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EVALUATION OF FORGINGS OF INCO AND TM-2 STEELS AT HIGH-STRENGTH LEVELS

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FOREWORD

This report was prepared by the Cleveland Pneumatic Tool Company, Cleveland, Ohio, under USAF Contract AF 33(616)-376 Supplemental Agreement S-3(54-802). The contract was initiated under Project 7351 "Metals and Metallic Materials", Task 70645 "Supporting Research on High-Strength Steel for Aeronautical Applications". The project was administered under the direction of the Metallurgy Research Branch, Aeronautical Research Laboratory, Directorate of Research, Wright Air Development Center with Mr. James W. Poynter as task scientist.

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ABSTRACT

Two potential aircraft structural steels known commercially as Inco Steel and TM-2 Steel were evaluated using specimens cut from large forged sections. While the test results covers only one strength level in each range, the data indicate that Inco Steel in the 290,000 - 310,000 psi range and TM-2 in the 200,000 - 220,000 psi and 220,000 - 240,000 psi ranges would probably be adequate for aircraft structural components. The Inco Steel in the 240,000 - 260,000 psi range is too brittle for use as an aircraft structural material. Good flash butt weldments can be made with Inco Steel.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

LESLIE B. WILLIAMS
Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

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I. INTRODUCTION

As a result of the aircraft industry's perennial desire for increased speed and load carrying capacity in both military and commercial aircraft, there has been constant pressure on the accessory manufacturers to decrease the weight and still maintain the strength of their products. This pressure has led to considerable study of light metals and various high-strength alloy steels.

Formerly alloys treated above 200,000 psi. were considered to be too brittle and too notch-sensitive to be used as structural materials. Not long ago, however, a new steel which could be treated to the 220-240,000 psi. strength range was developed. Next the 260-280,000 psi. range was reached. Further investigations showed that standard analysis steels improved in ductility when treated to high strength levels. Since that time many investigations have been conducted on numerous alloy steel compositions at high strength levels, but most of these have been on small section sizes, that is on a laboratory specimen scale. A survey of the results of many of these studies has been published by Dr. Sachs. (1)

In this investigation, which is an attempt to evaluate two new steels developed for use at high strength levels, and in a previous one by the same facility (2), steels were studied

using specimens cut from sections approximating the actual part. Landing gear cylinder forgings were machined to a shape very close to that of the actual cylinders; the parts were heat-treated; and finally specimens were machined from the forging and tested. A second phase of the project concerned the flash butt welding properties of one of the steels.

II. MATERIAL

The two steels investigated were:

Inco steel - an ultra high strength steel developed by the International Nickel Company for use in the 280,000-300,000 psi. heat treat range.

TM-2 steel - (also known as Cleveland Pneumatic Tool specification M-101) - an alloy developed by the Timken Steel Company for use in the 220,000 to 240,000 psi. ultimate strength range.

The specifications and analyses for the steels are given in table 1 in the appendix.

One B-47 landing gear main column was forged from each steel in closed dies, out of a 15 inch round corner square billet. The Inco steel used in the flash butt weld tests was received as 5-3/4" round bar stock.

Jominy hardenability tests were run for each steel. In order to be useful in the high strength ranges, a steel must have good hardenability.

III. PROCEDURE-FORGED SECTIONS

A. Forging History

A 5,000 pound blacksmith hammer, 25,000 pound blocking hammer, and 35,000 pound finishing hammer were used.

Furnace Schedules

	INCO	TM-2
Heated in warm unlit furnace	8 Hours	8 Hours
Preheated to	1700°F in 6 Hours	1700°F in 6 Hours
Held at heat	4 Hours	4 Hours
Blacksmith	2200°F - 2-1/4 Hours	2215°F - 2-5/6 Hours
Blocker	2250°F - 1/2 Hour	2235°F - 2/3 Hour
Finishing	2250°F - 3 Heats in 2-1/4 Hours	2260°F - 1/2 Hour

After finishing, the forgings were cooled in ashes to room temperature. Finally the forgings were isothermally annealed as follows:

	INCO	TM-2
Heated to annealing temperature	1600°F in 8 Hours	1575°F in 10 Hours
Held at heat	6 Hours	4 Hours
Cooled in furnace to	500°F in 16 Hours	1200°F in 12 Hours
Held at heat	-	24 Hours
Cooled in furnace to	-	300°F in 18 Hours
Reheated to	1300°F in 6 Hours	1300°F in 8 Hours
Held at heat	14 Hours	12 Hours
Cooled in furnace to	300°F in 18 Hours	12 Hours
Total furnace time	68 Hours	96 Hours

B. Machining Before Heat Treatment

The lug end was removed from each forging, and a 1/2 inch slab to be used for macro-examination was cut from each end of the remaining columnar section. These columns were then cut into two approximately equal sections and bored to an inner diameter consistent with the minimum wall thickness necessary for obtaining the required transverse specimens. The sections at time of heat treatment were approximately 18 inches long, 12 inches in diameter, and 1-1/8 to 1-1/2 inches in wall thickness. (see figure 1.)

C. Heat Treatment

The sections were normalized, austenitized, oil-quenched, and tempered. (see table 2 in the appendix for times and temperatures.) After final tempering the sections were magnafluxed.

Following are the strength levels examined:

Inco steel: 240-260,000 psi.
290-310,000 psi.

TM-2 steel: 200-220,000 psi.
220-240,000 psi.

D. Final Machining and Testing

From each section a set of longitudinal specimens parallel to the forging axis, a set of transverse specimens normal to the forging axis away from the flash line, and a set of transverse flash line specimens were machined. The transverse flash line specimens were directly across the flash line so that the critical section of each specimen was in the center

