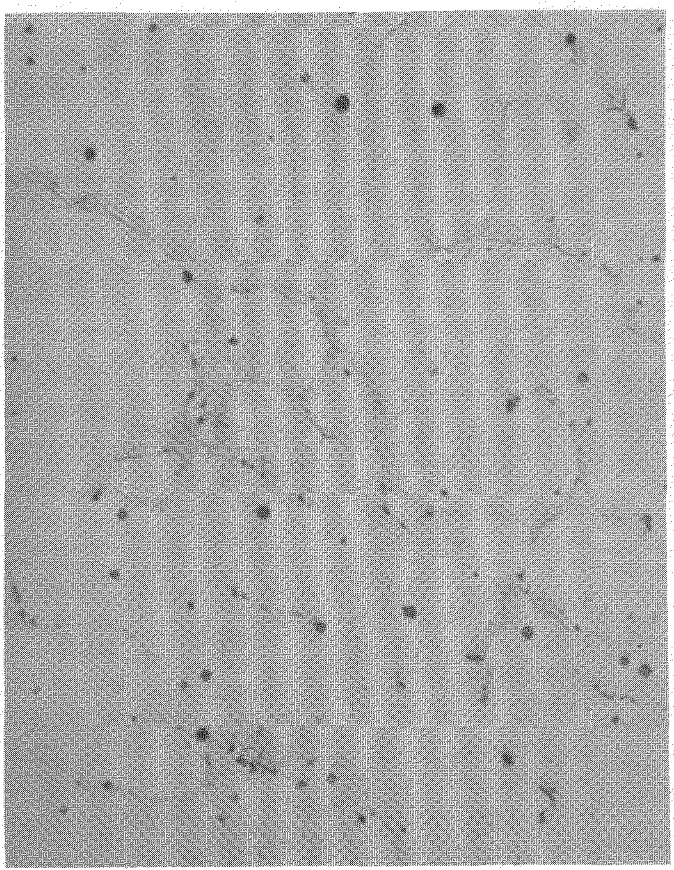


Fig. 4-11 — Type 309 Cb weld layer. Sigma phase. 2000X 10% Na CN electrolytic etch

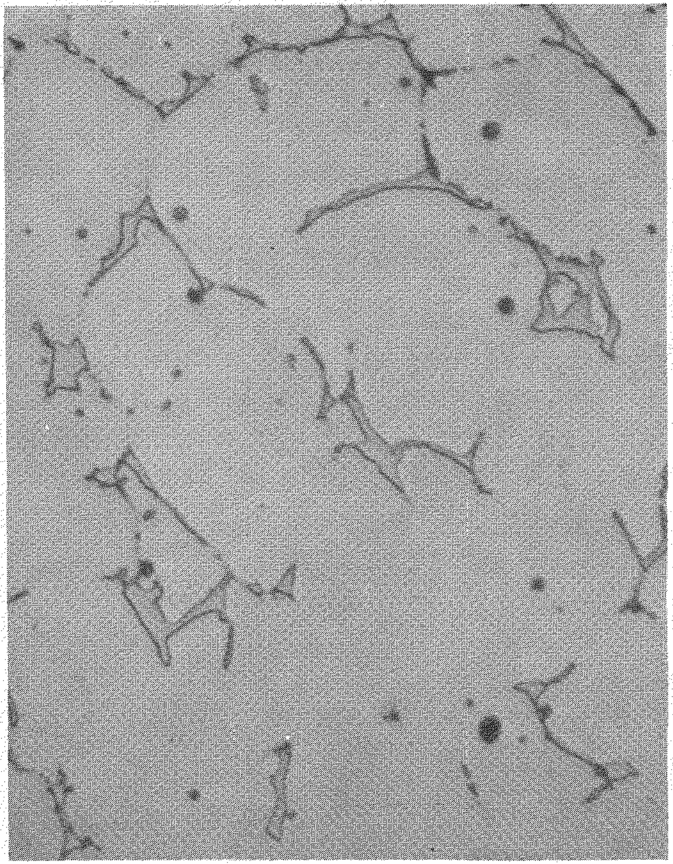


Fig. 4-12 — Type 309 Cb weld layer. Delta ferrite and sigma phase. 2000X 20% Na OH electrolytic etch

