68734

p 11

An Investigation Into Geometry and Microstructural Effects Upon The Ultimate Tensile Strengths of Butt Welds

Contract Number NAS8-38671

Final Report

February 5, 1992

Prepared for:
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Prepared by:
Nichols Research Corporation
4040 South Memorial Parkway
Huntsville, Alabama
35802

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ACRONYMS

ASTM	American Society for the Testing of Materials
FEA	Finite Element Analysis
FL	Fusion Line
FZ	Fusion Zone
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
KIP	Thousands (Kilo) of Pounds
KSI	Thousands (Kilo) of Pounds Per Square Inch
SDE	Standard Deviation of Errors between two sets of data
STD	Standard Deviation
UTS	Ultimate Tensile Strength
VPPAW	Variable Polarity Plasma Arc Welding
YS	0.2% Yield Strength

SECTION 1. INTRODUCTION

1.1 PURPOSE

This final report is submitted as partial fulfillment of NASA contract #NAS8-38671.

The purpose of this work was to evaluate empirically, and propose modifications to, a mathematical theory developed by Dr. Arthur J. Nunes, Jr., of NASA (ref. 1). This theory predicts the ultimate tensile strength (UTS) of butt welds as a function of the geometry of the welds and the base metal properties.

The objectives of this theory are:

(1) Understanding the causes of variations in UTS that occur in supposedly 'equivalent' welds. This may lead to reducing such variations, which leads to increased strength values for design use and associated weight reductions.

(2) Maximization of UTS through control of weld geometry. This leads to increased strength values for design use and associated weight reductions.

(3) Understanding why Gas Tungsten Arc (GTA) welds have historically been slightly stronger than Variable Polarity Plasma Arc (VPPA) welds. This may enable stronger VPPA welds to be made by altering their geometry.

(4) Applying the knowledge gained from objectives (1), (2), and (3) to fabrication of the Space Shuttle External Tank.

(5) To be able to assess the geometric effects in experimental weld studies so that they can be separated from non-geometric effects.

(6) Publication of the theory to disseminate the knowledge gained.

1.2 BACKGROUND

The mathematical equations derived in the theory have three terms, with each term making an adjustment to a nominal weld strength value.

The theory is primarily a function of fusion line angle, mismatch, and peaking. Fusion line angles are predicted to increase UTS at each toe, while mismatch and peaking can independently either increase or decrease UTS at each toe.

Using base metal properties and the weld geometry the theory equations are applied at each toe to determine which is the weakest. The predicted UTS at that toe is considered the predicted UTS for the sample.

The geometric features used in the theory are:

(1) Peaking
(2) Mismatch
(3) Fusion line angles at each weld toe
(4) Stress concentration factors at each weld toe
(5) Base metal thickness
(6) Weld width

These are discussed in greater detail in section 2.4.1.

A finite element analysis (FEA) study was conducted by Vanderbilt University for comparison to the theory (ref. 2). From this study, and several meetings between Vanderbilt, NASA, and Nichols Research, there appears to be general agreement between the Vanderbilt study and the NASA theory regarding effects of peaking and mismatch on UTS, however there was some disagreement over the effects of fusion line angle (used in NASA theory; not used by Vanderbilt), bead reinforcement (not used in NASA theory; used by Vanderbilt) and weld width (used by NASA theory only during peaking and mismatch effect calculations; used by Vanderbilt when weld width is less than weld thickness).

1.3 METHODOLOGY

The following methodology was followed in this experiment:

(1) A series of welds with varying geometries was made.

(2) Tensile specimens were fabricated from these welds.

(3) The geometries of each tensile specimen were measured.

(4) The theory was used to predict the UTS of each tensile specimen.

(5) The specimens were tensile tested.

(6) Comparisons of actual to predicted values were made.

SECTION 2. EXPERIMENTAL PROCEDURE

2.1 WELD MATRIX

The matrix of welds that were made and tested is shown in Table 1. Two thickness of 2219-T87 aluminum were used. Other thicknesses and materials had been planned, which is why there are gaps in the plate numbering sequence. Some of these others were welded, but none have been tested as of this writing, so this report will be confined to the work done on 1/4" and 1/2" thick aluminum 2219-T87.

Table 1. Weld Matrix

PANEL ID NUMBER	MATERIAL	THICKNESS	WIDE OR NARROW?	PURPOSELY PEAKED?	PURPOSELY MISMATCHED?
P-01	2219 AL	0.250"	WIDE	NO	NO
P-02	2219 AL	0.250"	WIDE	NO	YES
P-03	2219 AL	0.250"	WIDE	YES	NO
P-05	2219 AL	0.250"	NARROW	NO	NO
P-06	2219 AL	0.250"	NARROW	NO	YES
P-07	2219 AL	0.250"	NARROW	YES	NO
P-09	2219 AL	0.500"	WIDE	NO	NO
P-10	2219 AL	0.500"	WIDE	NO	YES
P-11	2219 AL	0.500"	WIDE	YES	NO
P-13	2219 AL	0.500"	NARROW	NO	NO
P-14	2219 AL	0.500"	NARROW	NO	YES
P-15	2219 AL	0.500"	NARROW	YES	NO
T-41	2219 AL	0.250"	WIDE	NO	NO
T-42	2219 AL	0.250"	WIDE	NO	YES
T-43	2219 AL	0.250"	WIDE	YES	NO
T-45	2219 AL	0.250"	NARROW	NO	NO
T-46	2219 AL	0.250"	NARROW	NO	YES
T-47	2219 AL	0.250"	NARROW	YES	NO
T-49	2219 AL	0.500"	WIDE	NO	NO
T-50	2219 AL	0.500"	WIDE	NO	YES
T-51	2219 AL	0.500"	WIDE	YES	NO
T-53	2219 AL	0.500"	NARROW	NO	NO
T-54	2219 AL	0.500"	NARROW	NO	YES
T-55	2219 AL	0.500"	NARROW	YES	NO

Each plate was given a 3 digit alpha-numeric identification number. The first digit was either a 'P' or a 'T' for Plasma (VPPAW) or TIG (GTAW) respectively. The second and third digits identify the plate number in accordance with the weld matrix. For example, plate P03 means that is was VPPA welded, and is plate number 3 from the matrix.

Each specimen from each plate was also given a unique identification number with 5 digits; the first 3 digits are the plate number; the fourth and fifth digits identify the location along the weld, in inches. For example, specimen T4702 was from plate T47 (GTA welded plate number 47 from the weld matrix) and was machined out of the second inch of the weld.

2.2 WELDING PROCEDURE

All welding was performed on weld station #5, Building 4707, at NASA/MSFC. All welding was done vertically up. All welds had 2319 aluminum filler wire added either during the root pass and/or the cover pass. A cover pass was required on all but 4 welds to produce welds with no undercut.

To create relative weld width differences, two nominal parameters were developed for each thickness of material, such that one parameter made welds that were wider than welds made with the other parameter.

To make mismatched welds, shims with thickness equal to the desired mismatch were placed under one plate during tack welding.

To cause some welds to have large peaking angles, they were clamped into the weld fixture on one side only, so that the other side was unrestrained. Shop air was blown on the cooling welds to increase peaking. The welds that were not purposely peaked were fully restrained in the weld fixture during welding and cooling, and were not cooled by shop air.

Two welding processes, variable polarity plasma arc (VPPA) and gas tungsten arc (GTA) were used. These are known to have different typical weld cross-sections and different fusion line angles.

2.3 SPECIMEN PREPARATION

All welds were inspected visually and radiographically. Some localized weld defects (such as undercut and tungsten inclusions) were observed. The locations of such weld defects were marked on the plate, and these locations were avoided when sectioning the plates into test specimens.

Each plate was marked for sectioning to provide tensile specimens and metallurgical mounts. The plates were machined into 6 tensile specimens (3 shaved and 3 unshaved) nominally 1 inch by 12 inch, and 3 metallurgical mounts. Both edges of each tensile specimen were polished, etched, and photographed at approximately 4X magnification. The metallurgical mounts were also etched and photographed at similar magnifications.

2.4 MEASUREMENTS

2.4.1 Geometry Measurements

Figure 1 shows how weld toes were numbered (1 through 8) for tensile specimens. Metallurgical mounts were mounted so toes 1 through 4 were observable.

The following measurements were taken from each photograph:

Weld width (crown and root)
Weld reinforcement height (crown and root)
Peaking
Mismatch
Fusion line angle at each weld toe
Reentrant angle at each weld toe

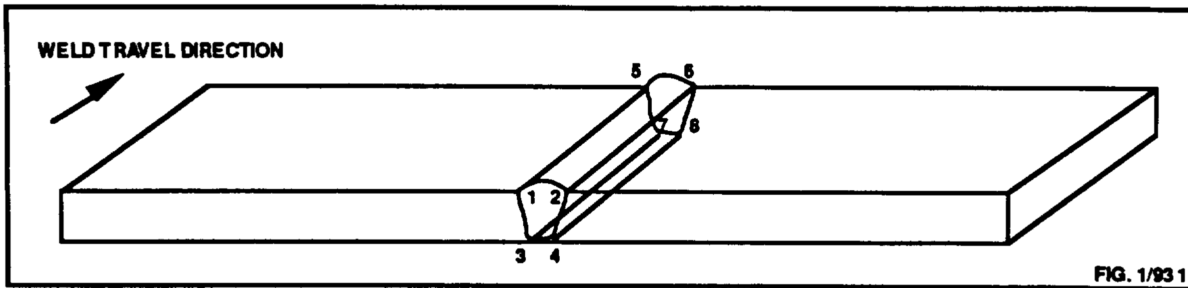

Figure 1. Tensile Specimen Weld Toe Numbering System

Figure 2 shows how the geometry was defined and measured. Most of these measurements were used in the NASA theory calculations for predicting UTS for each specimen. However, reinforcement heights and reentrant angles, although measured, are not used in the theory computations.

The weld reinforcement heights were measured to compare the UTS of shaved (i.e., zero reinforcement) specimens to the UTS of unshaved specimens (i.e., reinforcements intact) to determine if weld reinforcement should be considered in the theory calculations. Reentrant angles were measured for possible future use in explaining discrepancies between theory and results, particularly in the area of stress concentrations at the weld toes (stress concentrations of 1 are assumed in all the calculations, i.e., stress concentrations are assumed to be insignificant for 2219-T87 aluminum).

Geometry measurements were also taken from the metallurgical mount specimens for possible future use.

A crude prototype hand-held measurement tool was fabricated in an effort to measure peaking and mismatch non-destructively. This prototype tool did not prove to be particularly useful, however the tool concept is sound. With slight modifications the tool should be able to measure non-destructively peaking to the nearest degree and mismatch to the nearest 0.01".

2.4.2 Microhardness and Grain Size Measurements

Vickers microhardness and ASTM grain size measurements were taken from one metallurgical mount from each welded plate. Microhardness measurements were taken at the weld toes and at 0.050" increments along a line from the weld center to the base metal. Grain size measurements were taken in the heat affected zone (HAZ) adjacent to each weld toe.

2.5 TENSILE TESTING

Tensile testing was done on two MTS 880 machines: one with a 22 kip capacity for the 1/4" specimens; and one with a 55 kip capacity for the 1/2" specimens. The load rate for all tests was the ASTM-E8 standard for aluminum of 40 ksi/min. Stress-strain curves were obtained for most tests (two were missed due to plotter/tester problems).

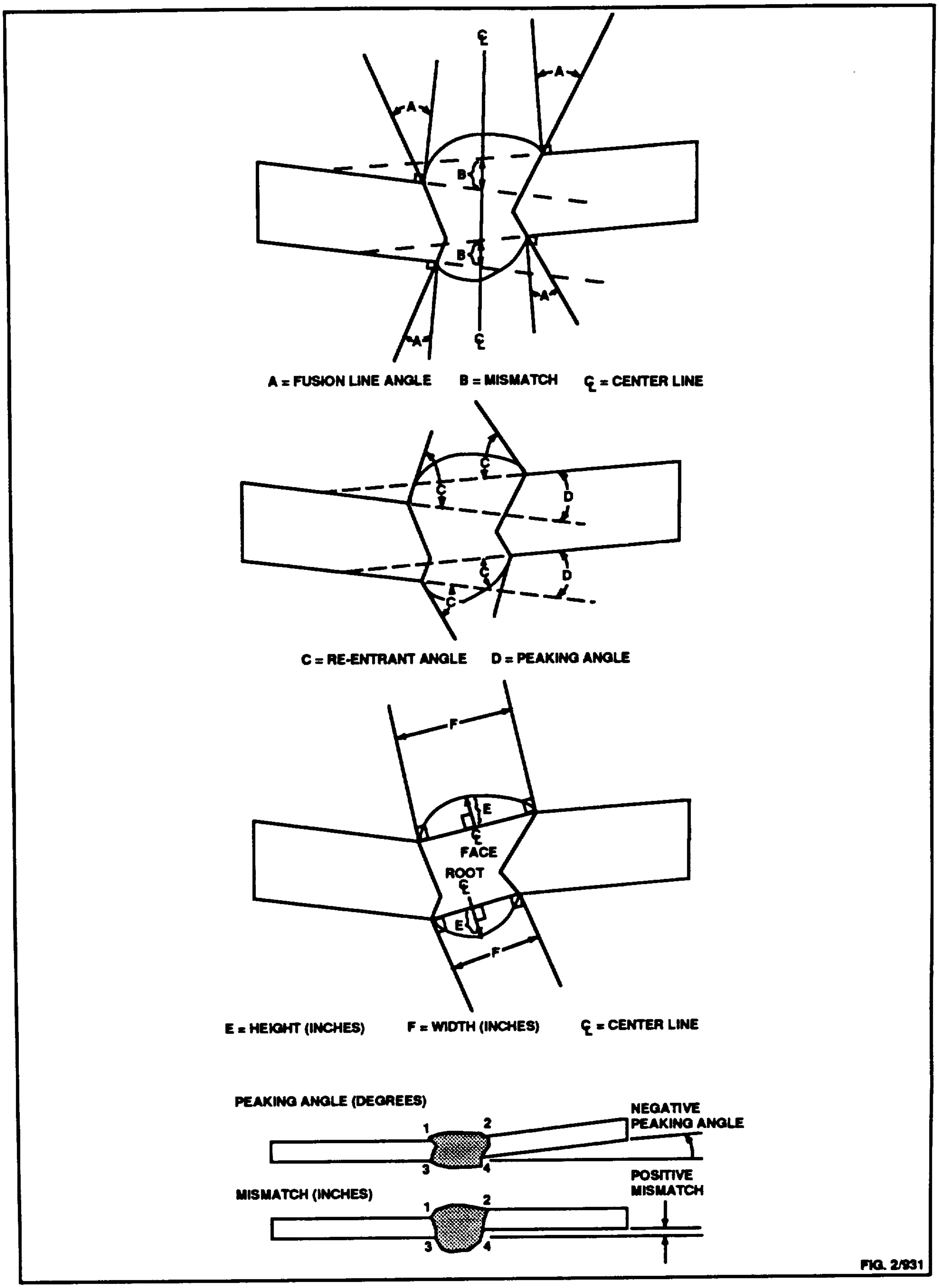

Figure 2. Guide to Measuring Weld Geometry

2.6 DATA MANAGEMENT

The geometry measurements, UTS predictions, tensile test data, microhardness and grain size data were all compiled and analyzed to:

(1) Determine how well the theory predicts UTS

(2) Identify causes for any discrepancies found between theory-predicted UTS and actual test results

(3) Propose modifications to the theory that experimental results indicate would improve correlation between predicted UTS and test results

SECTION 3. RESULTS

3.1 GEOMETRY MEASUREMENTS

Table 2 shows the amounts of mismatch and peaking that were obtained for each tensile specimen. Significant differences in both mismatch and peaking were obtained between plates, in order to evaluate the theory over a wide range of geometries. Note that large peaking variations were observed among specimens cut from a single plate, with peaking tending to be greater for specimens cut from the central portion of the weld than for those cut from near the beginning or end of the weld. Also note that some of the normal and intentionally mismatched specimens have relatively large peaking angles, even though they were not intentionally peaked.

All geometry measurements for all the tensile specimens are listed in Appendices A, B, and C. Appendix A contains weld width and fusion line angle measurements. Appendix B contains reentrant angle, mismatch, and peaking angle measurements. Appendix C contains reinforcement height measurements.

3.2 TENSILE TESTING

The predicted UTS values and predicted fracture origins (i.e., the toe at which fracture is predicted to originate) are listed in Appendix C. All the tensile test results are listed in Appendix D. The data from these appendices was used to create all the graphs and tables referenced in Section 4: Evaluation Of Results.

Tensile test results were used for comparison to predicted values. All predictions were made using a computer program that applied the NASA theory predictive equations to the weld geometry at each of the 8 weld toes of each tensile specimen. Appendix E lists the program calculation code used (written in 'C' programming language). The toe with the lowest predicted UTS is the predicted fracture origin, and the UTS calculated at that toe is the overall predicted UTS value. Note that there are 2 sets of predicted UTS and failure origin toe numbers in Appendix C. The set titled FULL PREDICTION uses the predictive equations exactly as in the NASA theory. The set titled PREDICTION W/O FL ANGLE uses the same equations except that the effects of the fusion line angle are neglected. This was done to determine whether fusion line angle effects should be considered when predicting UTS.

An additional set of eight specimens were tensile tested. There are designated in the Appendices as 'counter-peaking rotation trial specimens'. These specimens had their root reinforcements shaved off while the crown reinforcements were left intact. This was done to investigate a hypothesis that when tensile testing a negatively peaked sample, the peaking straightens by pivoting about a point on the center of the root face. If true, then shaving the root shifts that pivot point nearer to the weld face, thereby reducing the strain on the weld face, which in turn would increase UTS (assuming fracture originates at a crown toe).