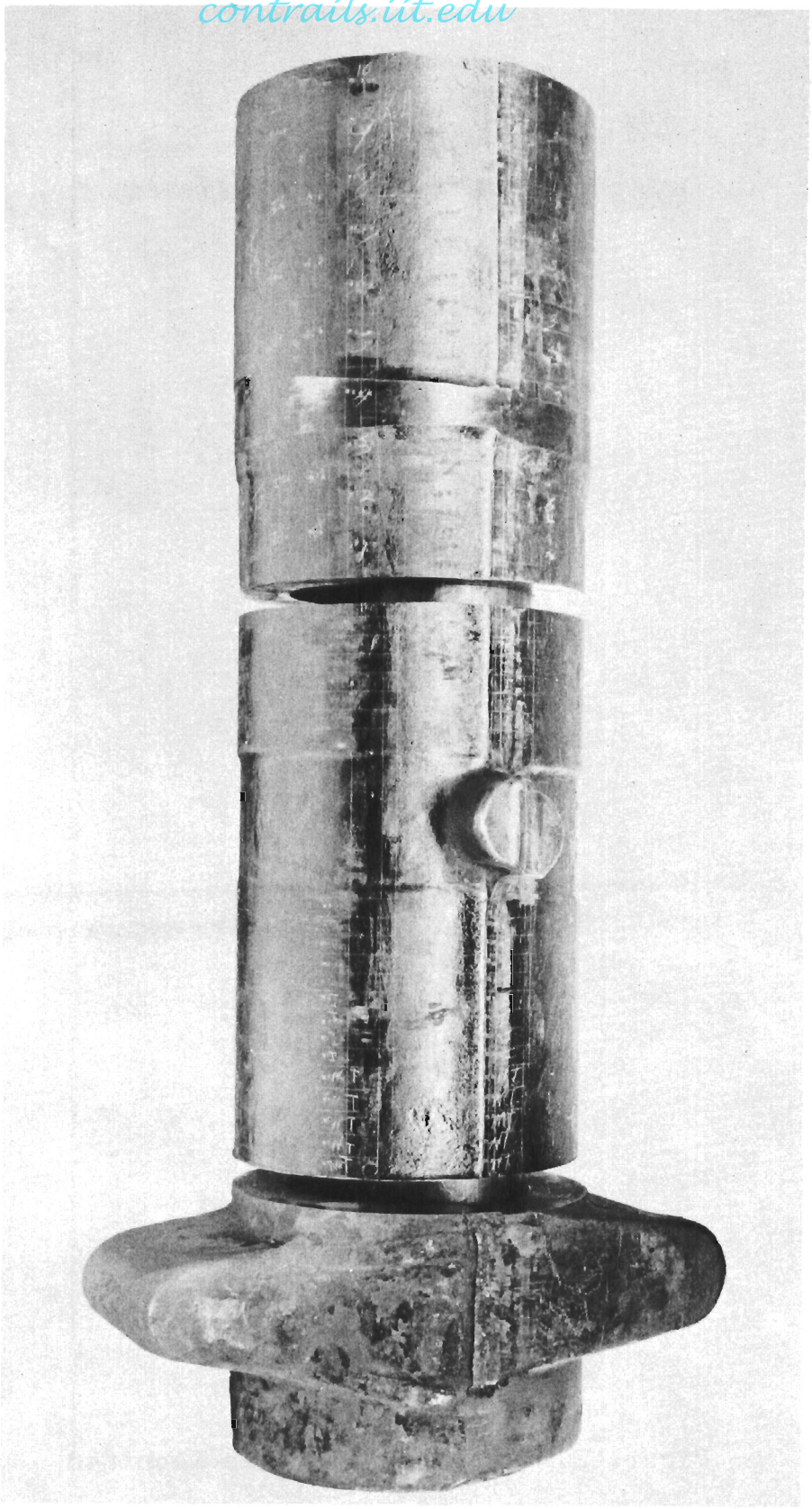


Figure 1. Forging as Machined Prior to Heat Treatment

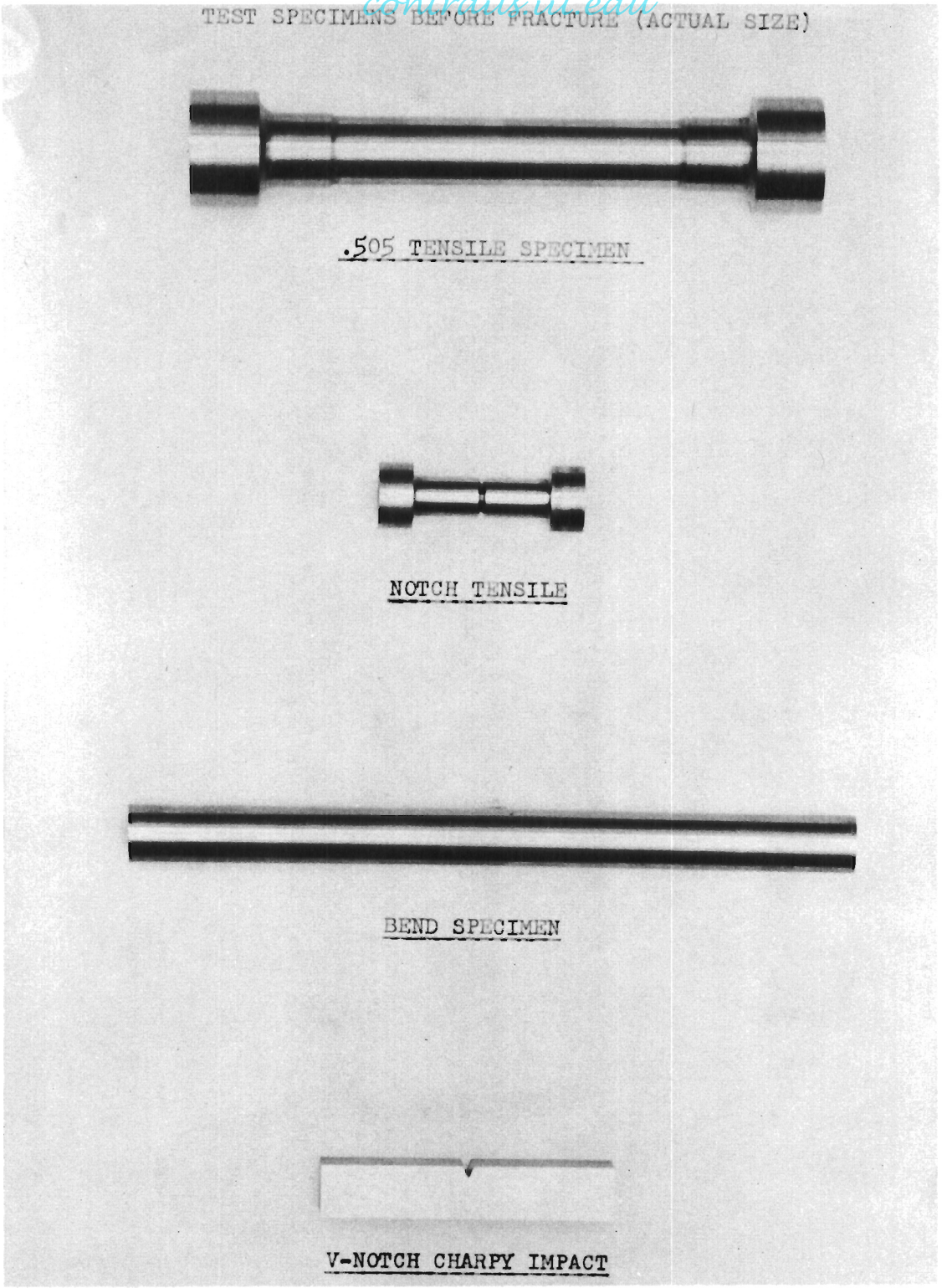


Figure 2. Test Specimens as Machined Prior to Testing

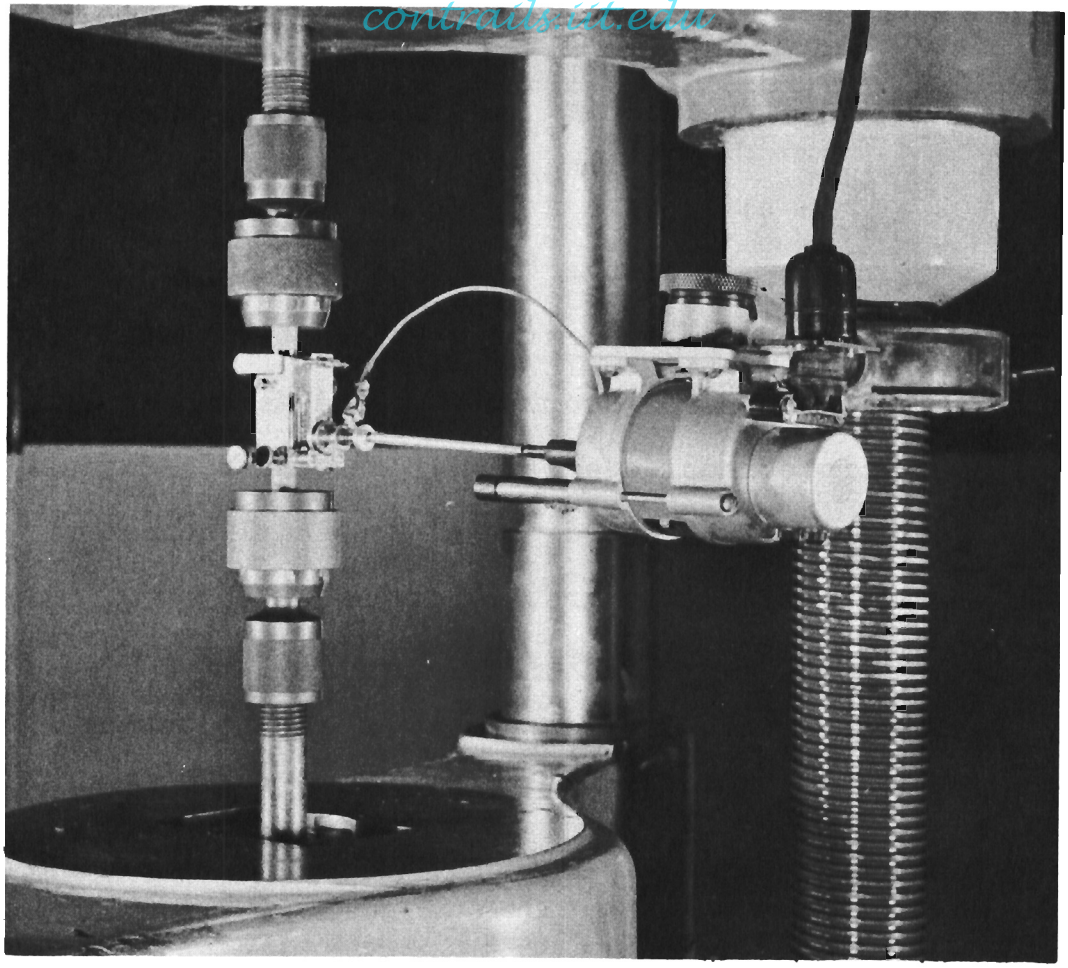


Figure 3. Extensiometer in Position for Recording Load-Strain Curves

of the flash line region. Each set of specimens consisted of the following:

1. Seven Tensile Specimens

Regular .505 inch round specimens, machined in accordance with figure 1 of Federal Specification QQ-M-151a. These were tested at room temperature on a 120,000 pound Baldwin Southwark testing machine. The 0.2% offset yield strength, ultimate strength, percentage elongation in a 2 inch gage length, and percentage reduction in area were determined. A Selsyn type

extensiometer (figure 3) was used to make load strain curves.

2. Ten Notch Tensile Specimens

These were machined with a circumferential 60° V-notch such that 50% of the section area was removed. The radius at the root of the notch was always less than 0.001 inches. Five specimens were tested at room temperature and five at -65°F. The notch strength and notch ductility were determined. All of these tests were conducted by the Metals Research Laboratory, Case Institute of Technology with a special concentric alligning tensile testing fixture. (figure 4)

3. Fifteen Charpy V-Notch Impact Specimens

Three specimens were tested at each of the following temperatures: room temperature, 32°F, 0°F, -65°F, and -100°F. A 264 foot-pounds Tinius-Olsen Change-O-Matic impact testing machine was used.