Section 5.0

FRACTURE MECHANICS EVALUATIONS

BASE MATERIALS TOUGHNESS, J_{Ic}

The 2¼Cr-1Mo pressure vessel steels when tested at room temperature and at simulated operating temperatures are near to or on the upper shelf of the brittle to ductile transition temperature behavior. Hence fracture mechanics specimens display extensive plasticity and slow stable crack growth prior to fracture. Therefore, it is necessary to incorporate elastic-plastic fracture mechanics analysis methods in the form of J-integral to make valid determinations. Specifically, J_{Ic} is determined, which is defined here as the J level where slow-stable crack growth first develops in the specimen. J_{Ic} is related to K_{Ic} by: $J_{Ic}E = (1 - \mu)^2 K_{Ic}^2$, where E is the elastic modulus and μ is Poisson's ratio.

J type crack growth resistance curves for SA387 base material developed over a temperature range from 297°K (75°F) to 727°K (850°F) are shown in Figure 5-1. Because of the combination of low strength and high toughness of the SA387 at room temperature, the resistance curve did not cross the blunting line and J_{Ic} could not be defined. In addition, room temperature J is not considered reliably valid beyond .351 MN/m (2000 in.-lbs/in.^{2}) because of minimum specimen size limitations on J. Therefore, it can only be stated that the J_{Ic} is more than the last valid value determined. To determine a J_{Ic} value, a specimen of larger planar dimensions would be required. For other conditions, J_{Ic} was found to decrease with elevated temperature testing and this is consistent with the general trend in upper shelf toughness observed in testing other materials.

Data of this type will serve as the baseline values for comparison to specimens exposed in the autoclave for long time periods in H_2. J type resistance curves for baseline data on SA542 at room temperature and Type 347 SS at room temperature and at 727°K (850°F) are shown in Figures 5-2 through 5-4. K_{Ic} values obtained from these plots and others are summarized in Table 5-1. Despite some significant difference in room temperature Charpy V toughness between SA387 and SA542, the crack initiation toughness appears to be essentially the same at room temperature.

The 347 SS overlay material has considerably less toughness in terms of K_{Ic}, but apparently the toughness increases with test temperature. This is suspected as being an artificial effect due to severe weakening of the weld metal at 727°K (850°F), with the SA387 base material properties controlling the J-R curve development.

FATIGUE CRACK GROWTH, da/dN

A type of subcritical cracking to be studied in the test program is the determination of fatigue crack growth rates. This represents a vital part of the data that is needed to predict vessel service life. Initial tests presented here are the baseline material characterization to be compared to fatigue crack growth in environments.

Figure 5-5 shows the baseline crack growth rates that characterize the SA387 at room temperature and at 727°K (850°F). Figure 5-6 compares the da/dN of SA542 at room temperature and 588°K (600°F), which is a representative coal gasification temperature. These tests indicate that the higher test temperature of 727°K, increased the crack growth rate of SA387 by a factor of two, while the growth rate of SA542 was unaffected by temperature up to 588°K.