Due to the extreme peaking and mismatch of many of the samples, the grips of the tensile tester were set-up to enable them to pivot about an axis parallel to the direction of weld. This prevented preloading the specimens, and allowed the grips to follow along with the straightening-out of the specimens during testing.

A typical stress-strain curve obtained during these tests is shown in Figure 3. The 'stair-steps' indicate that a dynamic strain aging process is occurring during testing of welded specimens. Tensile tests of base metal (no weld) yielded stress-strain curves without 'stain-steps' (Figure 4), showing that the phenomenon is occurring in the weld metal. This phenomenon appears to be a 'Portevin-LeChatelier effect', which is known to occur in some aluminums (ref. 3).

Table 2. Peaking and Mismatch Measurements For Each Tensile Specimen

	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P01	6	-1.00	-0.001	Plate # P41	3	-3.13	0.000
	8	-1.88	0.006		5	-3.75	-0.003
0.25″ Thick	11	-1.25	-0.006	0.25″ Thick	11	-5.63	-0.006
Normal	13	-0.88	-0.009	Normal	13	Specimen Lost	
VPPAW	17	-1.25	-0.007	GTAW	21	-4.13	0.006
	19	0.00	-0.003		23	-4.13	-0.009
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P02	15	-1.00	0.093	Plate # P42	4	-3.25	-0.053
	17	-0.88	0.089		6	-3.88	-0.058
0.25″ Thick	19	-1.25	0.110	0.25″ Thick	14	-5.00	-0.038
Purposely	21	-1.25	0.065	Purposely	16	-8.50	-0.054
Mismatched	22	-2.25	0.087	Mismatched	18	-6.63	-0.058
VPPAW	24	-1.13	0.062	GTAW	22	-3.75	-0.063
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P03	9	-4.88	0.017	Plate # P43	7	-4.13	0.014
	11	-5.38	0.016		9	-5.75	0.014
0.25″ Thick	13	-4.25	0.016	0.25″ Thick	12	-7.63	-0.003
Purposely	15	-6.75	0.022	Purposely	14	-7.63	-0.004
Peaked	20	-7.63	0.021	Peaked	18	-7.13	0.003
VPPAW	23	-4.63	0.013	GTAW	20	-6.88	-0.002
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P05	7	-1.88	0.002	Plate # P45	2	-1.88	0.006
	9	-1.00	-0.001		4	-2.75	0.003
0.25″ Thick	16	-1.50	0.004	0.25″ Thick	9	-5.00	-0.006
Normal	18	-2.13	-0.002	Normal	11	-5.63	0.008
VPPAW	21	-1.25	-0.003	GTAW	18	-3.25	0.000
	23	-0.63	-0.010		20	-3.38	0.006

Table 2. Peaking and Mismatch Measurements For Each Tensile Specimen (Continued)

	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P06	4	−1.75	0.089	Plate # P46	15	1.13	−0.111
	6	−1.75	0.106		17	2.00	−0.107
0.25″ Thick	12	−1.50	0.103	0.25″ Thick	19	0.13	−0.100
Purposely	14	−0.25	0.108	Purposely	21	1.13	−0.085
Mismatched	20	−0.75	0.094	Mismatched	23	0.25	−0.099
VPPAW	22	−1.25	0.096	GTAW	25	0.75	−0.078
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P07	4	−1.38	0.008	Plate # P47	2	−1.25	0.000
	6	−1.75	−0.006		4	−2.00	−0.006
0.25″ Thick	12	−3.00	−0.004	0.25″ Thick	8	−3.63	−0.009
Purposely	14	−2.88	−0.005	Purposely	10	−4.75	−0.016
Peaked	21	−2.63	−0.004	Peaked	20	−6.00	−0.002
VPPAW	23	−1.63	0.000	GTAW	22	−3.13	−0.004
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P09	6	−1.25	0.004	Plate # P49	3	−1.63	−0.001
	8	−1.63	0.005		5	−1.38	0.002
0.50″ Thick	16	−0.50	0.006	0.50″ Thick	10	−1.75	0.005
Normal	18	−2.00	−0.002	Normal	12	−1.13	−0.008
VPPAW	20	−1.13	−0.001	GTAW	21	−0.88	−0.002
	22	−1.25	0.004		23	−1.50	0.000
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P10	6	−1.13	−0.107	Plate # P50	5	−2.38	−0.089
	8	−0.50	−0.105		7	−3.00	−0.075
0.50″ Thick	11	−2.63	−0.114	0.50″ Thick	10	−2.75	−0.091
Purposely	13	−1.63	−0.112	Purposely	12	−1.75	−0.082
Mismatched	16	−1.75	−0.107	Mismatched	19	−1.75	−0.093
VPPAW	18	−0.88	−0.112	GTAW	21	−2.38	−0.088

Table 2. Peaking and Mismatch Measurements For Each Tensile Specimen (Concluded)

	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P11	3	−2.00	0.015	Plate # P51	4	−0.75	−0.003
	5	−1.38	0.005		6	−1.50	0.004
0.50" Thick	9	−2.25	0.022	0.50" Thick	7	−0.75	0.005
Purposely	11	−1.38	0.018	Purposely	9	−2.50	0.002
Peaked	15	−1.63	0.012	Peaked	12	−2.13	0.006
VPPAW	17	−2.13	0.022	GTAW	14	−1.38	0.000
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P13	10	−0.63	0.001	Plate # P53	2	−0.63	0.000
	12	−1.63	−0.004		4	−1.00	0.006
0.50" Thick	15	−1.25	−0.012	0.50" Thick	10	−1.38	0.006
Normal	17	−1.50	0.008	Normal	12	−1.38	0.005
VPPAW	19	−2.00	−0.002	GTAW	20	−1.88	0.007
	21	−0.75	0.005		22	−1.50	0.002
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P14	16	−1.50	0.112	Plate # P54	2	−2.13	0.073
	18	−1.75	0.110		4	−3.00	0.081
0.50" Thick	19	−0.88	0.102	0.50" Thick	11	−4.13	0.070
Purposely	21	−2.13	0.099	Purposely	13	−3.38	0.069
Mismatched	22	−2.00	0.097	Mismatched	17	−3.63	0.075
VPPAW	24	−1.75	0.090	GTAW	19	−2.38	0.088
	WELD INCH	PEAKING	MISMATCH		WELD INCH	PEAKING	MISMATCH
Plate # P15	9	−1.88	−0.005	Plate # P55	1	−1.50	0.000
	11	−2.13	−0.011		3	−0.88	−0.008
0.50" Thick	14	−1.75	−0.020	0.50" Thick	8	−1.88	0.007
Purposely	16	−3.00	−0.014	Purposely	10	−2.00	−0.002
Peaked	18	−1.50	−0.004	Peaked	19	−1.25	0.000
VPPAW	20	−2.13	−0.009	GTAW	21	−1.88	−0.003

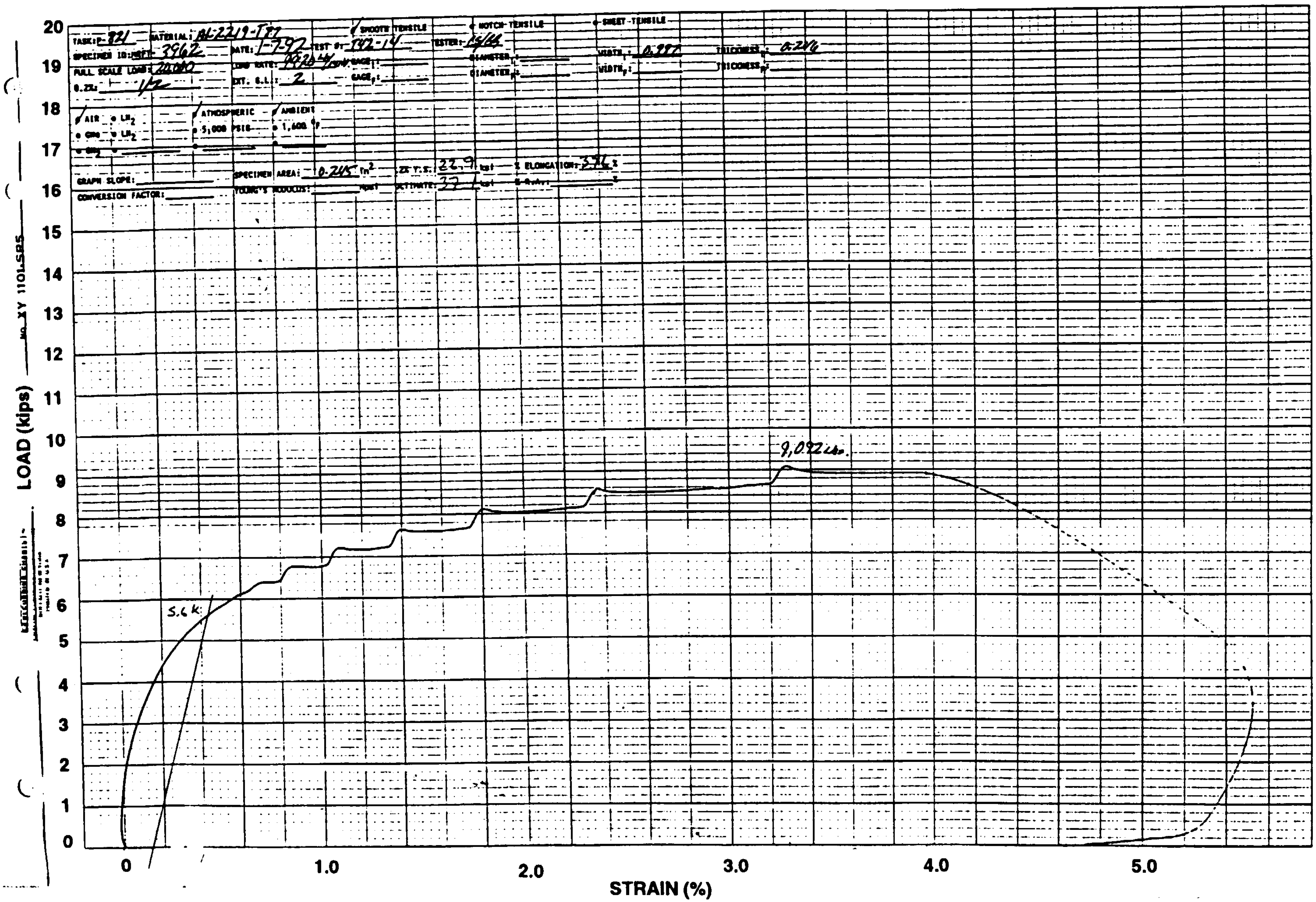

Figure 3. Stress-Strain Curve for Tensile Specimen With Weld

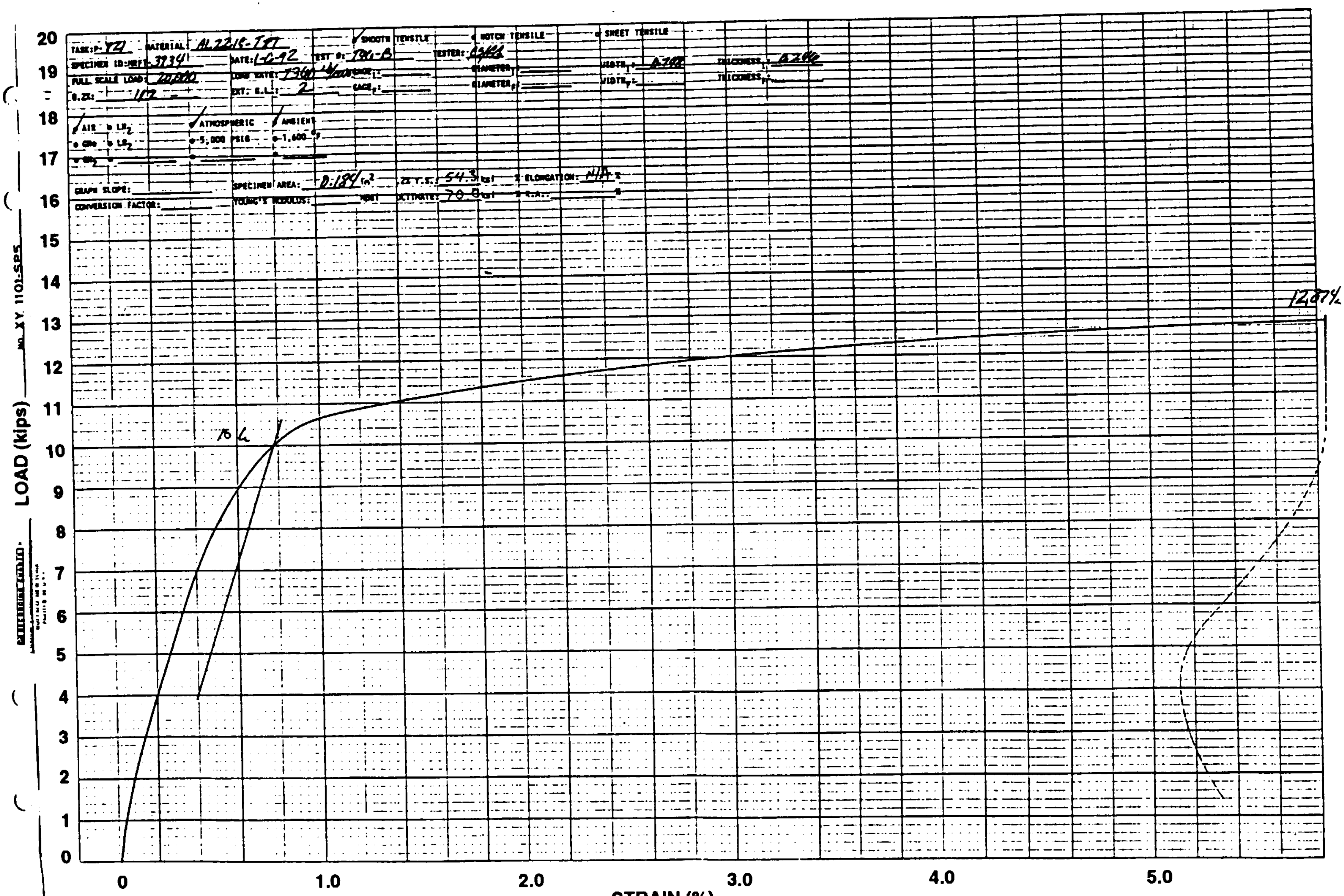

Figure 4. Stress-Strain Curve for Tensile Specimen Without Weld

3.3 MICROHARDNESS AND GRAIN SIZE

Vickers microhardness measurements were taken on one metallurgical mount from each weld. Measurements were taken in the fusion zone at each toe, and at 0.050" increments along a line from the center of fusion zone, through the HAZ, and into the base metal. These measurements are listed in Table 3.

Table 3. Vickers Microhardness Measurements

SAMPLE IDENT.	WELD METAL MEASUREMENTS:				HAZ					BASE METAL	
	1	2	3	4	1	2	3	4	5	6	7
P0112		78.5	81.6	76.3	114.0	100.0	85.8	81.6	91.7	98.6	
P0220		75.2	79.8	83.9	91.3	97.8	83.8	81.7	82.6		
P0314		72.9	87.5	69.9	94.0	103.0	96.2	89.9	84.8	94.2	
P0517		74.5	72.5	76.3	90.6	107.0	89.1	95.4	104.0	108.0	
P0613		76.8	77.8	77.3	100.0	100.0	82.0	79.9	81.6	96.6	
P0713		73.8	76.2	80.8	87.6	99.3	93.2	94.2	102.0		
P0917	72.1	71.7	71.5	74.9	105.0	91.8	84.7	84.6	90.9	101.0	101.0
P1012	70.1	72.4	72.9	72.2	91.0	94.3	86.6	81.7	82.8	94.5	99.2
P1110	71.6	71.1	74.5	74.4	91.1	95.1	82.3	83.7	92.4	97.9	
P1316	79.1	75.7	83.8	74.9	89.7	96.1	85.8	77.6	78.8	82.6	90.9
P1420	75.9	74.5	73.2	75.7	93.6	94.3	87.7	82.5	89.8	97.9	
P1515	73.9	75.3	73.2	79.3	90.2	95.4	83.7	88.1	94.8	102.0	105.0
T4112		82.0	83.7	82.3	100.0	97.1	86.6	89.0	96.7	103.0	105.0
T4215		71.0	70.2	69.1	84.9	97.3	94.6	80.2	80.0	83.8	96.8
T4313		74.8	72.3	75.1	93.6	99.0	88.3	81.5	88.9	95.6	105.0
T4510		73.1	72.3	76.1	95.7	102.0	88.8	91.2	100.0	100.0	
T4620		72.8	74.7	72.2	91.0	97.1	87.0	79.8	83.2	92.2	
T4709		82.7	78.3	77.8	106.0	116.0	89.5	90.8	103.0	108.0	
T4911	76.4	75.8	74.2	75.5	84.9	84.5	88.1	77.3	80.0	88.7	
T5011	75.4	75.7	76.7	72.5	91.9	86.3	85.8	76.9	79.3	84.0	93.2
T5108	75.7	77.7	78.2	81.7	104.0	101.0	93.9	79.2	81.3	85.0	88.8
T5311	82.5	78.1	85.5	87.7	100.0	93.0	85.0	80.0	90.8	96.9	103.0
T5412	75.5	73.8	78.4	78.5	93.1	89.6	85.0	77.9	84.6	92.3	
T5509	73.9	74.5	74.3	78.2	89.9	87.3	83.6	82.9	89.2		
MAX =	82.5	82.7	87.5	87.7	114.0	116.0	96.2	95.4	104.0	108.0	105.0
MIN =	70.1	71.0	70.2	69.1	84.9	84.5	82.0	76.9	78.8	82.6	88.8
RANGE =	12.4	11.7	17.3	18.6	29.1	31.5	14.2	18.5	25.2	25.4	16.2
AVG =	75.2	75.2	76.8	76.8	94.7	96.8	87.4	83.7	88.9	95.4	98.8
STD. =	3.2	2.9	4.7	4.3	7.0	6.6	3.8	5.4	7.8	7.2	5.8

ASTM grain size measurements were taken from the same mounts used for microhardness measurements. Grain size measurements were made in the HAZ adjacent to each weld toe. These measurements are listed in Table 4.