4. Five Bend Specimens

These were 7/16 inch diameter round by approximately 5 inches long. These were tested at room temperature using the restricted bend method, i.e. the specimen is supported at each end while the load is applied at the center of the specimen. Figure 5 shows a bend test in progress on the 120,000 pound Baldwin Southwark machine.

IV. PROCEDURE - FLASH BUTT WELD TESTS ON INCO STEEL

Four flash butt welded tubes and two non-welded tubes, (to be used for parent metal specimens) all approximately 5-1/2 inches in diameter and 3/4 inches in wall thickness were

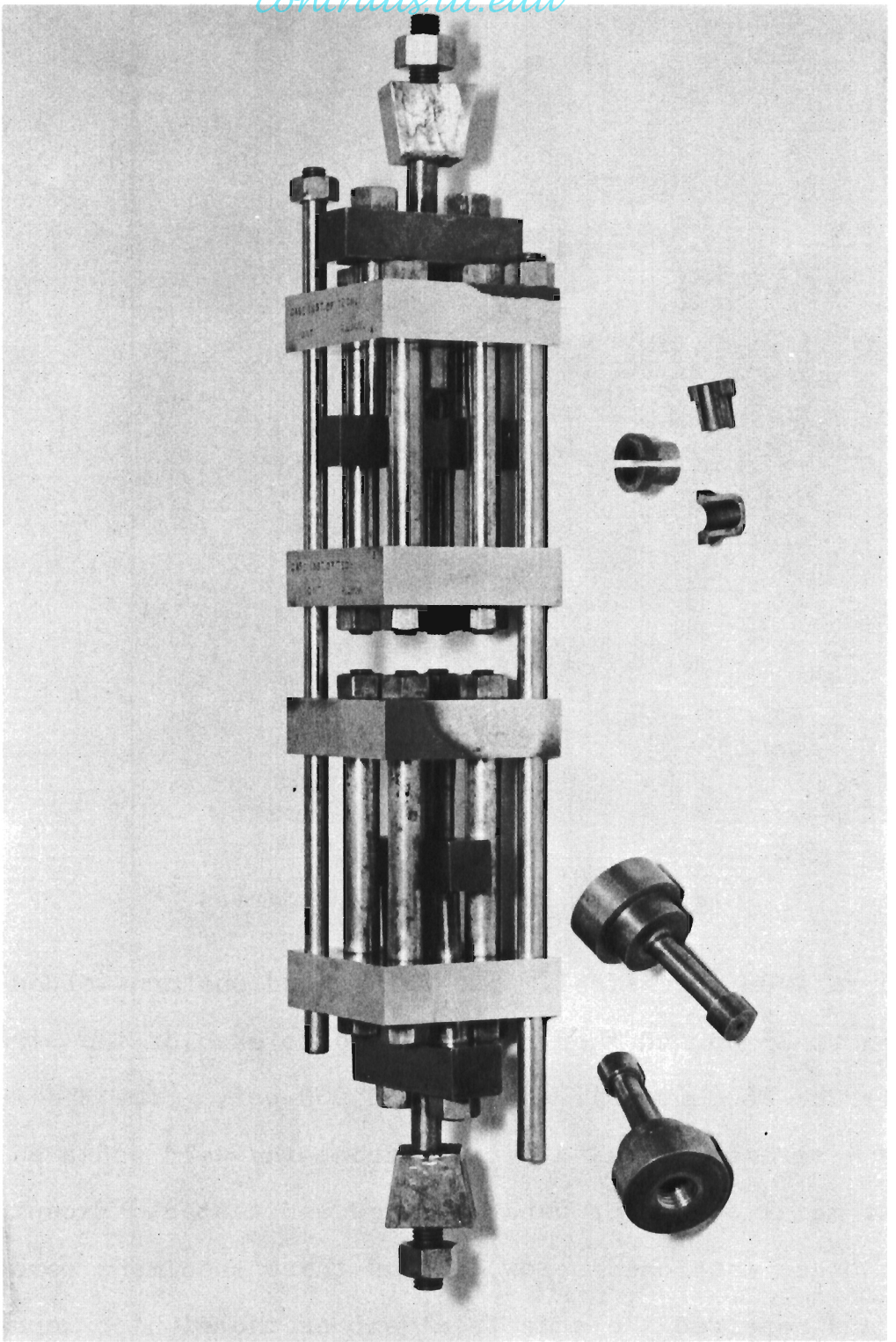


Figure 4. Concentric Notch Tensile Testing Fixture

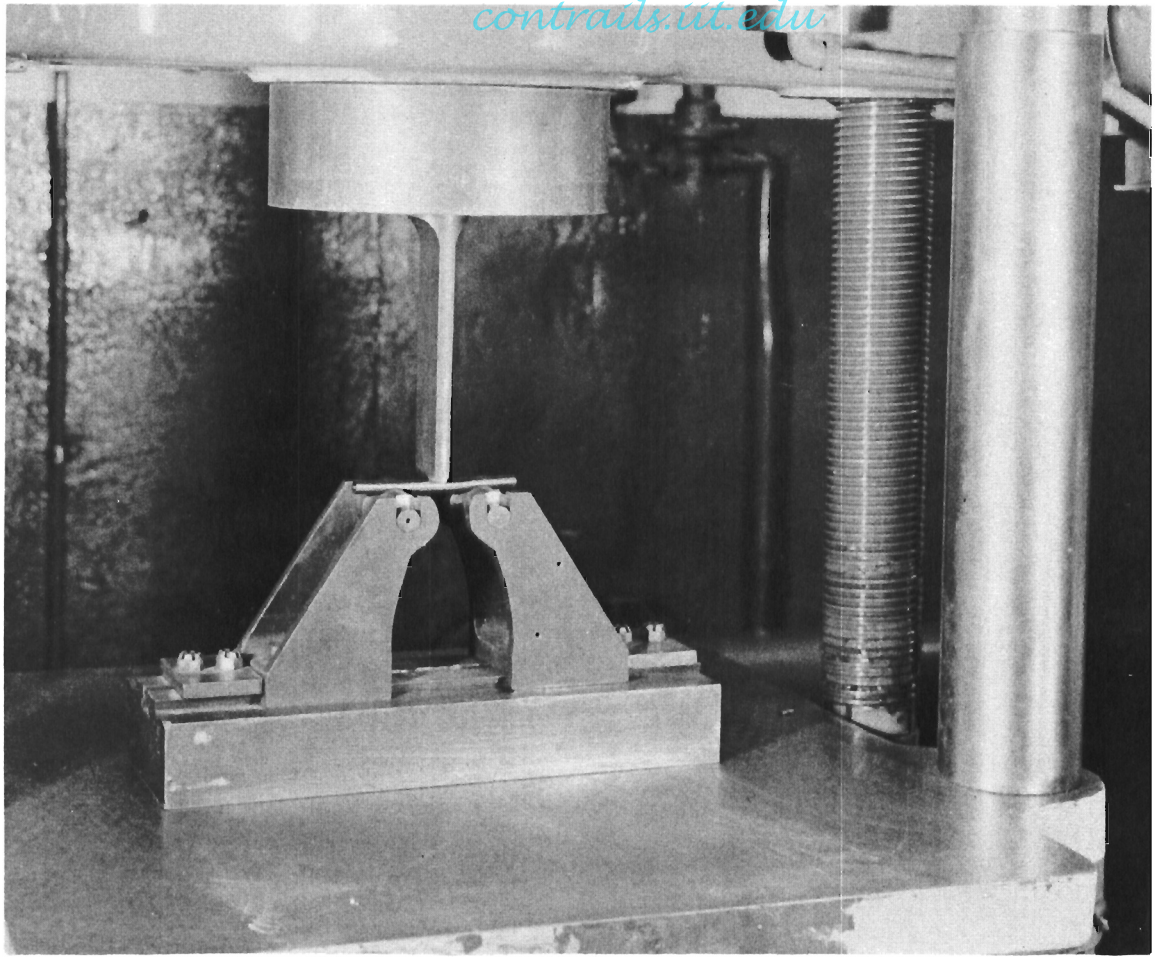


Figure 5. Bend Test in Progress

prepared from Inco steel. Two welded and one non-welded tubes were normalized and then heat treated to each of the strength levels 240-260,000 psi. and 290-310,000 psi. From the tubes at each strength level a set of across-the-weld and a set of parent metal specimens were machined and tested. Except for the changes mentioned below, all of these specimens were the same and received the same treatment as those which were machined from the forged sections. The sets of specimens consisted of the following:

1. Five Tensile Specimens

These were 7/16 inch diameter round specimens. In general they were the same as regular .505 inch diameter round tensile specimens. The wall thickness of the welded assemblies necessitated making the diameter slighly subsize. Tensile strength, percentage elongation, and percentage reduction in area were determined.