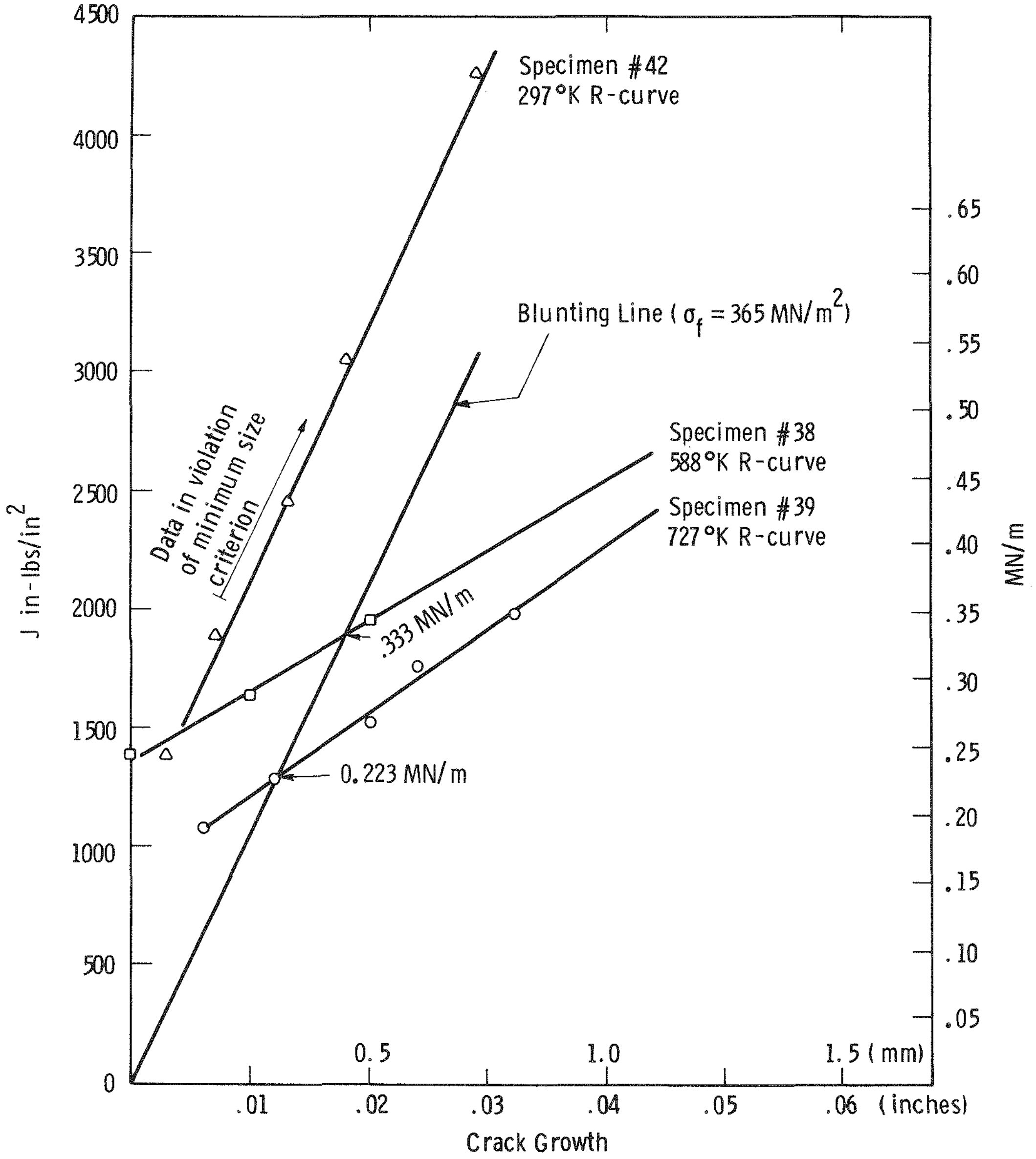


Fig.5-1—Resistance curves for the determination of J_{Ic} on SA387