Table 4. ASTM Grain Size Measurements in HAZ Adjacent to Each Weld Toe

SAMPLE IDENTIFICATION	TOE #1	TOE #2	TOE #3	TOE #4
P0112	4-5	4-5	4-5	5-6
P0220	4-5	4-5	4-5	4-5
P0314	4-5	4-5	4-5	4-5
P0517	4-5	4-5	4-5	4-5
P0613	4-5	4-5	4-5	4-5
P0713	4-5	4-5	4-5	4-5
P0917	4-5	4-5	4-5	4-5
P1012	3-4	4-5	4	4-5
P1110	4-5	5	4-5	4-5
P1316	4-5	5	5	4-5
P1420	4	4-5	4-5	4-5
P1515	4-5	4-5	4	4-5
T4112	5	5	5	5
T4215	4-5	4-5	4-5	4-5
T4313	4-5	4-5	4-5	4-5
T4510	5	5	5	5
T4620	4-5	4-5	4-5	4-5
T4709	5	5	5	5
T4911	4	4	4-5	4-5
T5011	4-5	4-5	4-5	4-5
T5108	4-5	5	5	4-5
T5311	5	5	5	5
T5412	4-5	4-5	4-5	4-5
T5509	5	4-5	5	4-5

SECTION 4. EVALUATION OF RESULTS

4.1 EXPLANATION OF ANALYSIS

The test results, and the correlations to the predictions, were evaluated in terms of the following comparisons:

Shaved vs. unshaved welds
Wide vs. narrow welds
Test results vs. predictions
Predicted UTS vs. actual yield strength

Several statistical analysis tools were used to evaluate this theory. The primary tool was the standard deviation of the error (SDE) between predicted and actual results for each specimen. This was used as a measure of how well the theory correlated to test results by providing a measure of how consistent the errors are. Sets of data with lower SDE values have more consistent errors and are considered to have better correlations of the predicted to the actual values, regardless of the difference between their means. The difference in the means can be accounted for by adding a constant equal to the difference between the means to the predicted values to make the mean of the predictions equal to the mean of the actual values. This constant may be a correction factor that compensates for any inaccuracies in the constant values (such as nominal weld metal strength or strain hardening rate) used in the predictions.

To understand the above paragraph, take the following example. Suppose that, for a given set of tensile tests, the actual UTS is consistently 4 ksi higher than the predicted UTS. The standard deviation of the errors would then be zero (because the error does not deviate). This indicates excellent correlation between the predicted and actual values because the predictions can be made to equal the actual values in all cases by adding a constant of 4 ksi (the difference between the means of the predictions and the actuals) to the predictions. The result is a slight modification to the prediction equations, resulting in perfect correlation to actual test results.

Another evaluation of the theory involves comparing it to the mean of the test results. If the theory correlates better to test results than the test result mean does, then the theory is a better predictor than the mean. If not, then the mean is a better predictor than the theory.

Table 5 lists the standard deviations of the errors (SDE) as well as the mean error and the maximum error for a variety of groupings of the data. Table 6 is the same as Table 5 except the fusion line angle effect has been neglected in the prediction calculations.

4.2 SHAVED VERSUS UNSHAVED WELDS

This comparison was made because the NASA theory does not use weld reinforcement for predicting UTS, while the Vanderbilt FEA study does.

Figures 5 and 6 show the actual UTS and predicted UTS, respectively, for each of the specimens, for both 1/4" and 1/2" thick welds. It can be seen in Figure 5 that the GTAW welds tend to have slightly higher actual UTS values than the VPPA welds, which is in accordance with the predicted values plotted in Figure 6. The overall large reduction of UTS for mismatched samples and little or no reduction of UTS for peaked samples (from Figure 5) also matches fairly well with the predictions (Figure 6).

Table 5. Statistical Analysis of Error Between Actual and Predicted UTS

		ACTUAL UTS - PREDICTED UTS			ACTUAL UTS STD
		MEAN	MAXIMUM	SDE	
ALL		-1.32	17.80	4.70	4.25
NORMAL	ALL	-1.76	3.94	2.38	1.99
VPPAW	ALL	-0.52	11.47	4.90	4.73
1/4"	ALL	-2.20	8.99	4.07	
	WIDE	-2.27	4.94	3.56	
	NARROW	-2.14	8.99	4.51	
	SHAVED	-1.75	8.99	3.71	
	UNSHAVED	-2.67	5.15	4.36	
	NORMAL	-1.30	3.94	2.25	
	MISMATCHED	-2.86	8.99	6.06	
	PEAKED	-2.41	5.15	2.46	
	VPPAW	-1.25	8.99	4.84	
	GTAW	-3.18	2.01	2.75	
WIDE	ALL	-2.04	10.94	4.37	
	SHAVED	-1.12	10.94	4.91	
	UNSHAVED	-3.01	3.94	3.46	
	NORMAL	-2.00	3.94	2.81	
	MISMATCHED	-0.59	10.94	6.25	
	PEAKED	-3.52	-0.66	2.27	
	VPPAW	-0.39	10.94	4.18	
	GTAW	-3.78	7.45	3.86	
SHAVED	ALL	-0.36	17.80	5.09	
	NORMAL	-2.00	1.19	2.00	
	MISMATCHED	4.29	17.80	5.86	
	PEAKED	-3.36	2.67	2.47	
	VPPAW	1.26	11.47	4.87	
	GTAW	-1.98	17.80	4.78	

		ACTUAL UTS - PREDICTED UTS			ACTUAL UTS STD
		MEAN	MAXIMUM	SDE	
MISMATCHED	ALL	0.21	17.80	7.03	3.95
PEAKED	ALL	-2.41	5.15	2.62	1.85
GTAW	ALL	-2.14	17.80	4.34	3.49
1/2"	ALL	-0.43	17.80	5.11	
	WIDE	-1.80	10.94	5.04	
	NARROW	0.90	17.80	4.81	
	SHAVED	1.04	17.80	5.85	
	UNSHAVED	-1.94	7.27	3.64	
	NORMAL	-2.23	1.19	2.42	
	MISMATCHED	3.28	17.80	6.57	
	PEAKED	-2.42	2.67	2.76	
	VPPAW	0.21	11.47	4.85	
	GTAW	-1.10	17.80	5.28	
NARROW	ALL	-0.62	17.80	4.90	
	SHAVED	0.40	17.80	5.16	
	UNSHAVED	-1.64	7.27	4.40	
	NORMAL	-1.55	1.19	1.89	
	MISMATCHED	1.01	17.80	7.64	
	PEAKED	-1.31	5.15	2.47	
	VPPAW	-0.64	11.47	5.52	
	GTAW	-0.59	17.80	4.19	
UNSHAVED	ALL	-2.31	7.27	4.03	
	NORMAL	-1.50	3.94	2.72	
	MISMATCHED	-3.88	7.27	5.57	
	PEAKED	-1.47	5.15	2.41	
	VPPAW	-2.30	5.15	4.23	
	GTAW	-2.31	7.27	3.80	

Table 6. Statistical Analysis of Predictions Neglecting Fusion Line Angle Effects

		UTS ACTUAL - (UTS PRD-FL) MEAN	MAXIMUM	SDE	ACTUAL UTS STD
ALL		1.42	17.81	3.73	4.25
NORMAL	ALL	0.26	4.69	2.09	1.99
VPPAW	ALL	1.36	12.58	4.06	4.73
1/4"	ALL	1.00	12.45	3.00	
	WIDE	0.78	5.20	2.49	
	NARROW	1.22	12.45	3.41	
	SHAVED	0.91	12.45	3.41	
	UNSHAVED	1.10	6.34	2.52	
	NORMAL	0.83	4.69	2.17	
	MISMATCHED	1.55	12.45	4.11	
	PEAKED	0.63	6.34	2.20	
	VPPAW	1.09	12.45	3.70	
	GTAW	0.92	5.16	2.04	
WIDE	ALL	0.78	10.94	3.38	
	SHAVED	1.33	10.94	3.97	
	UNSHAVED	0.20	5.16	2.48	
	NORMAL	0.20	4.69	2.29	
	MISMATCHED	2.26	10.94	4.65	
	PEAKED	-0.17	5.16	1.85	
	VPPAW	0.77	10.99	3.69	
	GTAW	0.79	9.04	3.02	
SHAVED	ALL	1.97	17.81	4.62	
	NORMAL	-0.32	2.36	1.63	
	MISMATCHED	7.05	17.81	4.61	
	PEAKED	-0.81	2.78	1.14	
	VPPAW	2.44	12.58	5.01	
	GTAW	1.50	17.81	4.13	
MISMATCHED	ALL	3.74	17.81	5.04	3.95
PEAKED	ALL	0.21	6.34	1.86	1.85
GTAW	ALL	1.48	17.81	3.35	3.49
1/2"	ALL	1.84	17.81	4.30	
	WIDE	0.78	10.94	4.07	
	NARROW	2.86	17.81	4.26	
	SHAVED	3.03	17.81	5.36	
	UNSHAVED	0.60	7.27	2.21	
	NORMAL	-0.31	3.04	1.84	
	MISMATCHED	5.93	17.81	4.93	
	PEAKED	-0.21	2.78	1.32	
	VPPAW	1.63	12.58	4.38	
	GTAW	2.05	17.81	4.20	
NARROW	ALL	2.04	17.81	3.95	
	SHAVED	2.62	17.81	5.10	
	UNSHAVED	1.47	7.27	2.11	
	NORMAL	0.31	3.04	1.89	
	MISMATCHED	5.23	17.81	4.97	
	PEAKED	0.59	6.34	1.79	
	VPPAW	1.95	12.58	4.33	
	GTAW	2.14	17.81	3.52	
UNSHAVED	ALL	0.85	7.27	2.38	
	NORMAL	0.90	4.69	2.35	
	MISMATCHED	0.43	7.27	2.77	
	PEAKED	1.23	6.34	1.88	
	VPPAW	0.27	6.34	2.36	
	GTAW	1.47	7.27	2.25	

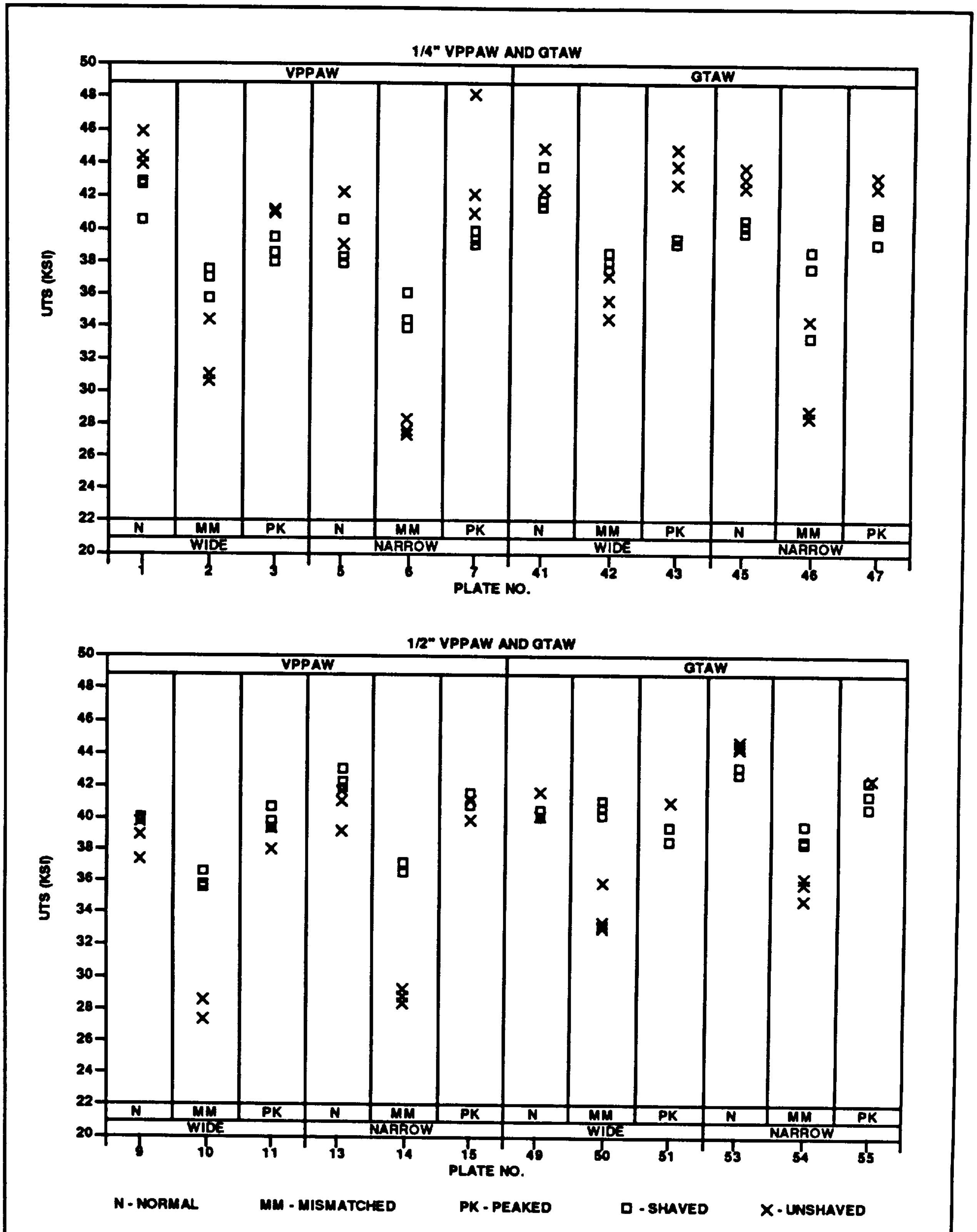

FIGURE 5/831

Figure 5. Actual UTS, Shaved vs. Unshaved

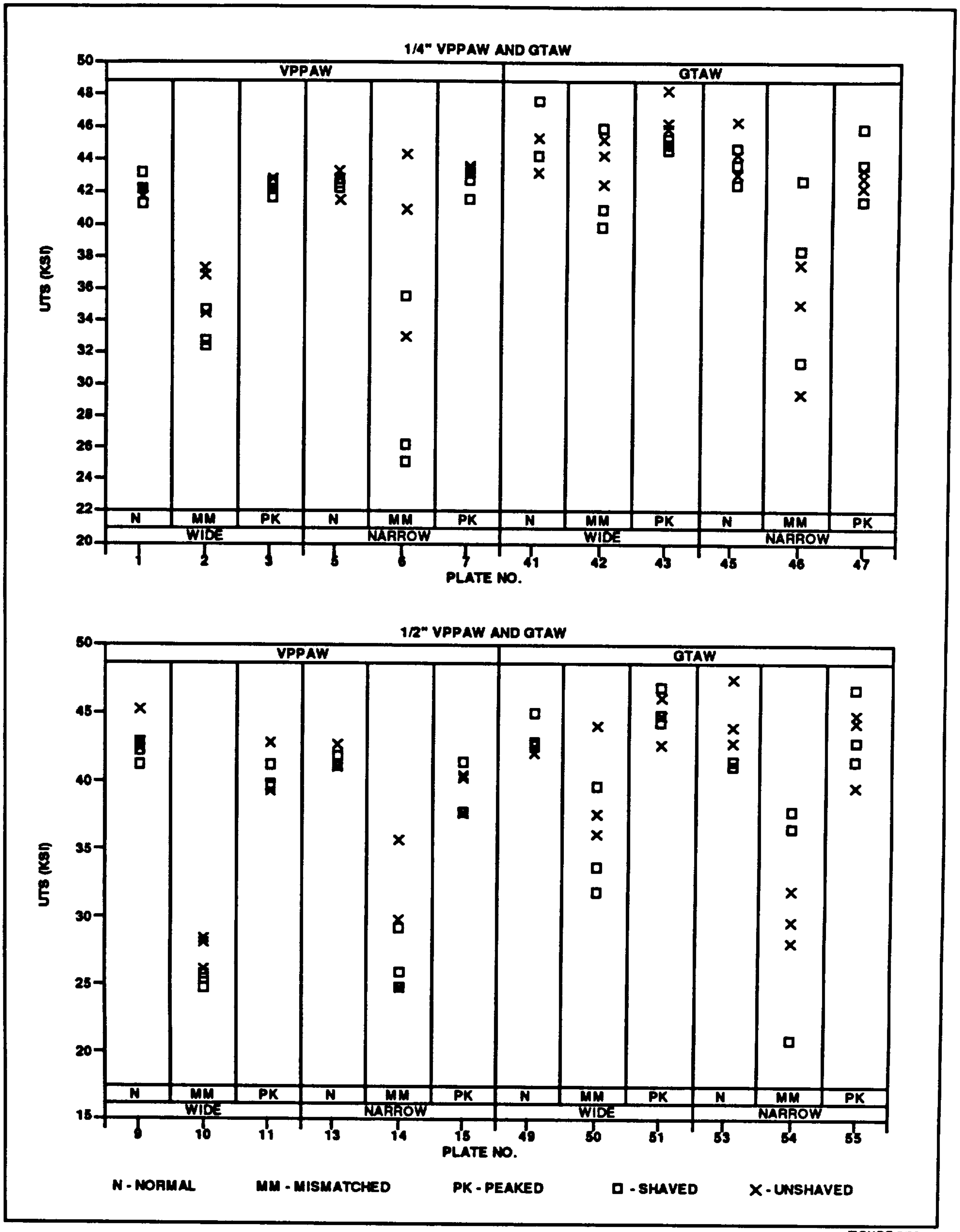

Figure 6. Predicted UTS, Shaved vs. Unshaved

When comparing shaved specimens vs. unshaved specimens there are major discrepancies between actual and predicted UTS values. Most noteworthy is that the shaved mismatched specimens tended to have higher UTS than the unshaved mismatched specimens. This does not correlate with the predictions. Actual UTS for the shaved 1/2" specimens are, on average, about 2 ksi stronger than the unshaved specimens. However, the predicted values for the shaved 1/2" specimens are about 1.5 ksi lower than for the shaved specimens.