2. Ten Notch Tensile Specimens

3. Nine Charpy V-Notch Impact Specimens

Three specimens were tested at each of the following temperatures: room temperature, 32°F., and -65°F.

4. Three Bend Specimens

V. RESULTS

A. Macro Examination of the Forgings

The flow line patterns (figures 7 and 8 of the appendix) were quite normal for forgings of the type used. No abnormal structures, such as those which have been observed in some high silicon high-strength steel forgings, were found.

B. Micro Examination

Typical micro-structures are shown in figure 9 of the appendix.

C. Jominy Hardenability

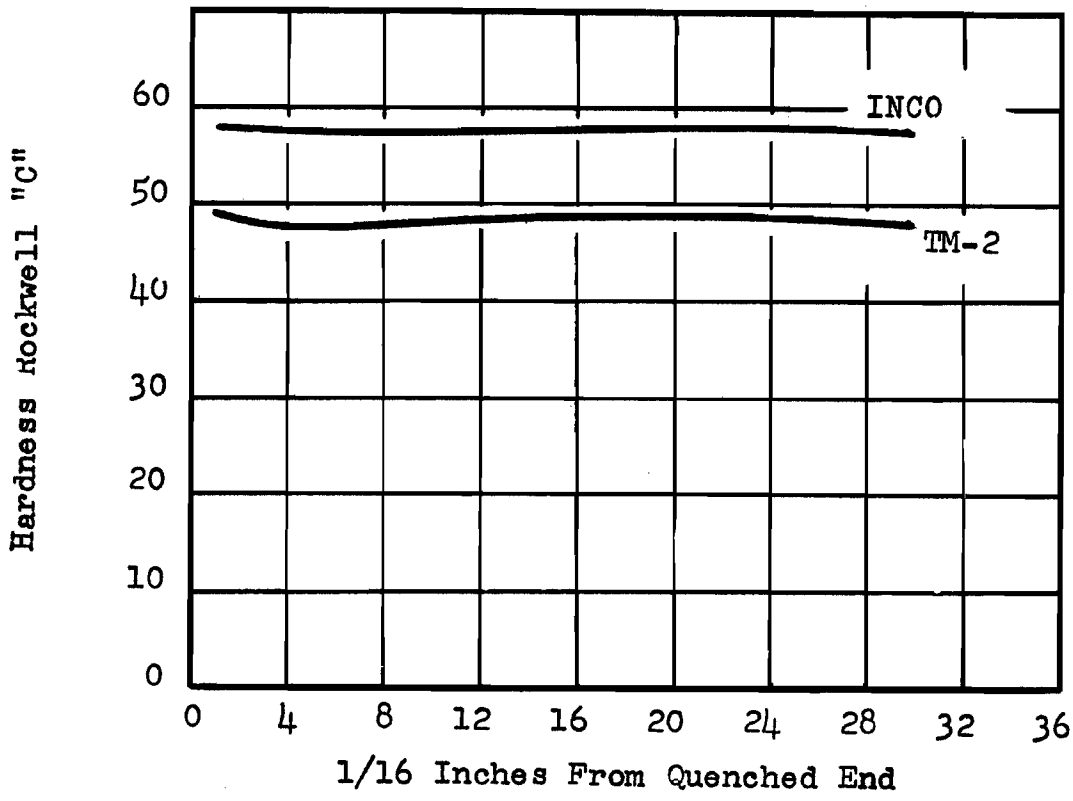


Figure 6. Jominy Hardenability Curves

D. Strength and Ductility Properties

1. Inco Steel 240-260,000 psi.

All tests showed Inco steel to be too brittle and notch sensitive in this strength range to be used as an aircraft structural material.

2. Inco Steel 290-310,000 psi.

Inco steel shows fairly good ductility at this high strength. Furthermore, the steel does not appear to be especially notch sensitive. It should be noted, however, that since only one strength was investigated, the results are not absolutely conclusive. The possibility does exist, to give one example, that at slightly higher tensile strengths the notch-strength to tensile-strength ratio could be considerably less. If that were true, the use of Inco steel in the 290-310,000 psi. strength range would be seriously limited. Perhaps it would be wise to check the properties of Inco steel at the high side of the strength range before the steel is considered for production on a large scale.

3. TM-2 Steel 200-220,000 psi.

The ductility and notch sensitivity properties of TM-2 steel in this strength range are very good, especially in the transverse flash line area.

4. TM-2 Steel 220-240,000 psi.

TM-2 steel also shows quite good properties in this higher strength range particularly in the transverse flash line area. Once again, however, intelligent evaluation is somewhat hindered since only one strength was used.

E. Flash Butt Weld Tests on Inco Steel

240-260,000 psi.

In this range, even though the steel itself has rather poor properties, the weldments were quite good. The across-the-weld properties compared very well to those of the parent metal. The ductility of the parent metal tubes, which had been machined from bar stock, was considerably greater than that of the longitudinal specimens from the Inco forging in this particular strength range. Nevertheless, even with this improvement, the steel was much less ductile than SAE 4340, for example, at this strength.

290-310,000 psi.

In this range the weldments were remarkably good, all tests showing the welds to be strong, fairly ductile, and not especially notch-sensitive. The average strength across-the-weld was 285,600 psi., and only one of six tensile specimens failed in the weld. These results are quite good considering that the upset metal around the weld was machined flush with the adjacent area. It was apparent, however, that the metal in the vicinity of the weld was affected by the welding operation, the out-of-weld failures being somewhat weaker and less ductile than those in the parent metal specimens.

Examination of the fractures of the tensile specimens revealed freckles in in-the-weld, out-of-weld, and parent metal failures; none had been observed in pieces from the forging. A fractured surface showing a comparatively large

freckle was polished enough to make the surface smooth and then was microexamined. The area immediately under the freckle was found to be consistent with the remainder of the specimen in hardness and microstructure.

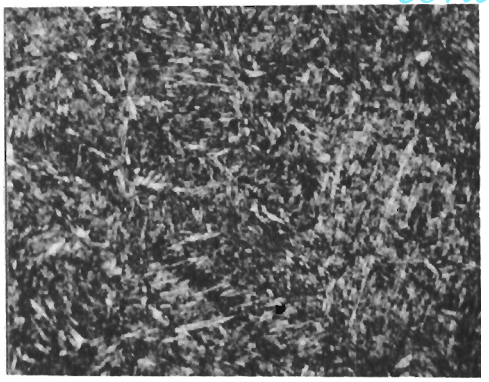
It was observed that the notch-strength of the parent metal was somewhat lower than that of the longitudinal specimens from the forging. Although the drop was not seriously great, it was noticeable. Here again tiny freckles were observed on the fractured surfaces.

It is possible that the differences in properties between the bar stock and the forging, and also the freckles may be due to some alloy segregation which was not present in the critical area of the forging or which was less effective in the forging because of different distribution.

It is conceivable that some further improvement in Inco weldments could be made as the operators gained experience in working with the new steel.

Figure 7. Typical Macro-Etched Section from the Middle of the Forging

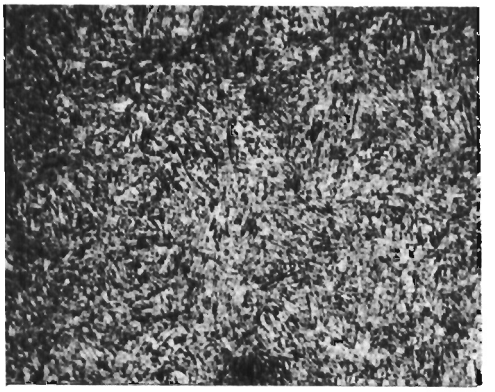
Figure 8. Typical Macro-Etched Section from the End of the Forging



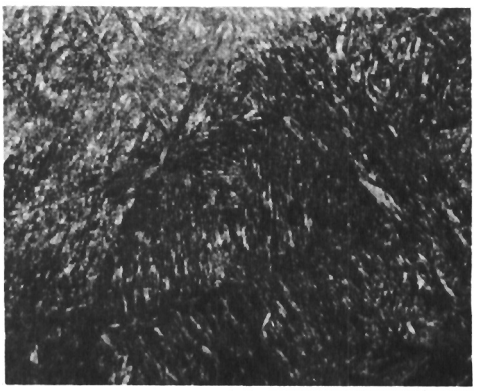
Inco Steel
As Quenched
R/c 56

TM-2 Steel
As Quenched
R/c 49

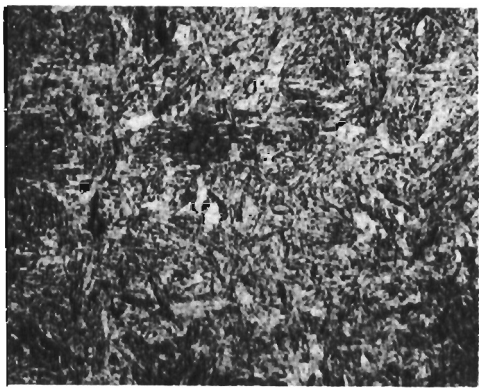
Inco Steel
Tempered 820°F
R/c 50½



TM-2 Steel
Tempered 750°F
R/c 46



Inco Steel
Tempered 500°F
R/c 54½



TM-2 Steel
Tempered 610°F
R/c 48

Figure 9. Typical Microstructures at 500X

TABLE 1

ANALYSES OF STEELS

Element	INCO STEEL					TM-2 STEEL		
	Spec.	Forging		5-3/4" RD.		Spec.	Forging	
		CPT	MILL	CPT	MILL		CPT	MILL
C	.38/.43	.44	.41	.445	.41	.27/ .33	.30	.31
Mn	.60/.90	.83	.82	.80	.82	.60/ .80	.71	.72
P	-	.012	.018	.012	.018	0/ .025	.012	.016
S	-	.010	.010	.010	.010	0/ .025	.015	.015
Si	1.5/1.7	1.58	1.58	1.81	1.58	.40/ .70	.48	.61
Cr	.70/.95	.91	.89	.91	.89	1.0 /1.4	1.23	1.32
Ni	1.8/2.0	1.88	1.89	1.94	1.89	1.85/2.25	2.10	1.91
Mo	.30/.50	.42	.38	.43	.38	.35/ .55	.40	.42
Va	0/.10	.12	.12	.06	.12	-	-	-
Al	0/.08	.15	.08	.134	.08	-	-	-