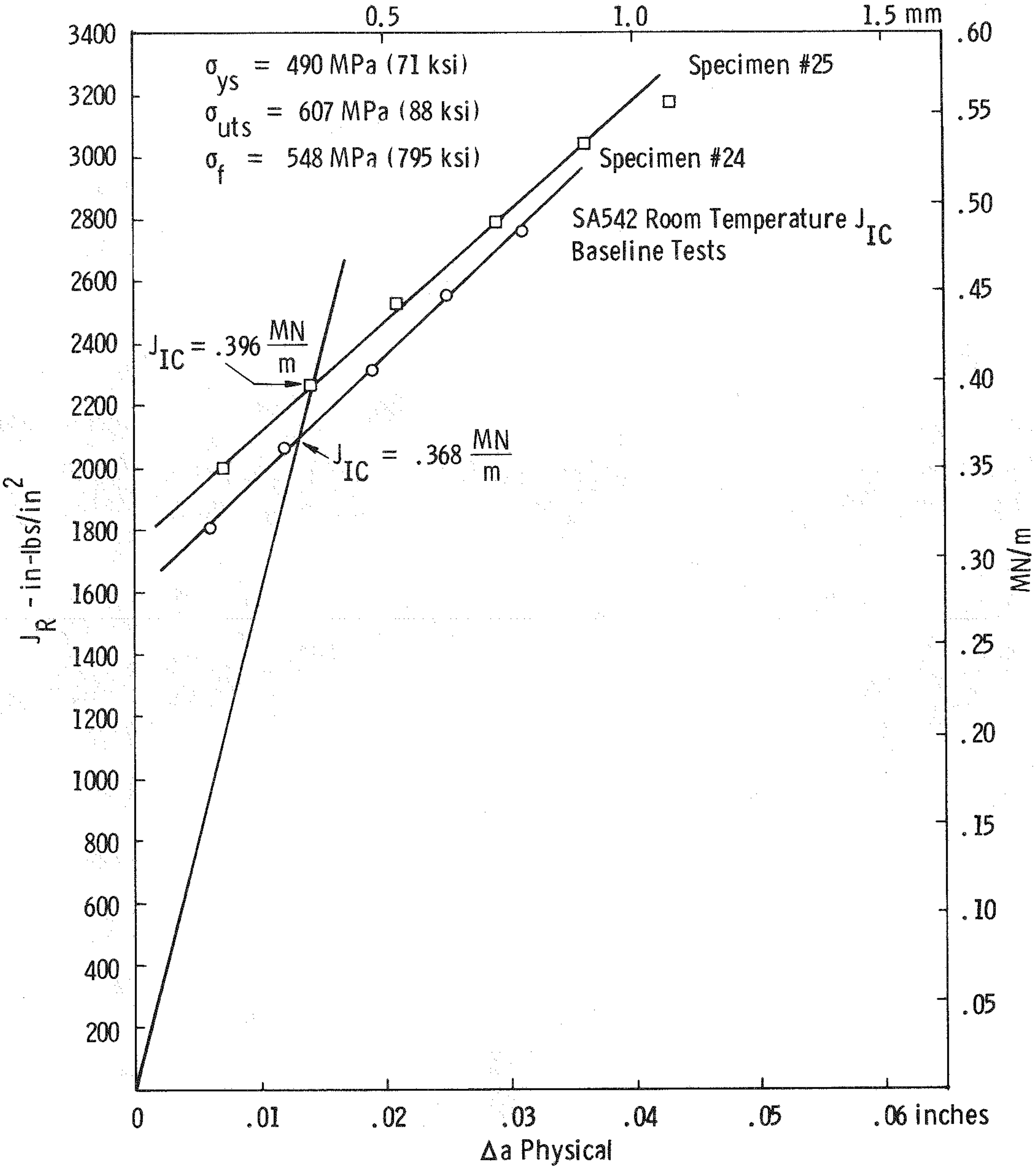


Fig.5-2– Resistance curves for the determination of J_{IC} on SA542