Shaving of samples was also noted to cause significant increases in % elongation, but had little effect on yield strength.

The eight 'counter-peaking rotation' specimens results were not plotted, but evaluation of the data for them in Appendix D shows that, contrary to the counter-peaking rotation hypothesis, shaving of the root did not increase the UTS over that of welds with both reinforcements intact.

4.3 WIDE VERSUS NARROW WELDS

Weld width was not considered a major factor in predicting UTS according to the NASA theory (although it is used in the calculations of the mismatch and peaking effects), while the Vanderbilt FEA study gives weld width importance if it is less than the weld thickness. Some of the weld widths obtained in this study, particularly on the root widths, were less than the weld thickness.

Figures 7 and 8 show the actual vs. predicted UTS for 1/4" and 1/2" material, respectively. This data shows that, on average, going from wide to narrow welds causes a decrease of several ksi in UTS for normal and mismatched 1/4" VPPA welds and mismatched 1/4" GTA welds. However, going from wide to narrow welds causes an increase in average UTS for normal 1/2" VPPA welds and normal and peaked GTA welds. These trends match the predictions only in the case of the 1/4" mismatched GTA welds.

Overall, the effect of weld width on UTS was not consistent in this data set, and is inconclusive regarding the effect of weld width on UTS. It should be noted that a set of welds in which all 'wide' welds have width-to-thickness ratios greater than one and all 'narrow' welds have width-to-thickness ratios less than one would be more conclusive.

4.4 TEST RESULTS VERSUS PREDICTIONS

Two questions are addressed in the evaluation of the theory. These are:

(1) How does the theory compare to the mean of the test results as a predictor of the test results?

(2) How well does the theory correlate to the test results?

The above questions can be answered for many cases by consulting Tables 5 and 6.

The standard deviation calculation (STD) of the actual UTS values is a measure of how well the mean of the test results correlates to the test results. This calculation has been done for all the data as well as the following data sub-sets: normal; mismatched; peaked; VPPAW; and GTAW.

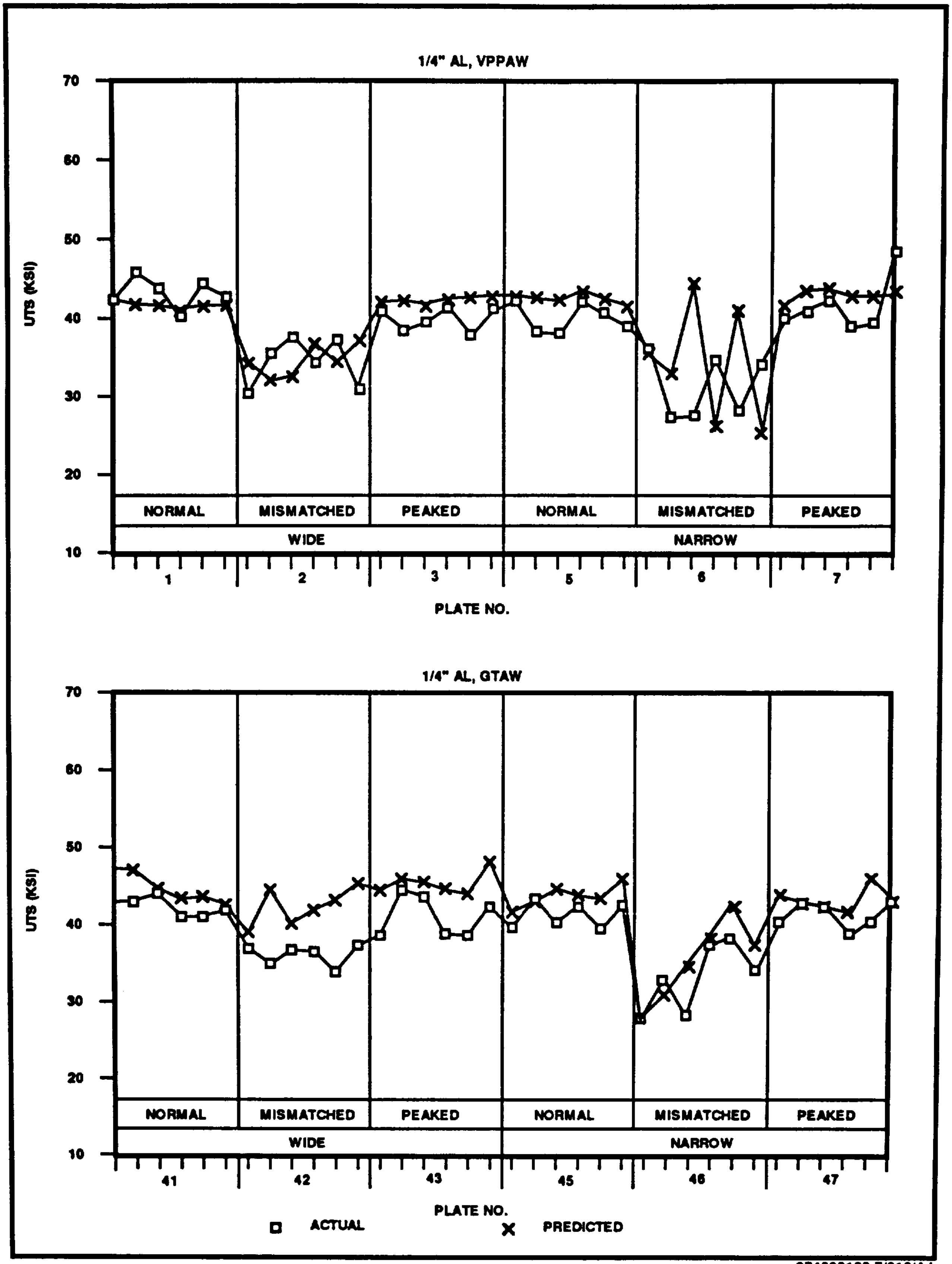

Figure 7. Actual Vs Predicted UTS, 1/4" Aluminum

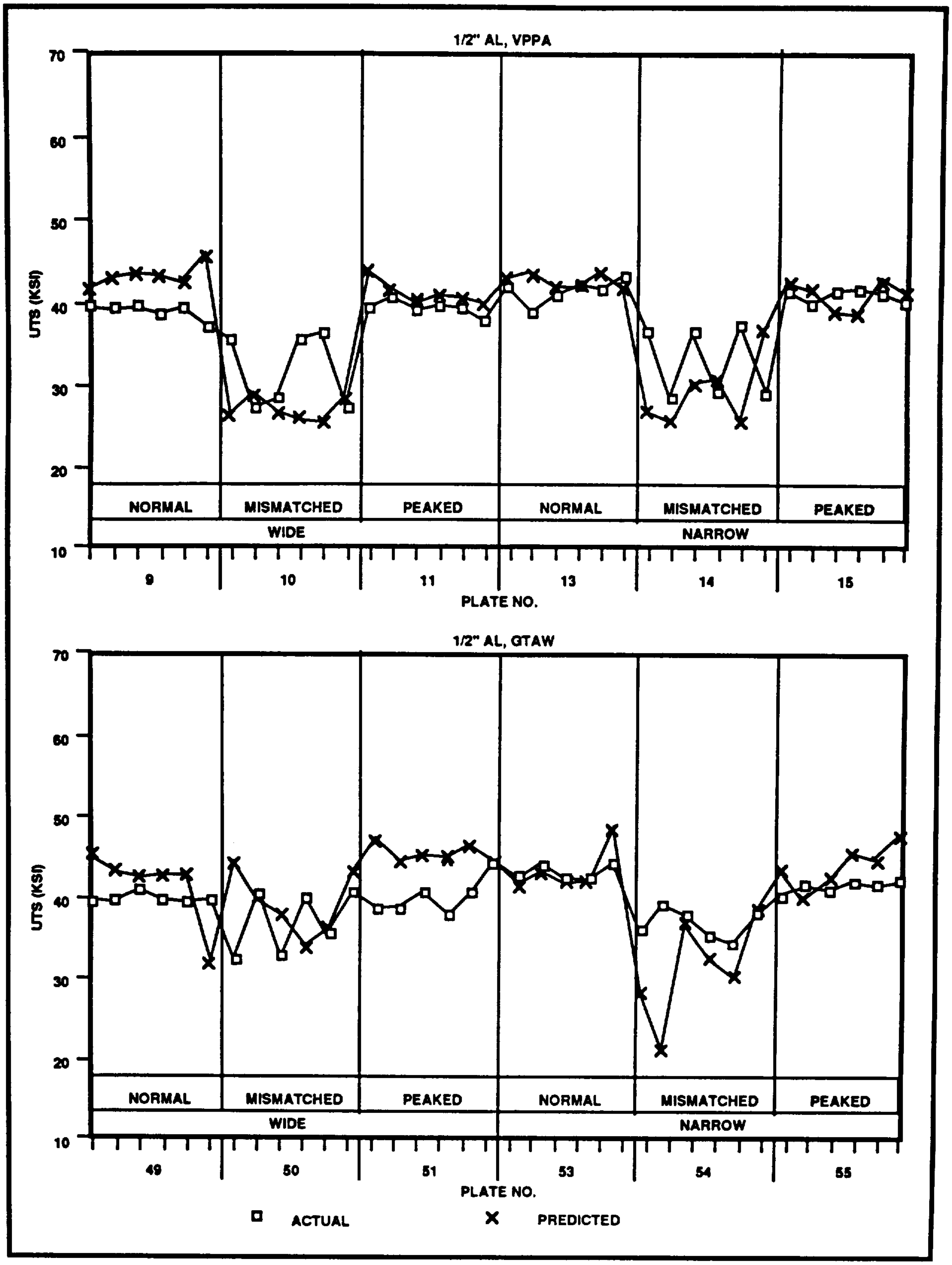

Figure 8. Actual Vs Predicted UTS, 1/2" Aluminum 07403192-8/919-KDS

To answer the first question above, compare values listed in Table 5 under the heading 'Actual UTS STD' to corresponding SDE values in the same table. The mean was a better predictor in every case when the full prediction was used.

Table 6 provides the same statistical calculations as Table 5, using the predictions that neglect fusion line angle effects. Here correlation of the theory to results improves for all six of the above mentioned data sub-sets. The theory becomes the better predictor overall and for the VPPAW and GTAW data sub-sets, and is nearly identical to the mean for the peaked sub-set. The theory remains worse than the mean as a predictor for the normal and the mismatched sub-sets.

To address the second question above, the SDE values from Table 5 should again be consulted. In some categories (such as all the normal (SDE = 2.38 ksi) and all the peaked welds (SDE = 2.62 ksi)) the theory correlates much better than it does in other categories (such as mismatched welds (SDE = 7.03 ksi)). Overall the predictions correlate better for 1/4" material than for 1/2" material, with SDE values of 4.07 ksi and 5.11 ksi respectively. Likewise, the predictions correlate slightly better to GTA welds than to VPPA welds, with SDE values of 4.34 ksi and 4.90 ksi respectively.

The data is broken into more specific groupings in Tables 5 and 6. The following examples show types of comparisons that can be made using these tables:

The best correlation of the theory full predictions to results is for narrow normal welds (SDE = 1.89 ksi) and the worst correlation is for mismatched narrow welds (SDE = 7.64 ksi).

For predictions that neglect fusion line angle effects, the best correlation is for shaved peaked welds (SDE = 1.14 ksi) and the worse correlation is for 1/2" shaved welds (SDE = 5.36 ksi).

Figures 9 and 10 show the actual UTS vs. the predicted UTS when the fusion line angle effects are neglected in the predictions. Table 6 provides the same statistical calculations as Table 5, using the predictions that neglect fusion line angle effects. Figures 9 and 10 and Table 6 can be compared to Figures 7 and 8 and Table 5 to see how neglecting the fusion line angle effects in the predictions affects correlation of the theory to test results.

Comparing Figures 9 and 10 to Figures 7 and 8 show an apparent improvement in correlation between predicted and actual UTS values. This is confirmed when comparing the SDE values from Table 6 to those from Table 5. Out of the 54 categories of data presented in Tables 5 and 6, in only one case (shaved VPPAW) the predictions without fusion line angle effects correlate worse than the full prediction. One case (narrow normal) correlates the same, and the remaining 52 cases correlate better (often with SDE values several ksi lower) when fusion line angle effects are neglected.

Obviously there are many possible combinations of categories in which the data can be sorted and evaluated. Tables 5 and 6 list only a fraction of these. Nonetheless, these tables, along with Figures 7 through 10, can be used to determine how well the theory correlates to the actual values for many different groupings of weld geometries.

The theory also predicts which weld toe will be the initiation site for fracture (Appendix C). Tensile test fracture surfaces were subject to naked eye examination only. The exact fracture origin was not able to be determined. However, any toe that the fracture intersected was considered a possible fracture origin, so these toes were identified (Appendix D) and compared to the predicted fracture origin toe. For example, if the fracture intersected toes 1, 3, 5 and 7 and the predicted fracture origin was toe 3, that is considered a correct prediction (although future detailed failure analysis may show differently).