TABLE 2

HEAT TREAT SCHEDULES

Material	Normalize	Austenitize	Final Draw
Inco Forgings			
240-260,000 psi.	1700°F.-4 Hr.	1650°F-4 Hr.	820°F-4 Hr.
290-310,000 psi.	1700°F.-4 Hr.	1600°F-4 Hr.	500°F-4 Hr.
TM-2 Forgings			
200-220,000 psi.	1650°F.-4 Hr.	1600°F-4 Hr.	750°F-4 Hr.
220-240,000 psi.	1650°F.-4 Hr.	1600°F-4 Hr.	610°F-4 Hr.
Inco Weld Tests			
240-260,000 psi.	1700°F.-6 Hr.	1650°F-6 Hr.	850°F-6 Hr.
290-310,000 psi.	1700°F.-6 Hr.	1650°F-6 Hr.	400°F-6 Hr.

TABLE 3

INCO STEEL
240-260,000 PSI. STRENGTH LEVEL

TENSILE DATA

Specimen Number	Yield Strength psi.	Tensile Strength psi.	% Elong.	% Red. in Area	% Yield of Tensile	Fracture
LONGITUDINAL SPECIMENS						
XE1N		254,800	1-1/2	3.9		Irregular
XE2N	199,200*	259,800	3-1/2	9.6	76.7	Irregular
XE3N		258,000	3	6.6		Irregular
XE4N		260,000	4-1/2	8.1		Irregular
XE5N	200,000*	257,500	-	-	77.7	Irregular
XE6N		252,800	1-1/2	4.3		Irregular
XE7N	200,000*	259,000	3	6.2	77.2	Irregular
Average	199,700	257,400	3	6.4	77.2	
TRANSVERSE SPECIMENS						
XB1N	199,000*	243,200	1	5.0	81.8	Irregular
XB2N		256,000	2-1/2	6.6		Irregular
XB3N	198,200*	250,200	1	5.8	79.2	Irregular
XB4N	199,500*	246,000	1	5.4	81.1	Irregular
XB5N		258,800	3	7.3		Irregular
XB6N		238,500	1/2	3.9		Irregular
XB7N		255,500	-	5.8		Irregular
Average	198,900	249,700	1-1/2	5.7	80.7	
TRANSVERSE FLASH LINE SPECIMENS						
XA1N		196,000	0	2.7		Irregular
XA2N		231,000	0	4.3		Irregular
XA3N	195,800*	204,200	0	2.7	95.9	Irregular
XA4N	198,000*	241,500	1/2	4.7	82.0	Irregular
XA5N	198,200*	242,200	1/2	4.7	81.8	Irregular
XA6N		217,200	0	2.7		Irregular
XA7N		235,500	-	-		Irregular
Average	197,300	223,900	0	3.6	86.6	

* 0.2% Offset Yield Strength

TABLE 4

INCO STEEL
240-260,000 PSI. STRENGTH LEVEL

NOTCH TENSILE DATA

Specimen Identification	Testing Temperature °F.	Notch Strength psi	Notch Ductility %
LONGITUDINAL SPECIMENS			
XE1N	RT	194,500	0.0
XE3N	RT	143,500	0.1
XE5N	RT	167,500	0.9
XE7N	RT	164,000	0.7
XE9N	RT	154,500	0.5
AVERAGE	RT	165,000	0.4
XE2N	-65	180,500	0.3
XE4N	-65	173,000	0.4
XE6N	-65	174,000	0.5
XE8N	-65	147,000	0.4
XE10N	-65	142,500	0.5
AVERAGE	-65	163,500	0.4
TRANSVERSE SPECIMENS			
XB1N	RT	232,000	0.7
XB3N	RT	239,000	0.4
XB5N	RT	192,000	0.9
XC2N	RT	198,500	0.2
XC4N	RT	219,000	0.2
Average	RT	216,100	0.5
XB2N	-65	199,500	0.5
XB4N	-65	167,700	0.9
XC1N	-65	198,500	0.2
XC3N	-65	169,500	0.3
XC5N	-65	162,500	0.2
AVERAGE	-65	179,500	0.4
TRANSVERSE FLASH LINE SPECIMENS			
XA1N	RT	183,000	0.0
XA3N	RT	186,000	0.6
XA5N	RT	186,500	0.2
XD2N	RT	178,500	1.3
XD4N	RT	171,500	0.1
AVERAGE	RT	181,000	0.4
XA2N	-65	169,000	0.6
XA4N	-65	167,500	0.1
XD1N	-65	141,000	0.3
XD3N	-65	147,500	0.2
XD5N	-65	147,500	0.0
AVERAGE	-65	154,500	0.2

TABLE 5

INCO STEEL
240-260,000 PSI. STRENGTH LEVEL

CHARPY V-NOTCH IMPACT DATA

Test Temp. °F.	LONGITUDINAL SPECIMENS			TRANSVERSE SPECIMENS			TRANSVERSE FLASH LINE SPECIMENS		
	Spec. No.	Impact Ft-Lbs.	Hard R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c
RT	XE1N	4	50	XC1N	5	50-½	XD1N	4	50-½
RT	XE6N	4	51	XC6N	4	50-½	XD6N	3	50-½
RT	XE11N	4	50-½	XC11N	4	50-½	XD11N	4	50-½
RT	AVERAGE	4	50-½	AVERAGE	4	50-½	AVERAGE	4	50-½
32°F	XE2N	4		XC2N	4		XD2N	4	
32°F	XE7N	5		XC7N	4		XD7N	4	
32°F	XE12N	4		XC12N	4		XD12N	4	
32°F	AVERAGE	4		AVERAGE	4		AVERAGE	4	
0°F	XE3N	4		XC3N	4		XD3N	3	
0°F	XE8N	4		XC8N	4		XD8N	3	
0°F	XE13N	4		XC13N	4		XD13N	4	
0°F	AVERAGE	4		AVERAGE	4		AVERAGE	3	
-65°F	XE4N	3		XC4N	3		XD4N	2	
-65°F	XE9N	3		XC9N	3		XD9N	3	
-65°F	XE14N	4		XC14N	4		XD14N	3	
-65°F	AVERAGE	3		AVERAGE	3		AVERAGE	3	
-100°F	XE5N	4		XC5N	-		XD5N	3	
-100°F	XE10N	3		XC10N	4		XD10N	2	
-100°F	XE15N	3		XC15N	4		XD15N	4	
-100°F	AVERAGE	3		AVERAGE	4		AVERAGE	3	

TABLE 6

INCO STEEL
240/260,000 PSI. STRENGTH LEVEL

BEND DATA

Specimen Number	Load Lbs.	Outside Bend Angle, Degrees
LONGITUDINAL SPECIMENS		
XE1N	7500	5
XE2N	7550	5
XE3N	7800	15
XE4N	7950	10
XE5N	7350	10
Average	7650	10
TRANSVERSE SPECIMENS		
XB1N	7700	10
XB2N	7000	5
XB3N	7550	10
XB4N	7200	5
XB5N	7850	15
Average	7450	10
TRANSVERSE FLASH LINE SPECIMENS		
XA1N	8100	15
XA2N	7400	10
XA3N	6700	5
XA4N	6950	5
XA5N	7550	10
Average	7350	10