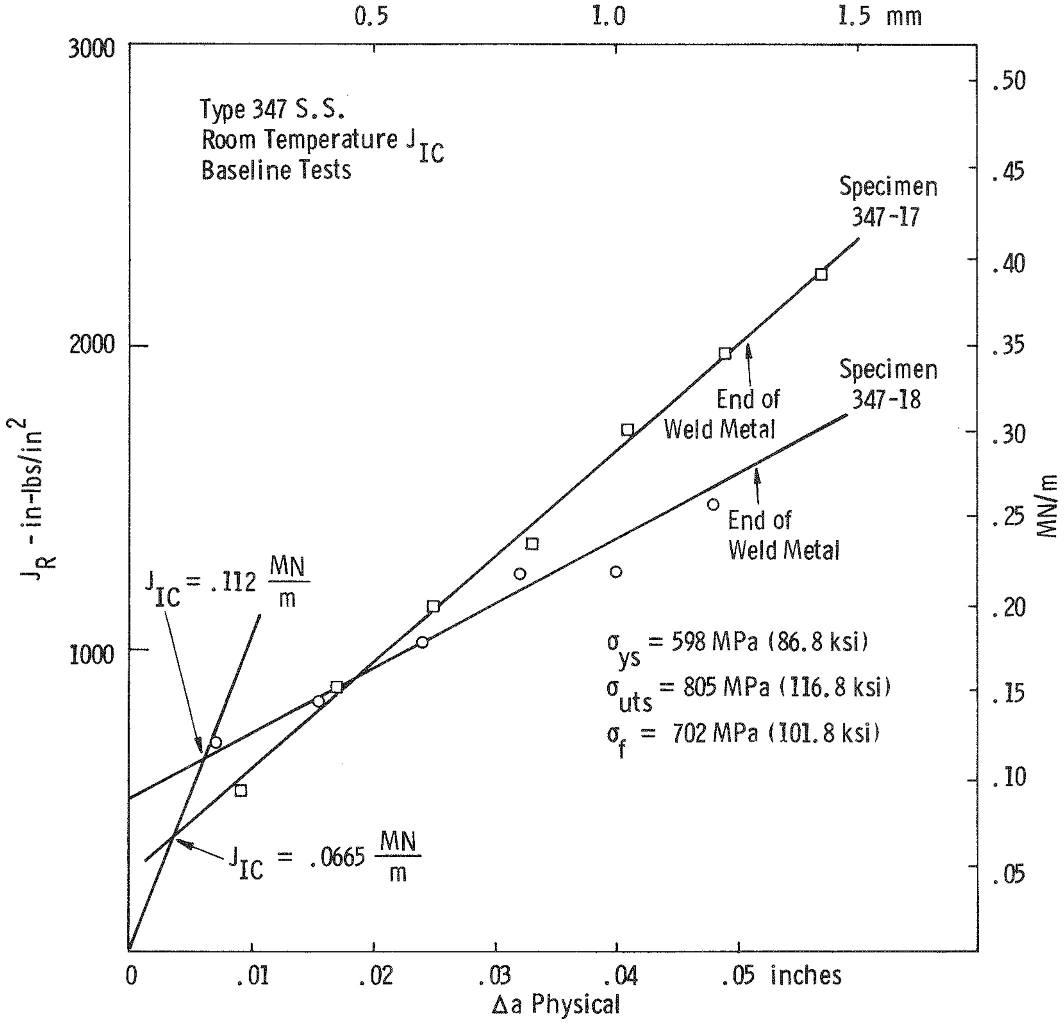


Fig. 5-3— Resistance curves for the determination of J_{IC} on Type 347 S. S. at room temperature