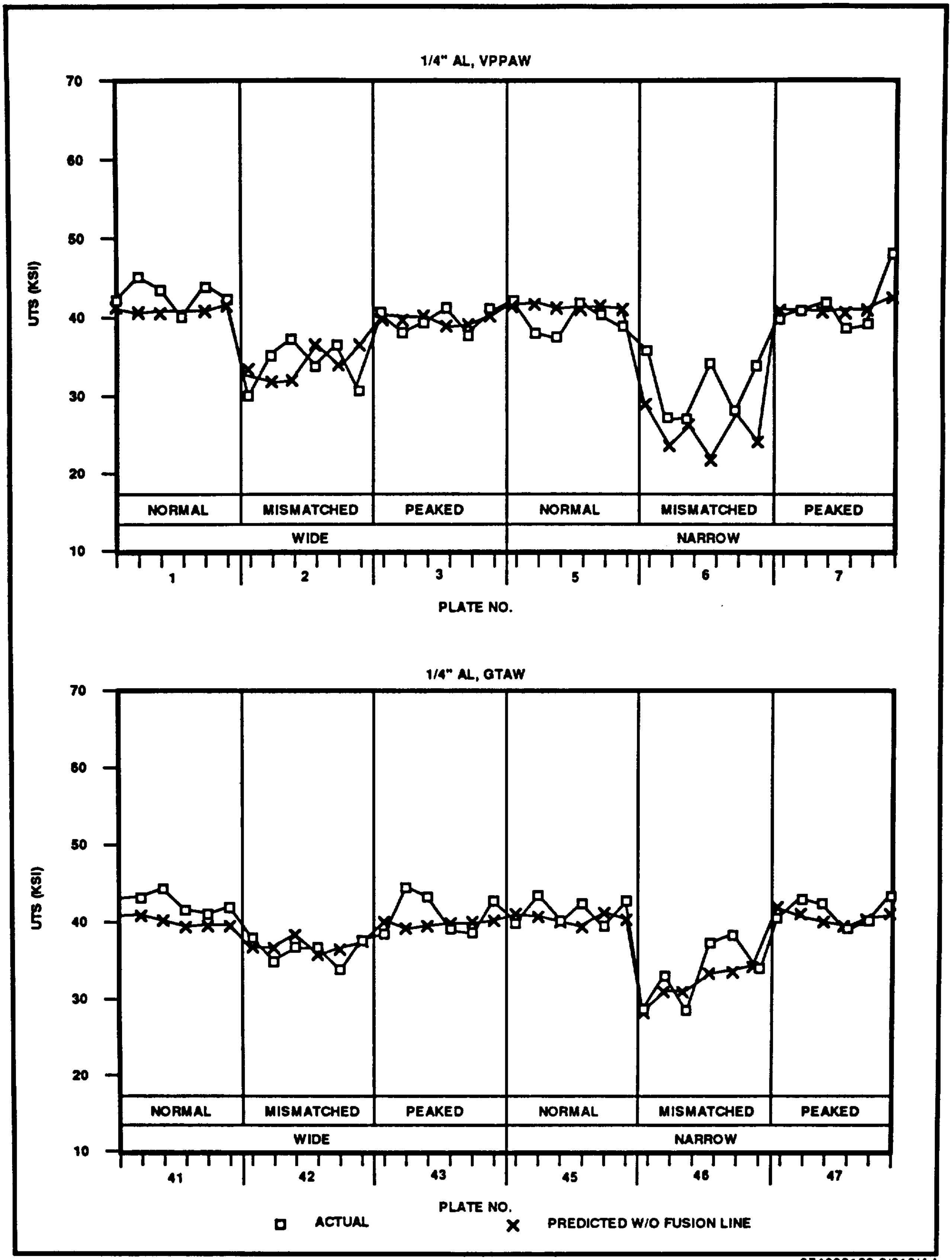

Figure 9. Actual UTS vs. Predicted W/O Fusion Line Angle, 1/4" Aluminum

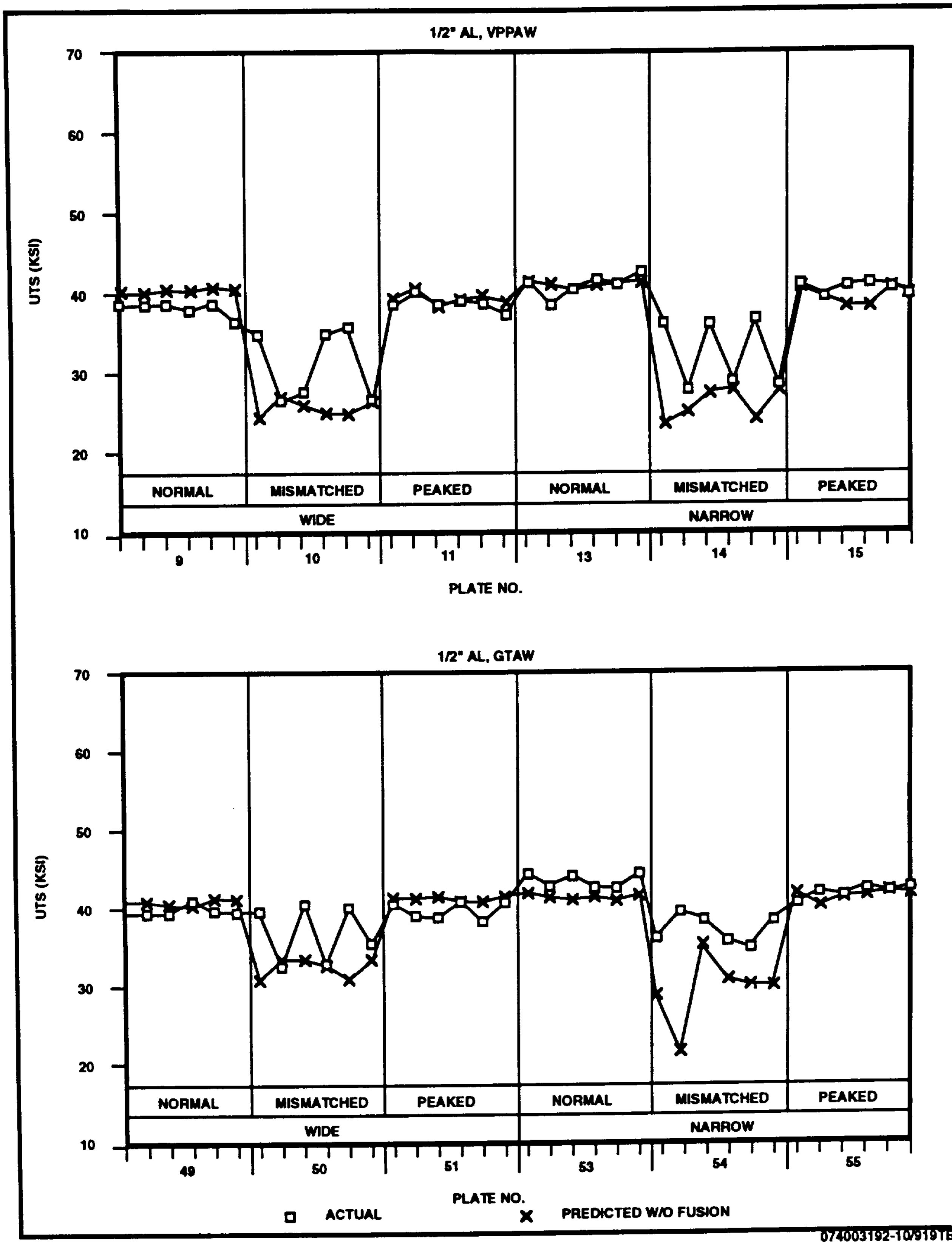

Figure 10. Actual UTS Vs Predicted W/O Fusion Line Angle, 1/2" Aluminum

All of the fractures occurred in the weld metal, either along the fusion line (FL) completely, in the fusion zone (FZ) completely, or partly along the FL and partly in the FZ. There were 143 tensile test specimens that fractured through at least one weld toe. Of these, the predicted toe matched 67 times (46.9%). Using the predictions that neglect fusion line angle effects changed many of the predicted fracture origins, however this resulted in only a slight improvement, matching 71 times (49.7%).

In evaluating the Vickers microhardness data (Table 3) and the ASTM grain size measurements (Table 4), no anomalies were noted that might explain the discrepancies between the theory and test results. Both microhardness and grain size measurement variations from specimen to specimen were considered to be within the normal scatter range for such measurements.

4.5 PREDICTED UTS VERSUS ACTUAL YIELD STRENGTH

Figures 11 and 12 show the measured yield strength (YS) vs. the predicted UTS for 1/4" and 1/2" material respectively. These were compared to see if perhaps the theory correlates better with test results when only the elastic portion of the tensile test is considered. If the error is more consistent than when comparing actual UTS to predicted UTS, that would indicate that improvements in the theory need to concentrate on the handling of plastic strain.

It must be noted here that taking YS measurements from stress-strain curves for specimens with peaking and/or mismatch may be misleading. As the specimens straighten during testing the strain is not uniform throughout the specimen, so one surface could be experiencing plastic yielding while the other surface is still elastic. Therefore the YS measurements should be considered very approximate.

The values of the SDE of errors between actual YS and predicted UTS are 3.45 ksi for 1/4" VPPAW, 2.88 ksi for 1/4" GTAW, 6.40 ksi for 1/2" VPPAW, and 5.44 ksi for 1/2" GTAW. Comparing these to the SDE values for actual UTS vs. predicted UTS show that YS correlates better for 1/4" VPPAW, but correlates worse for 1/2" VPPAW and 1/4" and 1/2" GTAW. Differences in YS behavior between the 2 material thicknesses also can be seen by the overall lower YS for 1/2" welds, and less fluctuation with weld geometry variations for 1/2" welds.

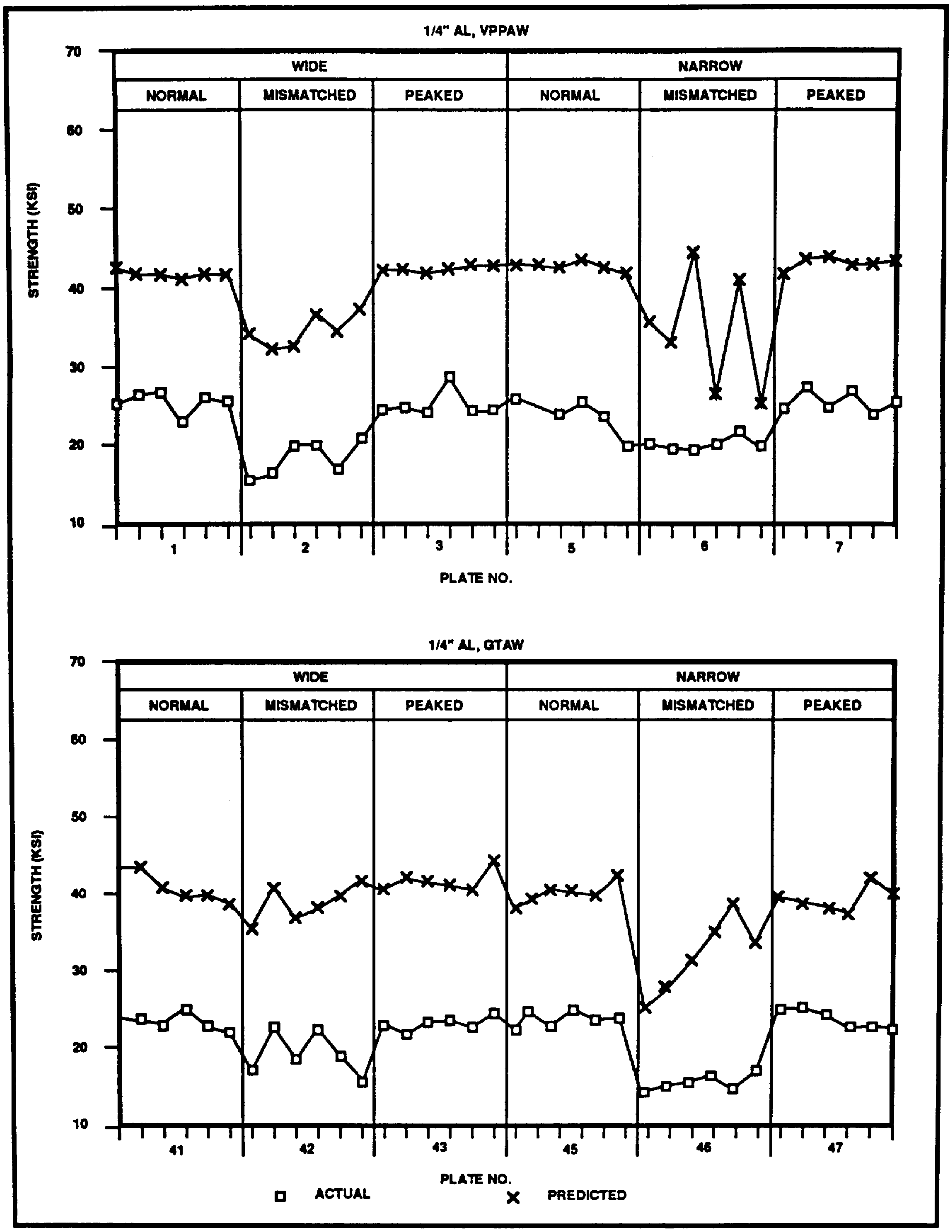

Figure 11. Predicted UTS Vs Actual YS, 1/4" Aluminum

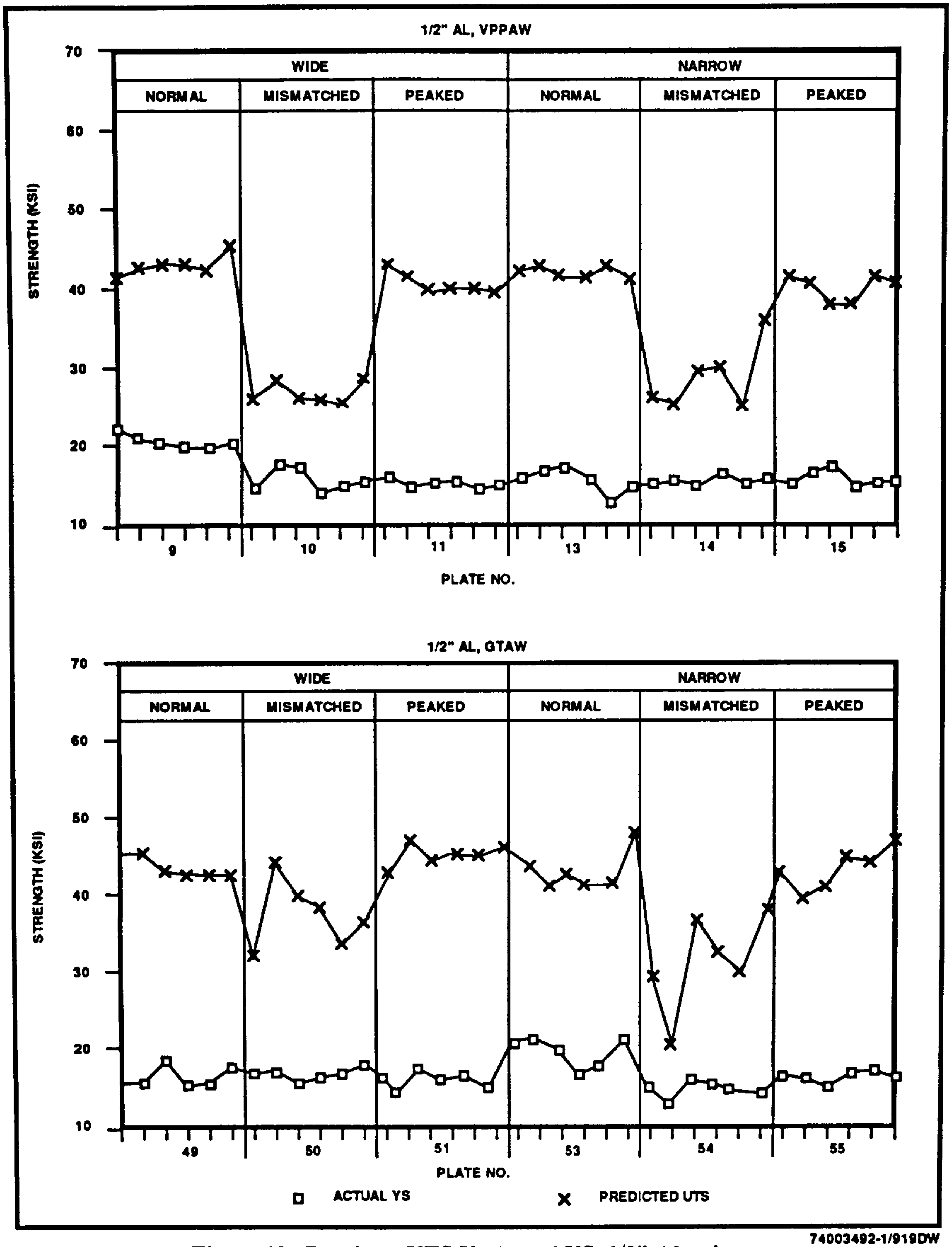

Figure 12. Predicted UTS Vs Actual YS, 1/2" Aluminum

SECTION 5. CONCLUSIONS

Based on the discussion, data, and analysis of the data presented in this report, the following conclusions are made:

Weld reinforcement was found to have a significant impact on UTS results.

For the overall data set, correlation to the UTS results is better for the mean of the results than for the full theory predictions.

For the overall data set, correlation to the UTS results is better for the predictions with fusion line angle effects neglected than for the mean of the results.

The theory correlates better to UTS results in 52 out of 54 cases when fusion line angle effects are neglected.

Fusion line angle effects upon UTS are not accounted for correctly in the theory.

Correlations of the theory predictions to UTS results vary with different data sub-sets. Best correlations generally are for the normal and peaked sub-sets. Worst correlations are generally for the mismatched sub-sets.

The theory does not correlate well with possible fracture origins. Regardless of whether fusion line angle effects are considered or not, the predicted fracture origin is wrong at least 50% of the time.

Overall, the theory does not correlate better to YS than to UTS. It must be pointed out that this conclusion, as well as any other conclusions based on YS results, is suspect due to uncertainty in the measurement of YS for peaked and/or mismatched specimens.

SECTION 6. RECOMMENDATIONS

The following actions are recommended to evaluate further the theory and to improve its correlation to the data:

Account for fusion line angle effects differently. If fusion line angle effects can be legitimately neglected, the theory becomes much more practical for production uses since fusion line angle is the only weld geometry characteristic used in the theory that is difficult or impossible, to measure non-destructively.

Having mentioned applying the theory to production parts, it is recommended that consideration be given to the restraint of the part and the effect of that restraint on the peaking measurement obtained. When a tensile specimen is machined out of a part, the specimen tends to change peaking angle because it is no longer restrained by the rigidity of the part. Correlating theory to peaking angles of unrestrained parts (i.e., tensile specimens) will not necessarily correlate well to the peaking angles of restrained parts, because a different peaking angle measurement will be obtained and used in the calculations. Consideration should be given to quantifying the difference in peaking between a production part and an equivalent tensile specimen, and to account for the difference in the theory with a safety factor on the peaking measurements.

Take weld reinforcement into account in the theory. Reinforcement tends to concentrate the strain closer to the edges of the weld. This is evidenced by smaller percent elongation measurements for the unshaved specimens than for the shaved specimens. The theory currently assumes the strain is uniform across the weld width, thereby neglecting any effects of weld reinforcement.

Modifications to the theory regarding the weld reinforcements should attempt to explain the significantly higher UTS results obtained for shaved mismatched specimens when compared with similar unshaved mismatched specimens. Possibilities may include strain distribution across the weld width (as discussed in the above paragraph), using a stress concentration factor greater than 1 at the toes of unshaved specimens, and/or accounting for lower ductility at the toes of unshaved specimens due to a localized region with higher Copper content (ref. 4) that may be removed during shaving.

Further analysis of the current data set should be done to help pinpoint the strengths and weaknesses of the theory. In a manner similar to that used to determine the correlation of the predictions when fusion line angle effects are neglected, evaluation should be made of at least 5 other variations of the theory:

(1) Neglecting peaking effects
(2) Neglecting mismatch effects
(3) Neglecting both peaking and mismatch effects
(4) Neglecting both mismatch and fusion line effects
(5) Neglecting both peaking and fusion line effects

Improvements in theory correlation to fracture origin locations are needed. The additional analysis recommended in the above paragraph may help improve this correlation. When the theory predicts the wrong failure origin (as occurred over half the time) and then predicts UTS based on the geometry at that wrong location, correlation is bound to suffer.

When considering the theory predictions of fracture origin it should be noted that the theory is limited to using weld geometry at only those weld toes at the edges of the specimen. However, it is quite possible that there are geometry variations of the weld toes that are not on the specimen edges such that the weakest point, and thus the actual fracture origination site, is not at any of the edges even though the fracture passes through some of the weld toes at the edges. Identification of the actual fracture initiation site is required to determine if this is occurring.