TABLE 7

INCO STEEL
290-310,000 PSI. STRENGTH LEVEL

TENSILE DATA

Specimen Number	Yield Strength psi.	Tensile Strength psi.	% Elong.	% Red. in Area	% Yield of Tensile	Fracture
LONGITUDINAL SPECIMENS						
VE1N		296,000	10	25.8		
VE2N	242,500*	297,000	7-1/2	20.6	81.6	1/2 Cup
VE3N	241,500*	297,000	8-1/2	24.1	81.3	1/2 Cup
VE4N	241,200*	298,200	8-1/2	26.2	80.9	1/2 Cup
VE5N		297,800	9	25.8		Irregular
VE6N		295,500	8	23.4		Irregular
VE7N		296,000	6	14.5		1/2 Cup
VE8N		295,000	8	23.7		Full Cup
Average	241,700	296,600	8	23.0	81.3	
TRANSVERSE SPECIMENS						
VB1N		296,000	3	8.1		Irregular
VB2N	237,000*	296,000	4	9.2	80.1	Irregular
VB3N		295,000	4	4.3		Irregular
VB4N	240,000*	295,500	5	13.0	81.2	Irregular
VB5N		-	4-1/2	11.9		Irregular
VB6N	238,500*	295,500	4	10.4	80.7	Irregular
VB7N		295,500	4	9.2		Irregular
Average	238,500	295,600	4	9.4	80.7	
TRANSVERSE FLASH LINE SPECIMENS						
VA1N		275,000	1	4.7		1/2 Cup
VA2N	237,500*	285,000	1	5.0	83.3	Irregular
VA3N	238,000*	266,000	1	4.7	89.5	Irregular
VA4N		278,000	1	5.4		Irregular
VA5N		275,500	1	5.4		1/2 Cup
VA6N		245,000	1/2	3.5		1/2 Cup
VA7N	234,500*	272,500	1	5.0	86.1	Irregular
Average	236,700	271,000	1	4.8	86.3	

* 0.2% Offset Yield Strength

TABLE 8

INCO STEEL
290-310,000 PSI. STRENGTH LEVEL

NOTCH TENSILE DATA

Specimen Identification	Testing Temperature °F	Notch Strength psi.	Notch Ductility %
LONGITUDINAL SPECIMENS			
VE1N	RT	317,000	1.9
VE3N	RT	301,000	1.5
VE5N	RT	291,000	1.6
VE7N	RT	304,000	1.3
VE9N	RT	301,000	1.2
AVERAGE	RT	303,000	1.5
VE2N	-65	301,000	1.2
VE4N	-65	285,000	1.6
VE6N	-65	295,000	0.9
VE8N	-65	283,000	1.0
VE10N	-65	272,000	1.1
AVERAGE	-65	287,000	1.2
TRANSVERSE SPECIMENS			
VB1N	RT	263,500	0.6
VB3N	RT	245,000	0.3
VB5N	RT	265,000	0.1
VC2N	RT	248,000	0.5
VC4N	RT	287,000	1.3
AVERAGE	RT	262,000	0.6
VB2N	-65	285,000	1.3
VB4N	-65	235,000	0.5
VC1N	-65	253,500	0.9
VC3N	-65	242,500	1.1
VC5N	-65	263,000	0.6
AVERAGE	-65	256,000	0.9
TRANSVERSE FLASH LINE SPECIMENS			
VA1N	RT	262,500	0.6
VA3N	RT	269,000	0.8
VA5N	RT	250,000	1.0
VD2N	RT	268,000	0.9
VD4N	RT	273,000	1.1
AVERAGE	RT	264,500	0.9
VA2N	-65	237,000	0.5
VA4N	-65	243,000	0.6
VD1N	-65	243,000	0.6
VD3N	-65	261,500	1.0
VD5N	-65	251,500	1.1
AVERAGE	-65	247,000	0.8

TABLE 9

INCO STEEL
290/310,000 PSI. STRENGTH LEVEL

CHARPY V-NOTCH IMPACT DATA

Test Temp. F	LONGITUDINAL SPECIMENS			TRANSVERSE SPECIMENS			TRANSVERSE FLASH LINE SPECIMENS		
	Spec. No.	Impact Ft-Lbs.	Hard. R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c
RT	VE1N	19	54-½	VC1N	7	54-½	VD1N	7	54-½
RT	VE6N	18	54-½	VC6N	9	54-½	VD6N	7	55
RT	VE11N	18	55	VC11N	10	55	VD11N	8	54-½
RT	AVERAGE	18	54-½	AVERAGE	9	54-½	AVERAGE	7	54-½
32°F	VE2N	16		VC2N	10		VD2N	-	
32°F	VE7N	12		VC7N	12		VD7N	8	
32°F	VE12N	17		VC12N	7		VD12N	8	
32°F	AVERAGE	15		AVERAGE	10		AVERAGE	8	
0°F	VE3N	16		VC3N	7		VD3N	8	
0°F	VE8N	18		VC8N	7		VD8N	10	
0°F	VE13N	14		VC13N	8		VD13N	8	
0°F	AVERAGE	16		AVERAGE	7		AVERAGE	9	
-65°F	VE4N	14		VC4N	8		VC4N	6	
-65°F	VE9N	16		VC9N	6		VC9N	8	
-65°F	VE14N	14		VC14N	6		VC14N	7	
-65°F	AVERAGE	15		AVERAGE	7		AVERAGE	7	
-100°F	VE5N	10		VC5N	6		VD5N	7	
-100°F	VE10N	12		VC10N	6		VD10N	8	
-100°F	VE15N	8		VC15N	7		VD15N	6	
-100°F	AVERAGE	10		AVERAGE	6		AVERAGE	7	

TABLE 10

INCO STEEL
290/310,000 PSI. STRENGTH LEVEL

BEND DATA

Specimen Number	Load Lbs.	Outside Bend Angle, Degrees
LONGITUDINAL SPECIMENS		
VE1N	10450	40
VE2N	10150	40
VE3N	10500	30
VE4N	9700	25
VE5N	10100	--
Average	10200	35
TRANSVERSE SPECIMENS		
VB1N	9300	15
VB2N	9650	25
VB3N	8950	15
VB4N	10000	30
VB5N	10250	35
Average	9650	25
TRANSVERSE FLASH LINE SPECIMENS		
VA1N	7450	5
VA2N	7200	5
VA3N	7900	10
VA4N	8000	10
VA5N	8200	10
Average	7750	10

TABLE 11

TM-2 STEEL
200/220,000 PSI. STRENGTH LEVEL

TENSILE DATA

Specimen Number	Yield Strength psi.	Tensile Strength psi.	% Elong.	% Red. in Area	% Yield of Tensile	Fracture
LONGITUDINAL SPECIMENS						
ZE1P		219,800	12	46.3		3/4 Cup
ZE2P		220,800	11	45.5		Full Cup
ZE3P		221,200	11-1/2	46.6		3/4 Cup
ZE4P		217,000	11	46.0		Full Cup
ZE5P	192,000*	220,200	11-1/2	45.8	87.2	3/4 Cup
ZE6P	195,000*	223,000	11-1/2	45.8	87.4	3/4 Cup
ZE7P	195,500*	224,000	11-1/2	46.0	87.3	3/4 Cup
Average	194,200	220,900	11-1/2	46.0	87.3	
TRANSVERSE SPECIMENS						
ZB1P	191,200*	220,200	9	34.4	86.8	3/4 Cup
ZB2P	191,500*	219,500	7	23.7	87.2	3/4 Cup
ZB3P		219,200	9	33.1		Full Cup
ZB4P		219,500	7	23.0		1/2 Cup
ZB5P		219,800	9-1/2	34.7		1/2 Cup
ZB6P		218,800	9	34.7		3/4 Cup
ZB7P	188,200*	218,200	7-1/2	28.8	86.3	3/4 Cup
Average	190,300	219,300	8-1/2	30.3	86.8	
TRANSVERSE FLASH LINE SPECIMENS						
ZA1P		218,800	6-1/2	22.0		Irregular
ZA2P	189,200*	218,800	6	20.6	86.5	1/2 Cup
ZA3P		217,500	6	20.6		1/2 Cup
ZA4P	188,000*	217,500	5-1/2	17.0	86.4	Irregular
ZA5P	188,500*	218,000	6-1/2	20.6	86.5	Irregular
ZA6P		217,000	6	11.5		1/2 Cup
ZA7P		217,200	6-1/2	17.7		1/2 Cup
Average	188,600	217,800	6	18.6	86.5	