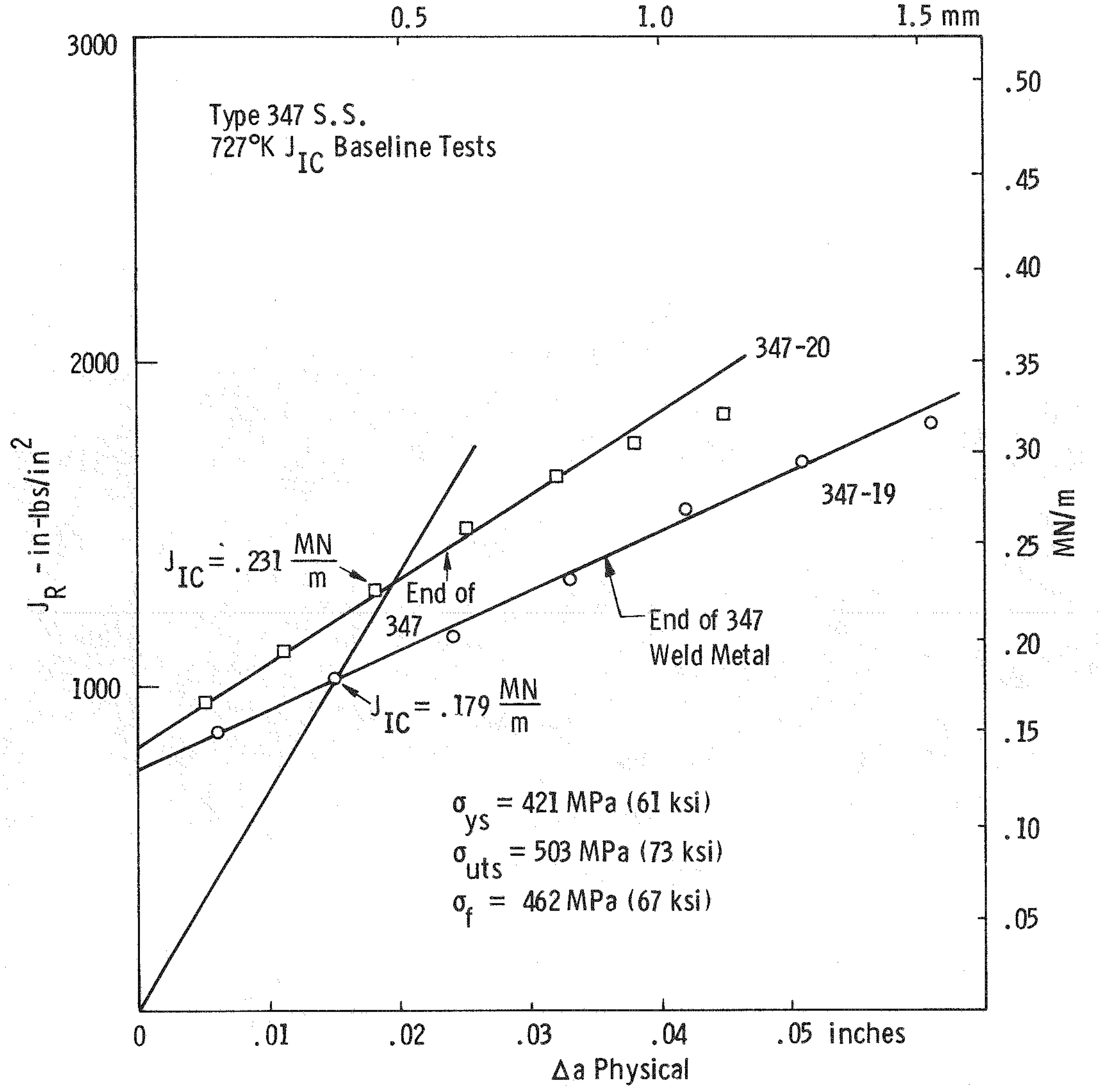


Fig. 5-4 — Resistance curves for the determination of J_{IC} on Type 347 S. S. at 727°K (850°F)