Improved correlation of predicted to actual UTS for mismatched samples should be sought. This may occur as a result of achieving better correlation of the predictions of fracture origin location, and from the inclusion of reinforcement effects in the theory.

Additional statistical analyses, such as a regression analysis, should be done to empirically 'tune' the theory to correlate better with the results.

Other thicknesses and materials, originally planned but not completed, should be completed and evaluated. Those originally planned, and their statuses, are:

> 0.750" thick 2219-T87 - Twelve welds originally planned. None were welded.
>
> 0.250" Inconel 718 - Twelve welds originally planned. Six VPPA welds were completed, inspected, and rough cut into tensile specimens. Plates for six additional welds have been prepared for GTAW.
>
> 0.450" HP9-4-30 - Two welds originally planned. Both were completed (one VPPA, one GTA), inspected, and marked for sectioning.
>
> Perform additional tests and/or analyses to determine conclusively the effect of weld width on UTS and account for it in the theory.

ACKNOWLEDGEMENTS

This work was performed under NASA contract #NAS8-38671.

Acknowledgements are due to the following people:

Mr. E. Bayless, NASA/MSFC, for providing funding, equipment, and personnel to support this work.

Dr. A. C. Nunes, Jr., NASA/MSFC, for developing this theory, and for providing many hours of enlightening discussions regarding it's derivation, application, and evaluation.

The NASA/MSFC and Martin-Marietta welders, machinists, inspectors, metallurgists, engineers, and mechanical test lab personnel who performed the majority of the hands-on work.

Mr. P. Bastias, Dr. G. Hahn, and their associates at Vanderbilt University for performing the finite element analysis study.

The Nichols Research Corporation technicians and engineers who performed the hundreds of measurements and analyzed the thousands of pieces of data required for this work.

REFERENCES

1. Nunes, A. C., Jr. March 5, 1991. THE ULTIMATE STRENGTH OF BUTT WELDS: BEAD GEOMETRY EFFECTS - THEORY. Prepared for NASA/MSFC by General Digital Industries, Inc., Huntsville, AL.

2. Bastias, P. C., et. al. July 26, 1991. THE ANALYSIS OF THE STRENGTH OF WELDS: A CRITIQUE OF A SIMPLIFIED ANALYSIS PROPOSED BY A. NUNES. Center For Materials Tribology, Vanderbilt University. Prepared for General Digital Industries, Inc., Huntsville, AL.

3. Fellner, M., Hamersky, M., and Pink, E. May 15, 1991. A COMPARISON OF THE PORTEVIN- LeCHATELIER EFFECT IN CONSTANT-STRAIN-RATE AND CONSTANT-STRESS-RATE TESTS. Materials Science and Engineering, A136 (1991) 157-161. Paper from the Fifth International Symposium on Plasticity of Metals and Alloys, Aug. 27-31, 1990, Prague, Czechoslovakia.

4. Hartman, J. A., Beil, R. J., and Hahn, G. T. March 1987. EFFECT OF COPPER-RICH REGIONS OF TENSILE PROPERTIES OF VPPA WELDMENTS OF 2219-T87 ALUMINUM. Welding Journal 66(3):73-s to 83-s.

APPENDIX A

Table A-1. Weld Width and Fusion Line Angle Measurements for Each Tensile Specimen

SPECIMEN NUMBER	WELD WIDTH (in)		FUSION LINE ANGLES (IN DEGREES) AT TOE NUMBER:							
	CROWN	ROOT	1	2	3	4	5	6	7	8
P0106	0.427	0.284	36.5	31.0	6.5	3.0	44.0	28.0	6.0	0.0
P0108	0.404	0.274	37.0	39.0	3.5	1.0	28.0	37.0	1.0	2.0
P0111	0.350	0.296	36.0	31.0	3.5	1.0	28.5	33.0	11.0	6.5
P0113	0.461	0.296	37.0	41.0	1.5	3.0	33.5	36.0	0.0	3.0
P0117	0.441	0.313	25.5	38.0	1.5	10.0	29.0	29.0	4.0	3.0
P0119	0.467	0.297	34.0	53.0	0.5	0.5	28.0	47.0	0.5	1.0
P0215	0.472	0.370	41.5	25.5	12.5	6.5	32.5	30.0	2.0	18.0
P0217	0.487	0.333	41.5	43.0	2.5	1.5	39.0	31.0	1.5	4.0
P0219	0.492	0.372	53.0	31.0	0.5	4.5	39.0	22.5	6.5	4.5
P0221	0.458	0.378	34.5	9.0	12.0	2.0	37.5	19.0	10.0	1.0
P0222	0.496	0.363	40.0	42.0	2.5	3.5	34.5	17.0	3.5	3.0
P0224	0.455	0.373	35.0	17.0	6.5	5.0	27.5	22.0	4.5	5.5
P0309	0.461	0.354	28.0	40.0	5.0	8.0	36.0	36.0	10.0	1.5
P0311	0.469	0.338	28.0	35.0	0.0	4.0	36.0	36.0	3.0	1.0
P0313	0.486	0.332	31.5	34.5	1.5	2.5	30.0	35.0	5.0	0.0
P0315	0.458	0.357	27.0	29.0	10.0	5.5	28.0	27.5	7.0	2.0
P0320	0.480	0.345	34.0	35.0	1.0	3.0	33.5	32.0	3.0	6.0
P0323	0.493	0.368	28.0	30.0	12.5	4.5	31.0	18.0	7.0	5.0
P0507	0.370	0.282	16.5	12.0	5.0	1.0	14.0	15.0	7.5	0.0
P0509	0.368	0.283	20.0	22.5	1.0	2.0	15.0	15.5	2.5	1.0
P0516	0.349	0.276	25.5	15.0	2.5	4.0	15.0	18.5	5.5	0.5
P0518	0.361	0.295	13.0	23.5	12.5	6.0	16.5	17.5	5.5	5.0
P0521	0.347	0.272	15.0	19.5	0.5	2.0	16.0	23.0	1.0	1.0
P0523	0.363	0.308	21.0	16.5	11.5	11.5	13.0	17.5	4.5	2.0

Table A-1. Weld Width and Fusion Line Angle Measurements for Each Tensile Specimen (Continued)

SPECIMEN	WELD WIDTH (in)		FUSION LINE ANGLES (IN DEGREES) AT TOE NUMBER:							
NUMBER	CROWN	ROOT	1	2	3	4	5	6	7	8
P0604	0.424	0.285	58.0	28.5	2.0	21.5	50.0	36.0	15.0	52.0
P0606	0.417	0.268	46.5	34.0	8.0	24.5	35.0	32.0	6.5	34.5
P0612	0.435	0.284	50.5	31.5	7.5	33.0	48.0	36.0	6.0	43.0
P0614	0.388	0.260	35.0	34.0	6.0	28.0	40.0	29.0	4.0	17.5
P0620	0.445	0.286	54.0	29.5	5.5	29.0	48.5	31.5	2.5	37.5
P0622	0.423	0.258	50.0	21.0	6.0	20.0	49.0	28.5	10.0	7.0
P0704	0.345	0.269	19.5	21.5	1.0	1.0	16.5	16.0	1.5	11.0
P0706	0.371	0.336	8.5	15.0	18.5	10.5	12.0	15.0	17.0	8.0
P0712	0.336	0.297	11.5	21.0	26.0	11.5	16.0	16.0	8.0	7.0
P0714	0.337	0.266	14.0	15.5	2.5	4.0	18.0	14.0	0.0	5.5
P0721	0.327	0.263	17.5	20.5	4.5	7.5	22.0	27.0	0.0	1.5
P0723	0.335	0.292	13.0	21.0	5.0	1.5	14.5	20.5	13.5	6.5
P0906	0.509	0.415	6.5	9.0	3.5	0.0	12.5	16.5	0.5	3.0
P0908	0.537	0.449	12.0	29.5	13.5	13.5	30.0	29.5	8.0	20.0
P0916	0.535	0.441	20.0	23.5	22.5	12.0	29.5	39.5	15.0	22.5
P0918	0.542	0.428	35.0	39.0	8.0	2.0	32.0	37.5	22.0	6.5
P0920	0.536	0.422	18.0	22.5	10.0	4.0	19.5	23.5	3.5	7.5
P0922	0.503	0.424	31.5	36.0	31.0	23.0	32.5	35.5	13.5	16.0
P1006	0.504	0.396	22.5	18.0	9.0	3.0	15.0	18.0	12.5	6.0
P1008	0.530	0.430	26.0	8.5	27.0	7.0	26.5	22.0	8.0	11.5
P1011	0.517	0.415	30.0	7.5	28.5	10.0	26.5	21.0	2.0	5.0
P1013	0.562	0.406	30.0	28.5	11.5	10.0	31.0	35.5	6.0	6.0
P1016	0.523	0.393	23.0	10.0	23.0	6.0	38.0	15.5	0.5	2.0
P1018	0.540	0.428	32.5	5.0	19.0	25.0	38.0	7.5	12.0	3.5
P1103	0.521	0.426	24.5	29.5	27.0	20.0	32.0	7.0	14.5	19.0
P1105	0.500	0.373	22.5	11.5	9.5	3.0	7.5	10.5	3.0	8.5
P1109	0.488	0.399	9.0	4.5	23.5	17.0	34.0	10.0	9.0	10.5
P1111	0.494	0.393	14.0	8.0	2.5	5.0	12.5	8.5	9.0	6.0
P1115	0.475	0.395	5.5	7.5	2.5	1.5	6.5	6.0	6.0	10.0
P1117	0.528	0.410	7.0	30.0	0.0	2.0	7.0	32.0	10.5	9.0

Table A-1. Weld Width and Fusion Line Angle Measurements for Each Tensile Specimen (Continued)

SPECIMEN	WELD WIDTH (in)		FUSION LINE ANGLES (IN DEGREES) AT TOE NUMBER:							
NUMBER	CROWN	ROOT	1	2	3	4	5	6	7	8
P1310	0.643	0.373	41.0	27.5	11.5	18.5	43.5	39.5	2.0	1.5
P1312	0.645	0.358	41.5	31.5	8.0	4.0	39.0	38.5	11.0	1.5
P1315	0.646	0.374	42.0	43.5	8.5	6.5	39.5	46.0	9.0	9.5
P1317	0.624	0.338	40.0	32.0	0.0	5.0	52.5	58.5	10.0	9.5
P1319	0.630	0.371	34.0	26.5	3.5	4.0	33.5	43.0	7.0	3.0
P1321	0.650	0.356	40.0	25.0	1.0	1.0	45.5	46.5	7.5	3.5
P1416	0.507	0.386	21.5	20.5	13.0	17.0	20.0	25.0	9.0	14.0
P1418	0.535	0.397	21.5	30.0	10.0	2.5	24.0	30.0	13.5	15.0
P1419	0.519	0.417	19.0	21.0	14.0	13.0	22.0	26.5	12.0	35.5
P1421	0.533	0.408	19.5	28.5	13.5	13.5	24.5	41.0	21.0	27.5
P1422	0.506	0.361	27.0	18.0	7.5	17.0	15.5	20.0	1.0	9.0
P1424	0.539	0.389	31.5	38.0	14.5	24.5	40.0	33.0	11.5	24.0
P1509	0.450	0.342	5.5	22.0	6.0	4.0	19.5	10.0	4.5	11.0
P1511	0.448	0.356	8.0	10.0	10.5	10.5	10.5	10.5	28.5	15.5
P1514	0.423	0.355	6.5	9.0	13.5	12.5	10.0	1.5	20.5	21.5
P1516	0.409	0.313	3.5	3.0	0.0	0.0	3.0	11.0	5.0	2.0
P1518	0.433	0.343	8.0	10.0	11.0	9.0	5.0	9.5	9.0	10.5
P1520	0.456	0.347	10.5	7.5	10.5	5.5	4.0	11.0	12.5	7.5
T4103	0.366	0.149	28.0	29.5	15.0	16.0	23.5	35.0	20.0	22.0
T4105	0.364	0.251	35.0	31.0	17.5	17.5	41.5	40.0	12.0	11.5
T4111	0.378	0.281	31.5	34.0	11.0	2.0	40.0	24.0	7.0	10.0
T4121	0.357	0.276	25.0	14.5	10.5	15.5	23.0	15.5	0.5	9.5
T4123	0.369	0.275	28.0	35.5	7.0	2.0	30.0	27.5	15.0	15.0
T4204	0.467	0.346	28.5	39.5	26.5	21.5	37.5	31.0	12.5	27.5
T4206	0.463	0.342	30.5	36.5	25.5	6.5	35.0	40.0	23.5	27.0
T4214	0.455	0.389	20.5	34.5	15.0	16.5	27.0	27.5	5.0	17.0
T4216	0.438	0.385	23.5	28.5	13.0	14.0	18.5	27.5	14.5	19.0
T4218	0.443	0.372	19.5	31.5	28.0	6.0	26.0	33.5	19.5	2.5
T4222	0.488	0.418	37.0	26.0	24.5	16.5	18.5	37.5	22.5	20.5

Table A-1. Weld Width and Fusion Line Angle Measurements for Each Tensile Specimen (Continued)

SPECIMEN	WELD WIDTH (in)		FUSION LINE ANGLES (IN DEGREES) AT TOE NUMBER:							
NUMBER	CROWN	ROOT	1	2	3	4	5	6	7	8
T4307	0.431	0.295	29.0	26.0	7.0	15.0	38.0	23.0	3.5	15.0
T4309	0.407	0.312	31.5	27.5	7.0	16.5	34.0	26.0	14.0	27.0
T4312	0.406	0.333	23.0	28.0	19.0	8.5	28.5	24.5	10.0	17.5
T4314	0.442	0.367	38.5	30.0	12.5	21.5	27.5	33.5	8.5	13.5
T4318	0.443	0.328	36.0	28.5	7.5	7.5	29.0	30.0	2.0	2.5
T4320	0.428	0.362	34.5	29.5	25.5	16.5	31.5	32.5	21.5	20.0
T4502	0.373	0.248	26.5	24.0	13.5	5.5	33.0	23.0	9.0	21.0
T4504	0.363	0.237	31.5	41.5	1.5	1.0	31.0	31.0	3.0	1.0
T4509	0.393	0.293	30.5	24.0	17.5	27.0	34.5	32.5	10.0	9.0
T4511	0.372	0.286	31.5	17.5	14.0	8.5	36.5	31.5	3.5	17.5
T4518	0.389	0.348	34.0	23.0	12.0	11.5	27.0	13.5	4.5	12.5
T4520	0.377	0.341	29.5	29.5	19.0	21.5	26.5	18.0	23.5	17.5
T4615	0.424	0.327	20.5	42.5	7.5	10.5	12.5	33.0	7.0	6.5
T4617	0.464	0.363	17.0	31.0	21.0	15.0	21.5	33.5	0.5	12.5
T4619	0.438	0.341	16.0	40.5	16.5	8.5	21.0	34.5	18.5	12.5
T4621	0.458	0.361	18.5	31.5	18.5	15.0	29.0	28.5	19.0	15.0
T4623	0.479	0.389	18.0	41.0	35.0	20.0	30.5	28.0	24.5	17.5
T4625	0.446	0.361	22.5	33.5	23.5	21.5	19.5	28.5	15.0	19.5
T4702	0.377	0.182	24.5	29.5	12.5	19.5	35.5	32.0	14.0	6.5
T4704	0.346	0.207	32.0	33.0	11.0	2.0	23.0	28.5	9.5	4.0
T4708	0.344	0.245	23.5	29.5	9.0	9.5	30.5	26.0	3.0	8.5
T4710	0.389	0.261	39.5	33.0	1.0	1.0	31.5	33.5	7.0	8.5
T4720	0.390	0.320	34.5	24.5	11.5	16.5	26.0	28.5	25.5	17.0
T4722	0.380	0.292	27.5	37.0	11.0	1.0	35.5	18.5	5.0	23.5
T4905	0.514	0.465	18.0	19.5	21.0	26.0	21.5	26.0	13.5	22.0
T4910	0.521	0.490	13.5	26.5	24.5	33.5	25.5	29.0	27.5	30.0
T4912	0.480	0.447	17.5	21.0	9.0	6.5	11.0	26.5	15.5	12.5
T4921	0.541	0.494	27.5	23.5	21.5	20.5	17.5	18.0	7.5	26.0
T4923	0.515	0.500	12.0	13.0	13.0	13.0	11.0	24.0	20.5	24.0

Table A-1. Weld Width and Fusion Line Angle Measurements for Each Tensile Specimen (Continued)