* 0.2% Offset Yield Strength

TABLE 12

TM-2 STEEL
200-220,000 PSI. STRENGTH LEVEL

NOTCH TENSILE DATA

Specimen Identification	Testing Temperature °F.	Notch Strength psi.	Notch Ductility %
LONGITUDINAL SPECIMENS			
ZE1P	RT	278,500	2.2
ZE3P	RT	281,000	2.0
ZE5P	RT	288,000	2.6
ZE7P	RT	289,000	2.2
ZE9P	RT	279,000	2.2
AVERAGE	RT	283,000	2.2
ZE2P	-65	269,000	1.1
ZE4P	-65	261,500	1.2
ZE6P	-65	271,500	1.7
ZE8P	-65	273,000	2.1
ZE10P	-65	261,000	1.6
AVERAGE	-65	267,000	1.5
TRANSVERSE SPECIMENS			
ZB1P	RT	281,000	2.0
ZB3P	RT	279,000	2.1
ZB5P	RT	271,000	3.3
ZC2P	RT	279,000	2.2
ZC4P	RT	277,000	2.3
AVERAGE	RT	277,000	2.4
ZB2P	-65	268,000	2.0
ZB4P	-65	263,000	1.5
ZC1P	-65	271,000	1.4
ZC3P	-65	267,500	1.7
ZC5P	-65	253,000	1.3
AVERAGE	-65	264,500	1.6
TRANSVERSE FLASH LINE SPECIMENS			
ZA1P	RT	278,000	1.7
ZA3P	RT	277,000	2.0
ZA5P	RT	267,000	2.2
ZD2P	RT	275,000	2.4
ZD4P	RT	266,000	2.0
AVERAGE	RT	273,000	2.1
ZA2P	-65	237,000	0.7
ZA4P	-65	264,000	0.7
ZD1P	-65	254,500	2.4
ZD3P	-65	255,500	1.9
ZD5P	-65	259,000	1.9
AVERAGE	-65	254,000	1.5

TABLE 13

TM-2 STEEL
200/220,000 PSI. STRENGTH LEVEL

CHARPY V-NOTCH IMPACT DATA

Test Temp. °F	LONGITUDINAL SPECIMENS			TRANSVERSE SPECIMENS			TRANSVERSE FLASH LINE SPECIMENS		
	Spec. No.	Impact Ft-Lbs.	Hard. R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c
RT	ZE1P	-	44-½	ZC1P	15	46	ZD1P	9	46
RT	ZE6P	17	45-½	ZC6P	12	46	ZD6P	9	46
RT	ZE11P	18	46	ZC11P	15	46	ZD11P	12	46
RT	AVERAGE	17-½	45-½	AVERAGE	14	46	AVERAGE	10	46
32°F	ZE2P	18		ZC2P	11		ZD2P	9	
32°F	ZE7P	18		ZC7P	12		ZD7P	11	
32°F	ZE12P	17		ZC12P	16		ZD12P	12	
32°F	AVERAGE	18		AVERAGE	13		AVERAGE	11	
0°F	ZE3P	15		ZC3P	14		ZD3P	9	
0°F	ZE8P	12		ZC8P	14		ZD8P	10	
0°F	ZE13P	18		ZC13P	15		ZD13P	12	
0°F	AVERAGE	15		AVERAGE	14		AVERAGE	10	
-65°F	ZE4P	16		ZC4P	11		ZD4P	8	
-65°F	ZE9P	11		ZC9P	12		ZD9P	9	
-65°F	ZE14P	15		ZC14P	15		ZD14P	10	
-65°F	AVERAGE	14		AVERAGE	13		AVERAGE	9	
-100°F	ZE5P	16		ZC5P	13		ZD5P	6	
-100°F	ZE10P	--		ZC10P	12		ZD10P	10	
-100°F	ZE15P	14		ZC15P	12		ZD15P	10	
-100°F	AVERAGE	15		AVERAGE	12		AVERAGE	9	

TABLE 14

TM-2 STEEL
200/220,000 PSI. STRENGTH LEVEL

BEND DATA

Specimen Number	Load Lbs.	Outside Bend Angle, Degrees
LONGITUDINAL SPECIMENS		
ZE1P	9350	180
ZE2P	7300	180
ZE3P	7150	180
ZE4P	7300	180
ZE5P	6850	90
Average	7600	160
TRANSVERSE SPECIMENS		
ZB1P	6550	75
ZB2P	6450	40
ZB3P	6050	20
ZB4P	6650	55
ZB5P	6750	70
Average	6500	50
TRANSVERSE FLASH LINE SPECIMENS		
ZA1P	6400	45
ZA2P	6050	25
ZA3P	6250	30
ZA4P	5150	5
ZA5P	5950	15
Average	5950	25

TABLE 15

TM-2 STEEL
220/240,000 PSI. STRENGTH LEVEL

TENSILE DATA

Specimen Number	Yield Strength psi.	Tensile Strength psi.	% Elong.	% Red. in Area	% Yield of Tensile	Fracture
LONGITUDINAL SPECIMENS						
YE2P		238,800	11	42.6		1/2 Cup
YE3P	195,800*	238,200	11	39.4	82.2	Full Cup
YE4P		233,800	10	41.2		Full Cup
YE5P	194,500*	238,000	11	43.1	81.7	1/2 Cup
YE6P		237,800	10-1/2	42.2		Full Cup
YE7P	195,200*	237,800	11	43.4	82.1	1/2 Cup
YE8P		234,200	10	41.9		3/4 Cup
Average	195,200	236,900	10-1/2	42.0	82.0	
TRANSVERSE SPECIMENS						
YB1P	200,000*	238,500	7-1/2	33.0	83.9	1/2 Cup
YB2P		238,500	7-1/2	34.5		1/2 Cup
YB3P		237,500	6	20.1		3/4 Cup
YB4P		237,500	5-1/2	24.6		1/2 Cup
YB5P		237,500	8	36.3		3/4 Cup
YB6P		237,500	8-1/2	38.5		3/4 Cup
YB7P	197,000*	238,000	8	33.5	82.8	3/4 Cup
Average	198,500	237,900	7-1/2	31.5	83.3	
TRANSVERSE FLASH LINE SPECIMENS						
YA1P		237,500	2	7.6		1/2 Cup
YA2P	199,000*	236,000	1-1/2	7.1	84.3	1/2 Cup
YA3P	199,000*	239,000	4	10.3	83.3	1/2 Cup
YA4P		237,000	4	16.6		Irregular
YA5P		237,500	3-1/2	9.8		1/2 Cup
YA6P	195,000*	237,000	3-1/2	10.3	82.3	Irregular
YA7P		238,000	5	20.1		1/2 Cup
Average	197,700	237,400	3-1/2	11.7	83.3	

* 0.2% Offset Yield Strength

TABLE 16

TM-2 STEEL
220-240,000 PSI. STRENGTH LEVEL

NOTCH TENSILE DATA

Specimen Identification	Testing Temperature °F.	Notch Strength psi.	Notch Ductility %
LONGITUDINAL SPECIMENS			
YE1P	RT	291,000	1.6
YE3P	RT	289,000	1.6
YE5P	RT	292,000	2.3
YE8P	RT	290,000	2.3
YE9P	RT	297,000	1.7
AVERAGE	RT	292,000	1.9
YE2P	-65	284,000	1.4
YE4P	-65	287,000	1.5
YE6P	-65	280,000	2.2
YE7P	-65	292,000	1.9
YE10P	-65	289,000	2.2
AVERAGE	-65	286,000	1.8
TRANSVERSE SPECIMENS			
YB1P	RT	276,000	2.8
YB3P	RT	278,000	1.8
YB5P	RT	284,000	2.1
YC2P	RT	287,000	3.0
YC4P	RT	285,000	2.3
AVERAGE	RT	282,000	2.4
YB2P	-65	277,000	2.3
YB4P	-65	274,000	1.9
YC1P	-65	308,000	1.9
YC3P	-65	290,000	2.3
YC5P	-65	296,000	2.7
AVERAGE	-65	289,000	2.2
TRANSVERSE FLASH LINE SPECIMENS			
YA1P	RT	274,000	1.8
YA3P	RT	270,000	2.5
YA5P	RT	269,000	2.4
YD2P	RT	280,000	1.8
YD4P	RT	285,000	1.6
AVERAGE	RT	276,000	2.0
YA2P	-65	272,000	2.2
YA4P	-65	250,000	1.9
YD1P	-65	260,000	1.4
YD3P	-65	272,000	2.1
YD5P	-65	283,000	1.8
AVERAGE	-65	267,000	1.9

TABLE 17

TM-2 STEEL
220-240,000 PSI. STRENGTH LEVEL

CHARPY V-NOTCH IMPACT DATA

Test Temp. °F	LONGITUDINAL SPECIMENS			TRANSVERSE SPECIMENS			TRANSVERSE FLASH LINE SPECIMENS		
	Spec. No.	Impact Ft-Lbs.	Hard. R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c	Spec. No.	Impact Ft-Lbs.	Hard. R/c
RT	YE1P	16	47-½	YC1P	12	47-½	YD1P	10	48
RT	YE2P	16	48	YC2P	--	48	YD2P	10	48
RT	YE3P	16	48	YC3P	12	47-½	YD3P	12	48
RT	YE4P	16	47-½	YC4P	14	48	YD4P	11	47-½
RT	YE5P	16	48	YC5P	--	47-½	YD5P	10	48
RT	AVERAGE	16	48	AVERAGE	13	47-½	AVERAGE	10-½	48
32°F	YE6P	17		YC6P	14		YD6P	12	
32°F	YE10P	16		YC10P	14		YD10P	11	
32°F	----	--		YC14P	12		YD14P	9	
32°F	AVERAGE	16-½		AVERAGE	13		AVERAGE	11	
0°F	YE7P	14		YC7P	14		YD7P	12	
0°F	YE11P	16		YC11P	14		YD11P	11	
0°F	YE14P	16		----	--		YD15P	12	
0°F	AVERAGE	15		AVERAGE	14		AVERAGE	12	
-65°F	YE8P	14		YC8P	11		YD8P	8	
-65°F	YE12P	14		YC12P	11		YD12P	8	
-65°F	----	--		--	--		--	--	
-65°F	AVERAGE	14		AVERAGE	11		AVERAGE	8	
-100°F	YE9P	10		YC9P	10		YD9P	8	
-100°F	YE13P	12		YC13P	12		YD13P	8	
-100°F	YE15P	11		YC15P	10		----	--	
-100°F	AVERAGE	11		AVERAGE	11		AVERAGE	8	