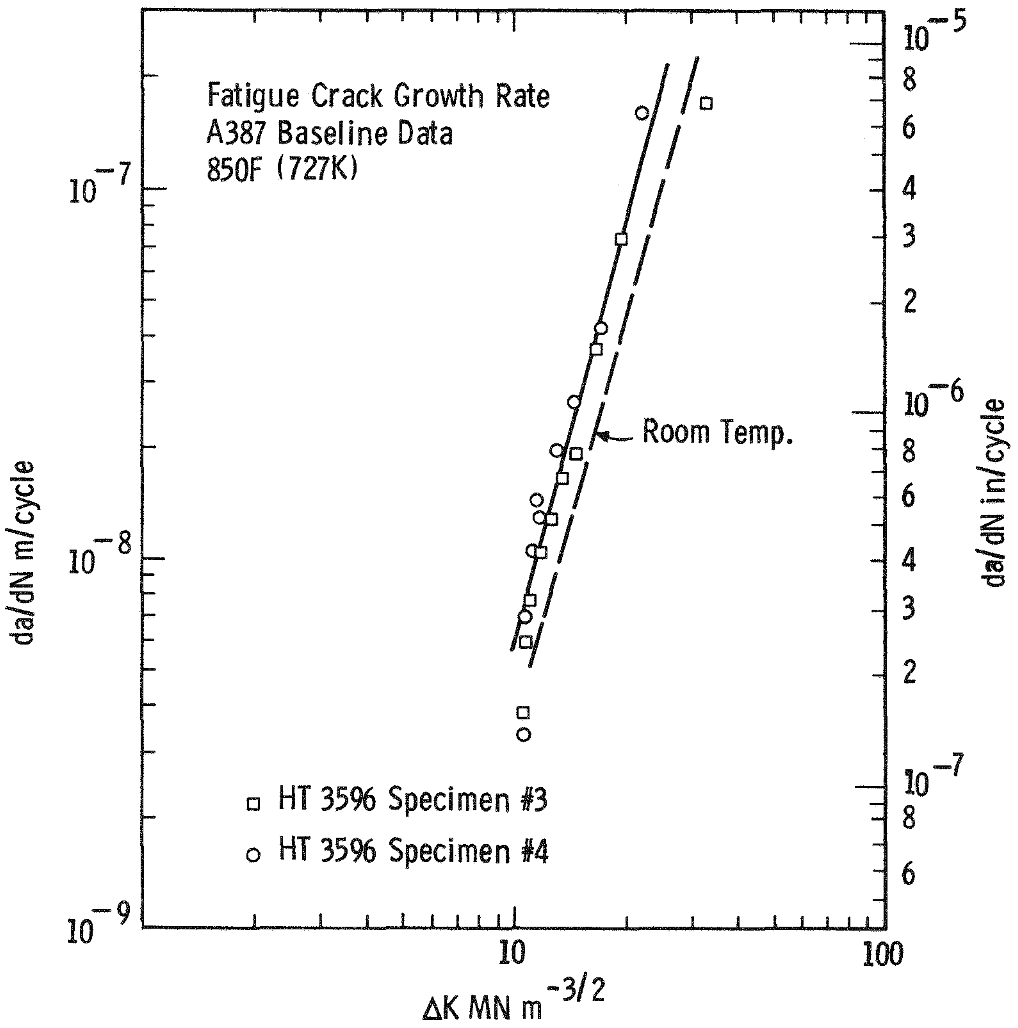


Fig.5-5 — Crack growth rate for SA387 at room temperature and 727°K (850°F)