TABLE 18

TM-2 STEEL
220/240,000 PSI. STRENGTH LEVEL

BEND DATA

Specimen Number	Load Lbs.	Outside Bend Angle, Degrees
LONGITUDINAL SPECIMENS		
YE1	6200	95
YE2	6200	150
YE3	6150	155
YE4	6200	150
YE5	6150	150
YE6	6000	180
Average	6150	145
TRANSVERSE SPECIMENS		
YB1	6000	60
YB2	6050	50
YB3	6100	75
YB4	6100	55
YB5	6150	80
Average	6100	65
TRANSVERSE FLASH LINE SPECIMENS		
YA1	5800	25
YA2	5700	25
YA3	6000	25
YA4	5900	25
YA5	5700	20
Average	5800	25

TABLE 19

FLASH BUTT WELD TESTS ON INCO STEEL

TENSILE DATA

Specimen Number	Tensile Strength, psi	% Elong.	% Red. in Area	Fracture
		240-260,000 PSI. ACROSS-THE-WELD SPECIMENS		
XH1N	162,000	0	2.7	In-the-weld
XH2N	251,300	3-½	8.0	Near-the-weld
XH3N	230,700	1-½	5.3	In-the-weld
XI1N	253,300	7	14.0	In-the-weld
XI2N	185,300	½	4.7	In-the-weld; penetrator
XI3N	251,300	4	7.3	In-the-weld
AVERAGE	222,300	3	7.0	
		240-260,000 PSI. PARENT METAL SPECIMENS		
XK1N	256,000	8	13.3	Irregular
XK2N	256,700	8	18.7	Irregular
XK3N	257,300	8	14.7	1/2 Cup
XK4N	256,700	8-½	16.0	Irregular
XK5N	256,700	8-½	14.7	1/2 Cup
AVERAGE	256,700	8	15.5	
		290-310,000 PSI. ACROSS-THE-WELD SPECIMENS		
VF1N	296,700	4	9.3	Out-of-weld; freckle
VF2N	260,700	1	4.7	Out-of-weld; freckle
VF3N	284,000	3	6.0	Out-of-weld; freckle
VG1N	295,300	4-½	7.3	Out-of-weld; freckle
VG2N	275,500	1	6.0	In-the-weld; freckle
VG3N	301,300	6	8.7	Out-of-weld; freckle
AVERAGE	285,600	3	7.0	
		290-310,000 PSI. PARENT METAL SPECIMENS		
VJ1N	303,300	11	21.3	1/2 Cup
VJ2N	302,700	6	10.1	1/2 Cup; freckle
VJ3N	302,700	10-½	22.7	1/2 Cup
VJ4N	302,000	7-½	12.8	3/4 Cup; freckle
VJ5N	302,000	11	23.3	1/2 Cup
AVERAGE	302,500	9	18.0	

TABLE 20

FLASH BUTT WELD TESTS ON INCO STEEL

NOTCH TENSILE DATA

TESTED AT ROOM TEMPERATURE			TESTED AT -65°F.		
Specimen Number	Notch Strength psi.	Notch Ductility %	Specimen Number	Notch Strength psi.	Notch Ductility %
240-260,000 PSI. ACROSS-THE-WELD SPECIMENS					
XH1N	208,000	0.7	XH2N	188,000	0.5
XH3N	193,500	0.5	XH4N	212,500	0.9
XH5N	205,000	1.2	XI1N	155,000	0.3
XI2N	207,000	0.8	XI3N	166,500	0.7
XI4N	227,000	0.6	XI5N	174,500	0.1
Average	208,000	0.8	Average	179,500	0.5
240-260,000 PSI. PARENT METAL SPECIMENS					
XK1N	225,000	1.0	XK2N	201,000	0.7
XK3N	221,500	1.0	XK4N	222,000	0.4
XK5N	222,500	1.5	XK6N	194,000	0.6
XK7N	213,000	0.9	XK8N	177,500	0.2
XK9N	223,500	1.0	XK10N	196,500	1.0
Average	221,000	1.1	Average	198,000	0.6
290-310,000 PSI. ACROSS-THE-WELD SPECIMENS					
VF1N	243,000	1.1	VF2N	223,000	0.5
VF3N	232,500	0.9	VF4N	246,000	0.6
VF5N	262,500	1.0	VG1N	230,000	0.7
VG2N	236,000	1.0	VG3N	224,000	0.7
VG4N	256,000	1.0	VG5N	263,000	0.3
Average	246,000	1.0	Average	237,000	0.6
290-310,000 PSI. PARENT METAL SPECIMENS					
VJ1N	270,000	1.1	VJ2N	239,000	0.8
VJ3N	272,000	0.9	VJ4N	253,000	0.7
VJ5N	285,000	1.6	VJ6N	256,000	0.9
VJ7N	265,500	1.6	VJ8N	265,500	0.6
VJ9N	258,500	1.4	VJ10N	249,000	1.0
Average	270,000	1.3	Average	252,500	0.8

TABLE 21

FLASH BUTT WELD TESTS ON INCO STEEL

CHARPY V-NOTCH IMPACT DATA

ROOM TEMPERATURE			32°F.		-65°F.	
Specimen Number	Impact Ft-Lbs.	Hardness R/c	Specimen Number	Impact Ft-Lbs.	Specimen Number	Impact Ft-Lbs.
240-260,000 PSI. ACROSS-THE-WELD SPECIMENS						
XH1N	8	-	XH2N	7	XH3N	7
XH4N	9	-	XH5N	4	XI3N	5
XI1N	8	-	XI2N	8	XI4N	6
AVERAGE	8	-	AVERAGE	6	AVERAGE	6
240-260,000 PSI. PARENT METAL SPECIMENS						
XK1N	8	50	XK2N	7	XK3N	7
XK4N	10	50	XK5N	7	XK6N	7
XK7N	8	50	XK8N	7	XK9N	7
AVERAGE	9	50	AVERAGE	7	AVERAGE	7
290-310,000 PSI. ACROSS-THE-WELD SPECIMENS						
VF1N	19	-	VF2N	17	VF3N	12
VF4N	18	-	VF5N	13	VG3N	14
VG1N	20	-	VG2N	20	VG4N	15
AVERAGE	19	-	AVERAGE	17	AVERAGE	14
290-310,000 PSI. PARENT METAL SPECIMENS						
VJ1N	21	54	VJ2N	20	VJ3N	19
VJ4N	20	54	VJ5N	22	VJ6N	18
VJ7N	20	54	VJ8N	20	VJ9N	18
AVERAGE	20	54	AVERAGE	21	AVERAGE	18

TABLE 22

FLASH BUTT WELD TESTS ON INCO STEEL

BEND DATA

Specimen Number	Load Lbs.	Outside Bend Angle, Degrees
240-260,000 PSI. ACROSS-THE-WELD SPECIMENS		
XH1N	7900	25
XH2N	7500	20
XH3N	7400	20
XI1N	7700	20
XI2N	7500	20
XI3N	7500	5
Average	7600	20
240-260,000 PSI. PARENT METAL SPECIMENS		
XK1N	8000	25
XK2N	7700	20
XK3N	7800	25
Average	7800	25
290-310,000 PSI. ACROSS-THE-WELD SPECIMENS		
VF1N	7500	10
VF2N	10300	45
VF3N	9700	35
VG1N	9200	25
VG2N	9400	25
VG3N	7500	20
Average	8900	25
290-310,000 PSI. PARENT METAL SPECIMENS		
VJ1N	9800	35
VJ2N	10200	40
VJ3N	9400	25
Average	9800	35

TABLE 23

FLASH BUTT WELD TESTS ON INCO STEEL

TUBE EFFICIENCY

Property	Efficiency %	
	240-260,000 psi.	290-310,000 psi.
Tensile Strength	87	94
% Elongation	37½	33
% Reduction in Area	47	39
Notch Strength, RT	94	91
Notch Strength, -65°F	91	94
Notch Ductility, RT	73	77
Notch Ductility, -65°F	83	75
Impact Energy, RT	89	95
Impact Energy, 32°F	86	81
Impact Energy, -65°F	86	78
Bend Load	97	91
Outside Bend Angle	80	71

$$\text{Tube Efficiency} = \frac{\text{Average Property of Weld X 100}}{\text{Average Property of Parent Metal}}$$

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