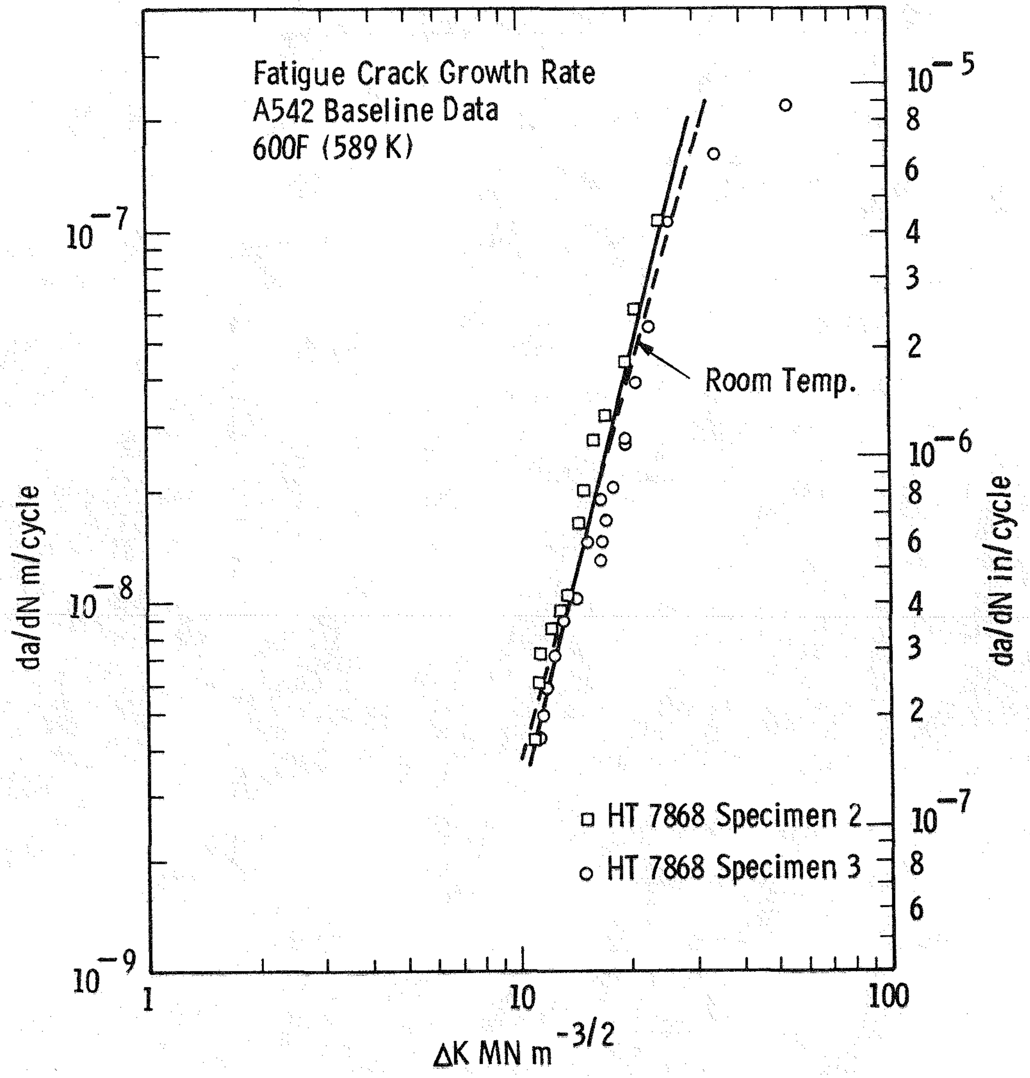


Fig.5-6— Crack growth rate for SA542 at room temperature and 589°K (600°F)

TABLE 5-1

SUMMARY OF BASELINE K_{Ic} FROM J_{Ic}

Test Temperature	SA387 Base Metal	SA542 Base Metal	Temper Emb. SA387 WM	Type 347 S.S. Overlay
297°K (75°F)	> 280 MN $m^{-3/2}$ (> 255 ksi$\sqrt{in.}$)	289/300 MN $m^{-3/2}$ (263/273 ksi$\sqrt{in.}$)	225*/278 MN $m^{-3/2}$ (204*/253 ksi$\sqrt{in.}$)	160/123 MN $m^{-3/2}$ (145/112 ksi$\sqrt{in.}$)
589°K (600°F)	273 MN $m^{-3/2}$ (248.3 ksi$\sqrt{in.}$)			
767°K (850°F)	217 MN $m^{-3/2}$ (197.2 ksi$\sqrt{in.}$)			201/230 MN $m^{-3/2}$ (183/209 ksi$\sqrt{in.}$)

*Terminated by brittle fracture.

Section 6

CONCLUSIONS

6-1 This report contains the complete log of chemistries and heat treatment histories on the weldments prepared by CB&I for this program.

6-2 The weldments received from CB&I of SA387, SA542, and simulated 347 stainless steel overlay were judged to be sufficiently typical or representative of commercial products and of sufficient uniformity in mechanical properties for commitment to an extensive fracture mechanics testing program. The heat of SA387 base metal chosen had slightly non-uniform surface to center yield strength but the slightly lower overall level was preferred. The Charpy impact properties were suitably uniform. The SA542 heat chosen had highly uniform properties from surface to center and the decision basis among the two available heats was arbitrary. The 347 SS overlay simulation material had higher toughness in the HAZ layer where the 309 Cb filler wire was used. The balance of the weldment where 347 SS filler wire was used was of considerably less toughness. The balance in strength between weld metals and base metals was suitable in all cases.

6-3 Charpy transition temperature curves were developed on the materials selected for the fracture mechanics type evaluations. The 50% FATT temperature for SA387 base metal was near room temperature and for SA542, 50% FATT was about 244°K (-20°F).

6-4 When temper embrittled, the transition temperature of the SA387 weld and base metals was increased about 67°K (120°F). Upper shelf Charpy impact energy of the SA387 base metal was observed to decrease by one-half after T.E. The upper shelf toughness of SA387 weld metal was relatively unaffected by T.E.

6-5 Tensile tests were made at temperatures up to 727°K (850°F) on the materials slated for fracture mechanics testing. All weld and base metals retained strength properties with the exception of the 347 SS weld metal which lost appreciable strength between 616°K (650°F) and 727°K (850°F).

6-6 Microstructure of the SA387 and SA542 base materials was evaluated. In both cases the microstructure was predominantly bainitic. According to CB&I practice, both grades are cooled from annealing temperature of 1227°K (1750°F) by fan circulated air. Tempering temperature for SA387 is 964°K (1275°F) and for SA542 is 936°K (1225°F).

6-7 A metallurgical evaluation was made of the simulated 347 SS overlay material. The examination was principally for percent retained ferrite and sigma phase from PWHT. The ferrite was about 5 percent which is on the low side of acceptable ferrite levels. However, essentially no sigma phase was detected which is reportedly detrimental to the embrittlement resistance properties.

6-8 Baseline J_{Ic} and fatigue crack growth rate tests were made on the base metal plate materials at room and at elevated temperatures.

Section 7

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