SPECIMEN NUMBER	WELD WIDTH (In)		FUSION LINE ANGLES (IN DEGREES) AT TOE NUMBER:							
	CROWN	ROOT	1	2	3	4	5	6	7	8
T5005	0.549	0.433	28.5	35.0	27.0	17.5	30.5	32.0	9.5	10.0
T5007	0.544	0.440	29.5	26.0	28.5	24.5	29.5	37.0	29.0	32.5
T5010	0.602	0.489	31.0	39.0	29.5	31.0	30.0	38.0	21.5	25.5
T5012	0.563	0.457	32.0	35.0	19.5	10.5	23.5	32.0	31.0	19.0
T5019	0.590	0.449	21.5	29.0	22.0	8.0	18.0	31.0	15.0	7.5
T5021	0.600	0.483	43.0	30.0	21.0	27.0	13.0	31.5	15.0	18.0
T5104	0.494	0.554	20.0	11.5	15.5	17.5	20.0	23.5	21.0	17.5
T5106	0.550	0.592	27.5	20.5	22.0	19.0	24.5	24.5	22.0	27.0
T5107	0.533	0.548	232.5	23.0	12.0	22.5	18.5	21.0	20.0	17.5
T5109	0.512	0.551	28.0	17.5	18.0	18.0	22.0	20.0	18.5	19.0
T5112	0.568	0.591	25.5	22.5	15.5	14.5	23.0	23.5	20.5	16.5
T5114	0.517	0.578	24.5	19.0	18.0	21.0	21.5	21.0	20.0	19.0
T5302	0.512	0.295	36.5	30.0	15.5	16.5	33.5	33.5	17.0	12.0
T5304	0.544	0.313	33.5	32.5	2.5	5.0	32.0	25.0	3.5	4.5
T5310	0.498	0.366	33.5	29.5	7.0	10.0	28.0	30.5	10.0	14.5
T5312	0.509	0.333	26.0	26.5	0.0	1.5	26.5	32.0	0.5	1.5
T5320	0.534	0.312	32.5	38.5	1.0	5.0	38.0	35.5	2.0	6.5
T5322	0.523	0.374	26.5	24.5	22.0	21.0	27.5	34.0	21.5	20.0
T5402	0.506	0.354	28.5	4.0	4.5	0.5	34.0	4.5	3.5	1.5
T5404	0.542	0.300	33.5	12.0	2.5	4.5	42.0	5.5	14.0	1.0
T5411	0.565	0.509	45.5	33.0	1.0	1.5	36.0	27.0	0.5	2.0
T5413	0.527	0.362	32.0	9.0	5.0	11.5	35.0	11.5	7.5	20.5
T5417	0.534	0.364	37.0	20.0	15.5	18.5	29.0	19.5	15.0	6.0
T5419	0.577	0.404	37.0	28.5	20.5	26.0	39.5	26.0	12.0	24.5
T5501	0.500	0.288	22.5	23.5	1.0	3.5	25.5	17.5	5.5	3.5
T5503	0.527	0.262	26.5	23.5	7.5	2.5	27.0	30.0	1.0	6.0
T5508	0.542	0.241	26.5	22.0	10.5	11.5	24.0	28.5	7.5	9.5
T5510	0.507	0.288	17.0	22.0	12.5	9.5	22.5	25.5	25.0	16.5
T5519	0.509	0.342	35.0	24.5	17.5	11.0	30.0	30.5	25.5	16.0
T5521	0.542	0.223	20.0	25.5	19.0	11.0	35.5	21.5	22.5	17.0

Table A-1. Weld Width and Fusion Line Angle Measurements for Each Tensile Specimen (Concluded)

SPECIMEN	WELD WIDTH (In)		FUSION LINE ANGLES (IN DEGREES) AT TOE NUMBER:							
NUMBER	CROWN	ROOT	1	2	3	4	5	6	7	8
**T4109	0.371	0.240	27.5	26.5	7.0	9.0	28.0	28.0	2.0	0.5
**T4110	0.357	0.257	30.5	27.5	3.0	1.0	29.5	29.5	3.0	0.5
**T4114	0.362	0.256	26.5	40.0	1.0	2.5	39.5	38.0	6.0	4.0
**T4115	0.363	0.264	31.0	33.0	1.5	5.0	29.0	24.5	5.0	6.5
**T4207	0.452	0.328	36.0	37.5	8.5	15.5	27.0	29.0	19.5	24.0
**T4208	0.437	0.339	24.0	25.0	21.5	17.5	25.0	31.0	24.5	15.0
**T4506	0.362	0.242	31.0	21.0	9.5	20.0	27.5	19.0	8.0	11.0
**T4507	0.362	0.253	35.5	34.5	16.5	15.5	35.0	26.5	12.0	10.0
***T4903	0.474	0.440	15.5	16.0	17.0	20.5	14.5	16.5	15.5	11.5

**Counter-peaking rotation trial specimens
***Test equipment malfunctioned, destroying specimen before any mechanical properties obtained

APPENDIX B

Figure B-1. Reentrant Angle, Mismatch, and Peaking Measurements for Each Tensile Specimen

SPECIMEN NUMBER	REENTRANT ANGLES (IN DEGREES) AT TOE NUMBER 1	2	3	4	5	6	7	8	MISMATCH (INCHES)	PEAKING ANGLE
P0106	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.001	-1.0
P0108	17.0	23.0	37.0	38.5	17.5	17.5	34.0	35.0	0.006	-1.9
P0111	18.5	21.0	31.5	37.0	18.0	17.0	37.5	35.5	-0.006	-1.3
P0113	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.009	-0.9
P0117	28.0	16.5	33.0	35.0	15.0	16.0	39.0	30.5	-0.007	-1.3
P0119	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.003	0.0
P0215	34.5	11.5	29.0	75.0	33.0	12.0	32.0	72.0	0.093	-1.0
P0217	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.089	-0.9
P0219	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.110	-1.3
P0221	32.0	17.0	34.0	67.0	33.0	14.0	34.0	52.5	0.065	-1.3
P0222	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.087	-2.3
P0224	34.0	20.5	30.5	55.0	31.0	14.0	31.0	74.5	0.062	-1.1
P0309	31.0	27.5	36.0	43.5	26.0	27.0	39.5	44.0	0.017	-4.9
P0311	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.016	-5.4
P0313	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.018	-4.3
P0315	24.5	18.0	36.0	39.5	36.0	26.0	42.0	47.0	0.022	-6.8
P0320	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.021	-7.6
P0323	27.0	23.0	36.0	36.0	24.0	20.0	33.5	37.5	0.013	-4.6
P0507	18.0	15.5	31.0	36.5	17.0	15.5	36.5	33.5	0.002	-1.9
P0509	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.001	-1.0
P0516	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.004	-1.5
P0518	19.5	21.0	37.5	48.0	18.0	18.0	33.5	34.5	-0.002	-2.1
P0521	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.003	-1.3
P0523	17.5	21.0	30.5	35.0	17.0	16.5	39.0	30.5	-0.010	-0.6

Figure B-1. Reentrant Angle, Mismatch, and Peaking Measurements for Each Tensile Specimen (Continued)

SPECIMEN NUMBER	REENTRANT ANGLES (IN DEGREES) AT TOE NUMBER								MISMATCH (INCHES)	PEAKING ANGLE
	1	2	3	4	5	6	7	8		
P0604	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.089	-1.8
P0606	49.5	24.5	8.0	63.0	48.5	27.5	7.0	65.0	0.106	-1.8
P0612	42.5	28.5	24.5	64.5	45.5	18.0	12.5	60.5	0.103	-1.5
P0614	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.108	-0.3
P0620	46.0	23.5	7.5	63.0	42.0	15.0	19.0	61.5	0.094	-0.8
P0622	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.096	-1.3
P0704	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.008	-1.4
P0706	23.5	26.0	37.0	34.0	22.0	21.5	32.0	35.0	-0.006	-1.8
PO712	18.0	18.0	41.0	40.0	19.0	16.5	36.0	34.0	-0.004	-3.0
P0714	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.005	-2.9
P0721	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.004	-2.6
P0723	19.0	33.0	49.0	40.0	21.0	19.5	45.0	34.0	0.000	-1.6
P0906	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.004	-1.3
P0908	42.0	41.0	47.0	44.5	42.0	40.0	49.0	42.0	0.005	-1.6
P0916	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.006	-0.5
P0918	36.0	35.0	45.5	50.5	32.5	30.0	49.0	51.5	-.0002	-2.0
P0920	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.001	-1.1
P0922	28.0	28.0	53.0	52.5	43.0	41.0	54.0	48.5	0.004	-1.3
P1006	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.107	-1.1
P1008	12.5	54.0	54.0	29.5	15.0	53.0	62.0	31.0	-0.105	-0.5
P1011	16.5	61.5	61.5	32.5	18.5	56.5	60.5	44.5	-0.114	-2.6
P1013	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.112	-1.6
P1016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.107	-1.8
P1018	17.0	61.0	59.5	31.5	22.0	51.0	64.0	35.0	-0.112	-0.9
P1103	26.0	26.0	49.0	48.0	32.5	21.0	44.5	50.0	0.015	-2.0
P1105	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.005	-1.4
P1109	27.5	17.5	55.0	51.5	27.5	17.0	46.0	63.0	0.022	-2.3
P1111	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.018	-1.4
P1115	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.012	-1.6
P1117	39.0	26.5	54.0	49.5	35.0	27.5	53.5	47.0	0.022	-2.1

Figure B-1. Reentrant Angle, Mismatch, and Peaking Measurements for Each Tensile Specimen (Continued)

SPECIMEN	REENTRANT ANGLES (IN DEGREES) AT TOE NUMBER								MISMATCH	PEAKING
NUMBER	1	2	3	4	5	6	7	8	(INCHES)	ANGLE
P1310	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.001	-0.6
P1312	25.5	22.0	35.0	30.0	26.5	30.0	39.0	31.0	-0.004	-1.6
P1315	24.5	23.0	40.0	34.0	22.5	27.5	39.0	33.0	-0.012	-1.3
P1317	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.008	-1.5
P1319	25.0	25.0	42.0	29.0	23.5	23.5	38.5	37.0	-0.002	-2.0
P1321	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.005	-0.8
P1416	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.112	-1.5
P1418	65.5	17.0	33.0	66.0	52.5	22.0	38.0	67.5	0.110	-1.8
P1419	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.102	-0.9
P1421	52.0	30.0	36.0	66.0	60.0	23.5	30.5	56.5	0.099	-2.1
P1422	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.097	-2.0
P1424	66.5	34.5	28.5	34.5	58.5	25.5	38.0	57.5	0.090	-1.8
P1509	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.005	-1.9
P1511	18.5	34.0	43.0	45.0	22.5	33.0	43.5	37.0	-0.011	-2.1
P1514	19.0	28.5	46.5	45.0	16.5	25.0	48.0	46.0	-0.020	-1.8
P1516	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.014	-3.0
P1518	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.004	-1.5
P1520	26.0	44.5	48.0	46.5	33.0	36.0	48.0	45.0	-0.009	-2.1
T4103	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000	-3.1
T4105	29.5	29.5	19.0	23.0	30.5	29.0	21.0	20.0	-0.003	-3.8
T4111	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.006	-5.6
T4121	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.006	-4.1
T4123	30.5	30.0	12.5	19.0	29.0	28.0	13.0	10.0	-0.009	-4.1
T4204	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.053	-3.3
T4206	16.0	32.5	38.0	18.5	14.5	31.0	38.0	16.0	-0.058	-3.9
T4214	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.038	-5.0
T4216	10.0	23.0	53.5	29.5	10.5	24.5	65.0	41.0	-0.054	-8.5
T4218	13.0	27.5	41.0	20.0	13.0	29.0	34.0	19.0	-0.58	-6.6
T4222	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.063	-3.8

Figure B-1. Reentrant Angle, Mismatch, and Peaking Measurements for Each Tensile Specimen (Continued)

SPECIMEN NUMBER	REENTRANT ANGLES (IN DEGREES) AT TOE NUMBER								MISMATCH (INCHES)	PEAKING ANGLE
	1	2	3	4	5	6	7	8		
T4307	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.014	-4.1
T4309	16.5	14.0	28.5	17.5	15.5	13.5	26.5	17.0	0.014	-5.8
T4312	15.5	13.5	24.0	25.5	13.0	14.0	26.5	20.0	-0.003	-7.6
T4314	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.004	-7.6
T4318	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.003	-7.1
T4320	19.0	18.0	13.5	16.5	16.0	16.0	20.5	20.0	-0.002	-6.9
T4502	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.006	-1.9
T4504	15.0	11.0	21.0	19.5	10.5	7.0	20.5	25.0	0.003	-2.8
T4509	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.006	-5.0
T4511	11.5	10.0	22.0	22.5	11.5	6.5	16.5	16.0	0.008	-5.6
T4518	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000	-3.3
T4520	12.5	14.0	8.0	13.0	9.5	7.5	12.0	23.0	0.006	-3.4
T4615	0.0	28.5	61.0	10.5	0.0	31.0	59.0	7.5	-0.111	1.1
T4617	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.107	2.0
T4619	0.0	28.0	45.0	10.5	0.0	30.5	48.5	13.0	-0.100	0.1
T4621	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.085	1.1
T4623	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.099	0.3
T4625	5.0	24.5	44.5	17.5	0.0	24.0	50.0	15.5	-0.078	0.8
T4702	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000	-1.3
T4704	11.0	11.5	20.0	21.5	12.0	10.5	25.0	23.0	-0.006	-2.0
T4708	8.0	12.0	22.5	17.5	6.0	11.0	26.0	24.0	-0.009	-3.6
T4710	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.016	-4.8
T4720	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.002	-6.0
T4722	10.0	11.0	14.0	15.5	10.0	7.5	13.5	12.5	-0.004	-3.1
T4905	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.002	-1.4
T4910	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.005	-1.8
T4912	24.0	25.5	17.0	25.0	25.0	23.0	28.0	16.5	-0.008	-1.1
T4921	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.002	-0.9
T4923	23.0	22.5	15.5	17.0	25.5	23.0	18.5	20.0	0.000	-1.5

Figure B-1. Reentrant Angle, Mismatch, and Peaking Measurements for Each Tensile Specimen (Continued)

SPECIMEN NUMBER	REENTRANT ANGLES (IN DEGREES) AT TOE NUMBER 1	2	3	4	5	6	7	8	MISMATCH (INCHES)	PEAKING ANGLE
T5005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.089	-2.4
T5007	22.0	39.5	42.5	24.5	23.0	40.0	47.0	22.0	-0.075	-3.0
T5010	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.091	-2.8
T5012	20.5	34.5	42.5	20.0	22.5	39.5	46.5	23.0	-0.082	-1.8
T5019	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.093	-1.8
T5021	26.0	42.5	41.5	16.0	27.0	42.5	46.0	15.0	-0.088	-2.4
T5104	18.0	16.0	27.0	20.0	19.5	18.0	20.0	19.5	-0.003	-0.8
T5106	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.004	-1.5
T5107	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.005	-0.8
T5109	21.0	16.0	19.0	23.0	20.5	21.0	18.5	19.0	0.002	-2.5
T5112	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.006	-2.1
T5114	24.5	23.5	19.5	26.5	22.0	20.5	21.0	21.0	0.000	-1.4
T5302	27.0	28.0	18.0	28.5	25.5	24.0	27.5	25.5	0.000	-0.6
T5304	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.006	-1.0
T5310	25.0	24.0	20.5	28.5	26.0	26.5	26.5	21.5	0.006	-1.4
T5312	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.005	-1.4
T5320	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.007	-1.9
T5322	27.0	21.0	19.5	22.5	22.5	23.5	20.5	21.0	0.002	-1.5
T5402	28.5	15.0	33.0	53.0	28.0	14.5	31.0	41.0	0.073	-2.1
T5404	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.081	-3.0
T5411	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.070	-4.1
T5413	32.0	20.0	23.5	36.0	34.0	19.0	34.5	37.0	0.069	-3.4
T5417	35.0	16.5	35.0	39.0	36.0	13.5	30.5	32.0	0.075	-3.6
T5419	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.088	-2.4
T5501	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000	-1.5
T5503	22.5	24.5	26.0	38.5	28.5	25.0	28.5	23.0	-0.008	-0.9
T5508	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.007	-1.9
T5510	29.0	25.0	23.0	26.5	26.0	26.0	27.0	20.5	-0.002	-2.0
T5519	27.5	25.0	29.5	24.5	26.0	25.0	27.0	16.0	0.000	-1.3
T5521	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.003	-1.9

Figure B-1. Reentrant Angle, Mismatch, and Peaking Measurements for Each Tensile Specimen (Concluded)

SPECIMEN	REENTRANT ANGLES (IN DEGREES) AT TOE NUMBER								MISMATCH	PEAKING
NUMBER	1	2	3	4	5	6	7	8	(INCHES)	ANGLE
**T4109	27.0	29.5	0.0	0.0	26.0	30.5	0.0	0.0	-0.005	-3.3
**T4110	31.0	36.5	0.0	0.0	27.5	31.0	0.0	0.0	-0.008	-4.3
**T4114	31.5	33.0	0.0	0.0	29.0	30.0	0.0	0.0	0.000	-5.1
**T4115	30.5	30.5	0.0	0.0	30.5	27.5	0.0	0.0	0.004	-6.0
**T4207	16.0	35.0	15.5	0.0	15.0	32.5	12.5	0.0	-0.061	-3.6
**T4208	13.5	33.5	13.0	0.0	12.5	31.0	16.5	0.0	-0.064	-3.6
**T4506	10.0	8.0	0.0	0.0	8.5	8.0	0.0	0.0	-0.003	-2.9
**T4507	9.5	8.0	0.0	0.0	10.0	8.5	0.0	0.0	0.004	-3.6
***T4903	22.0	19.5	17.5	24.5	24.5	21.0	22.5	18.0	-0.001	-1.6

** Counter-peaking rotation trial specimens

*** Test equipment malfunctioned, destroying specimen before any mechanical properties obtained

APPENDIX C

Figure C-1. Measured Reinforcement Heights, and Predicted UTS and Failure Origins, for Each Tensile Specimen

ASSUMPTIONS USED IN PREDICTIONS:

NOMINAL WELD METAL STRENGTH: 42 ksi

STRESS CONCENTRATION FACTOR AT WELD TOES: 1.00

WORK HARDENING COEFFICIENT: 51.21*

			FULL PREDICTION:		PREDICTION W/O FL ANGLE:	
SPECIMEN NUMBER	REINFORCEMENT HEIGHT CROWN	REINFORCEMENT HEIGHT ROOT	UTS	FAILURE ORIGIN TOE NUMBER	UTS	FAILURE ORIGIN TOE NUMBER
P0106	0.000	0.000	42.6	8	41.7	2
P0108	0.050	0.065	41.8	4	41.0	1
P0111	0.037	0.064	41.8	3	41.0	2
P0113	0.000	0.000	41.0	7	41.0	3
P0117	0.049	0.070	41.6	3	41.2	2
P0119	0.000	0.000	41.6	3	41.6	3
P0215	0.072	0.108	34.2	4	33.6	4
P0217	0.000	0.000	32.1	4	32.0	4
P0219	0.000	0.000	32.5	4	32.2	4
P0221	0.063	0.108	36.6	8	36.6	4
P0222	0.000	0.000	34.4	8	34.2	4
P0224	0.000	0.000	37.0	4	36.6	4
P0309	0.077	0.090	41.8	8	39.8	1
P0311	0.000	0.000	42.0	8	39.8	1
P0313	0.000	0.000	41.3	8	40.1	1
P0315	0.073	0.093	42.0	8	39.0	1
P0320	0.000	0.000	42.3	4	39.1	1
P0323	0.073	0.090	42.4	4	40.3	1
P0507	0.041	0.058	42.4	8	41.3	1
P0509	0.000	0.000	42.3	3	41.6	2
P0516	0.000	0.000	41.9	8	41.1	1
P0518	0.055	0.064	42.9	7	41.1	2
P0521	0.000	0.000	42.0	3	41.3	2
P0523	0.050	0.057	41.1	7	40.8	2

*Calculated from results of an unpublished study by S. Phillips & Dr. A. Nunes, Jr. of NASA/MSFC

Figure C-1. Measured Reinforcement Heights, and Predicted UTS and Failure Origins, for Each Tensile Specimen (Continued)

			FULL PREDICTION:		PREDICTION W/O FL ANGLE:	
SPECIMEN NUMBER	REINFORCEMENT HEIGHT CROWN	REINFORCEMENT HEIGHT ROOT	UTS	FAILURE ORIGIN TOE NUMBER	UTS	FAILURE ORIGIN TOE NUMBER
P0612	0.088	0.102	44.0	4	26.2	4
P0614	0.000	0.000	25.8	8	21.7	4
P0620	0.088	0.060	40.5	4	27.6	4
P0622	0.000	0.000	24.7	8	24.1	4
P0704	0.000	0.000	41.2	4	40.7	1
P0706	0.040	0.073	43.0	1	40.9	2
P0712	0.047	0.066	43.2	1	40.6	2
P0714	0.000	0.000	42.3	7	40.5	2
P0721	0.000	0.000	42.4	7	40.6	2
P0723	0.043	0.059	42.7	4	41.5	1
P0906	0.000	0.000	41.6	1	41.1	1
P0908	0.108	0.135	42.8	1	40.9	1
P0916	0.000	0.000	43.4	4	41.3	1
P0918	0.100	0.146	43.4	4	41.0	2
P0920	0.000	0.000	42.6	7	41.4	2
P0922	0.087	0.155	45.5	8	41.0	1
P1006	0.000	0.000	26.2	3	25.2	3
P1008	0.105	0.133	28.6	7	27.7	3
P1011	0.111	0.129	26.5	7	26.5	3
P1013	0.000	0.000	26.0	7	25.5	3
P1016	0.000	0.000	25.3	7	25.3	3
P1018	0.108	0.140	28.7	7	26.8	3
P1103	0.085	0.121	43.2	6	39.7	1
P1105	0.000	0.000	41.6	5	40.9	1
P1109	0.075	0.137	39.7	1	38.6	1
P1111	0.000	0.000	40.1	4	39.5	1
P1115	0.000	0.000	40.3	1	39.9	1
P1117	0.092	0.122	39.7	1	39.1	1

Figure C-1. Measured Reinforcement Heights, and Predicted UTS and Failure Origins, for Each Tensile Specimen (Continued)

			FULL PREDICTION:		PREDICTION W/O FL ANGLE:	
SPECIMEN NUMBER	REINFORCEMENT HEIGHT CROWN	REINFORCEMENT HEIGHT ROOT	UTS	FAILURE ORIGIN TOE NUMBER	UTS	FAILURE ORIGIN TOE NUMBER
P1310	0.000	0.000	42.2	8	41.7	1
P1312	0.093	0.094	43.1	3	41.2	2
P1315	0.098	00.89	41.5	3	40.6	3
P1317	0.000	0.000	41.5	4	40.9	1
P1319	0.087	0.097	43.0	3	41.2	2
P1321	0.000	0.000	41.5	4	41.4	1
P1416	0.000	0.000	26.2	8	23.6	4
P1418	0.116	0.126	25.2	4	25.1	4
P1419	0.000	0.000	29.7	4	27.5	4
P1421	0.116	0.120	30.4	4	27.9	4
P1422	0.000	0.000	25.2	8	24.2	4
P1424	0.123	0.118	36.1	8	27.8	4
P1509	0.000	0.000	41.7	6	40.4	2
P1511	0.075	0.101	40.8	2	39.5	2
P1514	0.066	0.098	38.2	6	38.2	2
P1516	0.000	0.000	38.3	2	38.2	2
P1518	0.000	0.000	41.9	6	40.7	2
P1520	0.086	0.111	40.6	2	39.9	2
T4103	0.000	0.000	47.4	3	41.0	1
T4105	0.063	0.036	45.0	7	40.6	2
T4111	0.000	0.000	43.9	7	39.8	2
T4121	0.000	0.000	43.8	8	40.1	1
T4123	0.067	0.031	42.8	3	39.9	2
T4204	0.000	0.000	39.5	7	37.4	3
T4206	0.061	0.058	44.9	7	36.9	3
T4214	0.000	0.000	40.5	7	38.4	2
T4216	0.037	0.087	42.0	3	36.2	2
T4218	0.049	0.068	43.9	7	36.5	2
T4222	0.000	0.000	45.6	7	37.8	2

Figure C-1. Measured Reinforcement Heights, and Predicted UTS and Failure Origins, for Each Tensile Specimen (Continued)

			FULL PREDICTION:		PREDICTION W/O FL ANGLE:	
SPECIMEN	REINFORCEMENT HEIGHT			FAILURE ORIGIN		FAILURE ORIGIN
NUMBER	CROWN	ROOT	UTS	TOE NUMBER	UTS	TOE NUMBER
T4307	0.000	0.000	44.5	4	40.0	1
T4309	0.037	0.044	45.9	4	39.3	1
T4312	0.028	0.056	45.5	7	39.7	2
T4314	0.000	0.000	44.9	7	39.8	2
T4318	0.000	0.000	44.2	8	40.0	1
T4320	0.039	0.051	48.0	4	40.1	2
T4502	0.000	0.000	42.0	4	40.9/	1
T4504	0.032	0.037	42.6	4	40.9	1
T4509	0.000	0.000	44.3	7	40.1	2
T4511	0.018	0.039	43.9	4	39.6	1
T4518	0.000	0.000	43.3	7	41.1	1
T4520	0.024	0.025	46.0	6	40.5	1
T4615	0.040	0.058	29.0	7	28.3	3
T4617	0.000	0.000	31.0	7	31.0	3
T4619	0.046	0.059	34.6	3	31.0	3
T4621	0.000	0.000	38.0	3	33.3	3
T4623	0.000	0.000	42.3	7	33.6	3
T4625	0.041	0.054	37.1	7	34.1	3
T4702	0.000	0.000	43.3	8	41.6	1
T4704	0.024	0.030	42.5	7	40.7	2
T4708	0.022	0.034	41.9	7	39.9	2
T4710	0.000	0.000	41.0	3	39.3	2
T4720	0.000	0.000	45.6	3	39.3	2
T4722	0.025	0.032	42.9	7	40.7	2
T4905	0.000	0.000	45.3	7	41.2	1
T4910	0.000	0.000	43.2	1	40.8	1
T4912	0.071	0.068	42.6	3	40.6	2
T4921	0.000	0.000	42.9	7	41.5	2
T4923	0.076	0.068	42.9	5	41.4	1

Figure C-1. Measured Reinforcement Heights, and Predicted UTS and Failure Origins, for Each Tensile Specimen (Continued)

			FULL PREDICTION:		PREDICTION W/O FL ANGLE:	
SPECIMEN	REINFORCEMENT HEIGHT			FAILURE ORIGIN		FAILURE ORIGIN
NUMBER	CROWN	ROOT	UTS	TOE NUMBER	UTS	TOE NUMBER
T5005	0.000	0.000	32.3	7	31.1	3
T5007	0.109	0.090	44.3	2	33.6	3
T5010	0.000	0.000	40.0	7	33.5	3
T5012	0.109	0.094	38.1	3	32.8	3
T5019	0.000	0.000	34.1	7	31.1	3
T5021	0.120	0.086	36.5	7	33.4	3
T5104	0.058	0.075	43.1	2	41.4	2
T5106	0.000	0.000	47.3	4	41.1	1
T5107	0.000	0.000	44.6	3	41.2	1
T5109	0.074	0.076	45.3	2	40.7	1
T5112	0.000	0.000	45.2	4	40.7	1
T5114	0.075	0.079	46.4	2	41.4	1
T5302	0.078	0.051	44.4	8	41.7	1
T5304	0.000	0.000	41.4	8	41.1	1
T5310	0.086	0.062	43.0	4	40.8	1
T5312	0.000	0.000	41.8	4	40.9	1
T5320	0.000	0.000	41.8	4	40.6	1
T5322	0.074	0.056	48.1	8	41.2	1
T5402	0.065	0.086	28.4	4	28.4	4
T5404	0.000	0.000	21.2	8	21.2	4
T5411	0.000	0.000	36.9	4	34.8	1
T5413	0.084	0.080	32.3	4	30.6	4
T5417	0.077	0.086	30.2	8	29.7	4
T5419	0.000	0.000	38.2	8	39.5	4
T5501	0.000	0.000	43.2	3	41.3	1
T5503	0.072	0.058	39.8	7	39.8	3
T5508	0.000	0.000	41.8	8	40.6	1
T5510	0.076	0.052	45.0	3	40.9	2
T5519	0.074	0.055	44.4	4	41.5	1
T5521	0.000	0.000	47.0	4	41.0	2

Figure C-1. Measured Reinforcement Heights, and Predicted UTS and Failure Origins, for Each Tensile Specimen (Concluded)

			FULL PREDICTION:		PREDICTION W/O FL ANGLE:	
SPECIMEN NUMBER	REINFORCEMENT HEIGHT CROWN	ROOT	UTS	FAILURE ORIGIN TOE NUMBER	UTS	FAILURE ORIGIN TOE NUMBER
**T4109	0.062	0.000	42.5	7	40.6	2
**T4110	0.060	0.000	42.4	3	39.9	2
**T4114	0.063	0.000	44.3	3	40.4	1
**T4115	0.059	0.000	44.1	4	39.8	1
**T4207	0.051	0.017	36.9	3	36.0	3
**T4208	0.055	0.015	42.6	3	36.1	3
**T4506	0.014	0.000	43.5	7	40.8	2
**T4507	0.017	0.000	44.1	8	40.5	1
***T4903	0.068	0.060	44.2	5	41.1	2

*Calculated from results of an unpublished study by S. Phillips & Dr. A. Nunes, Jr. of NASA/MSFC
**Counter-peaking rotation trial specimens
***Test equipment malfunctioned, destroying specimen before any mechanical properties obtained

APPENDIX D

Figure D-1. Measured UTS, Failure Location, Yield Strength, and % Elongation for each Tensile Specimen

SPECIMEN NUMBER	FAILED THROUGH:			0.2% YS	% EL
	UTS	ZONE	TOES		
P0106	42.4	FZ	3,7	25.5	*
P0108	45.7	FL	2, 4, 6, 8	26.5	*
P0111	43.8	FL	2, 4, 6, 8	26.9	*
P0113	40.3	FZ	4, 8	23.0	*
P0117	44.3	FL	2, 4, 6, 8	26.1	*
P0119	42.6	FZ	3, 7	25.7	*
P0215	30.4	FL	2, 4, 6, 8	15.4	2.5
P0217	35.5	FL	1, 3, 5, 7	16.3	3.4
P0219	37.4	FL	1, 3, 5, 7	19.8	3.5
P0221	34.2	FL	2, 4, 6, 8	19.9	2.2
P0222	36.9	FL	1, 3, 5, 7	16.7	3.9
P0224	30.9	FL	2, 4, 6, 8	20.7	1.5
P0309	40.7	FL	1, 3, 5, 7	24.3	3.0
P0311	38.3	FZ	1, 5, 7	24.6	4.8
P0313	39.3	FZ	1, 5	23.9	4.1
P0315	41.0	FL	1, 3, 5, 7	28.3	2.6
P0320	37.7	FL	1, 3, 5, 7	24.2	5.7
P0323	40.9	FL	1, 3, 5, 7	24.1	3.9
P0507	41.9	FL	2, 4, 6, 8	25.6	4.8
P0509	38.0	FZ	4, 8	*	*
P0516	37.6	FZ	3, 7	23.6	*
P0518	41.8	FL	1, 3, 5, 7	24.9	4.8
P0521	40.3	FZ	4, 8	23.3	4.2
P0523	38.8	FL	1, 3, 5, 7	19.4	*

Figure D-1. Measured UTS, Failure Location, Yield Strength, and % Elongation for each Tensile Specimen (Continued)

SPECIMEN NUMBER	FAILED THROUGH:			0.2% YS	% EL
	UTS	ZONE	TOES		
P0604	35.8	FZ	1, 5	19.6	2.7
P0606	27.0	FL	1, 3, 5, 7	19.0	1.0
P0612	27.2	FL	1, 3, 5, 7	19.0	1.2
P0614	34.1	FZ	1, 5	19.6	2.2
P0620	27.9	FL	1, 3, 5, 7	21.2	0.9
P0622	33.7	FZ	1, 3	19.3	2.0
P0704	39.5	FZ	4, 8	24.2	*
P0706	40.7	FL	1, 3, 5, 7	26.9	2.2
P0712	41.7	FL	2, 4, 6, 8	24.3	*
P0714	38.7	FZ	NONE	26.3	2.5
P0721	38.9	FZ	NONE	23.3	2.9
P0723	47.8	FL	1, 3, 5, 7	24.7	*
P0906	39.5	FZ	3, 7	22.2	3.1
P0908	39.3	FZ	1, 5, 4, 8	21.0	6.2
P0916	39.5	FZ	4, 8	20.5	6.8
P0918	38.6	FZ	2, 6, 3, 7	20.0	3.1
P0920	39.4	FZ	4, 8	20.0	6.8
P0922	37.0	FL	2, 4, 6, 8	20.7	3.2
P1006	35.5	FZ	2, 6, 3, 7	14.7	4.6
P1008	27.1	FZ	2, 6, 3, 7	18.0	1.5
P1011	28.2	FZ	2, 6, 3, 7	17.3	1.8
P1013	35.3	FZ	2, 6, 8	14.0	4.1
P1016	36.2	FZ	2, 6, 3, 7	15.1	4.2
P1018	27.1	FZ	2, 6, 3, 7	15.7	2.0
P1103	39.1	FZ	2, 6, 3, 7	16.1	3.9
P1105	40.3	FZ	4, 8	14.9	6.7
P1109	39.0	FZ	1, 5, 4, 8	15.4	3.8
P1111	39.4	FZ	1, 4, 8	15.7	6.7
P1115	39.1	FZ	4, 8	14.6	7.1
P1117	37.6	FZ	1, 5, 4, 8	15.0	3.4

Figure D-1. Measured UTS, Failure Location, Yield Strength, and % Elongation for each Tensile Specimen (Continued)

SPECIMEN NUMBER	FAILED THROUGH: UTS	ZONE	TOES	0.2% YS	% EL
P1310	41.4	FZ	4, 8	16.1	8.2
P1312	38.7	FL	2, 4, 6, 8	17.1	4.0
P1315	40.6	FL	2, 4, 6, 8	17.5	4.4
P1317	41.7	FZ	4, 8	16.1	8.6
P1319	41.2	FL	2, 4, 6, 8	12.8	4.4
P1321	42.6	FZ	2, 6	15.1	8.6
P1416	36.2	FZ	1, 5, 4, 8	15.2	4.0
P1418	28.0	FZ	1, 5, 4, 8	15.6	2.0
P1419	36.1	FZ	1, 5, 4, 8	15.2	4.4
P1421	28.9	FZ	1, 5, 4, 8	16.6	2.0
P1422	36.7	FZ	1, 5, 4, 8	15.2	4.7
P1424	28.5	FZ	1, 5, 4, 8	15.8	2.1
P1509	40.9	FZ	2, 6, 3, 7	15.3	5.8
P1511	39.5	FZ	2, 6, 3, 7	16.8	3.7
P1514	40.7	FZ	2, 6, 3, 7	17.6	3.8
P1516	41.0	FZ	2, 6, 3, 7	15.0	6.9
P1518	40.4	FZ	2, 6, 3, 7	15.5	6.5
P1520	39.5	FZ	2, 6, 3, 7	15.6	3.7
T4103	43.4	FZ	3	28.1	3.6
T4105	44.6	FL	1, 3, 5, 7	27.4	3.3
T4111	41.6	FZ	2, 6	29.1	4.4
T4121	41.3	FZ	NONE	27.3	3.8
T4123	42.1	FL	2, 4, 6, 8	26.5	3.0
T4204	38.1	FZ	2, 6	21.3	3.4
T4206	35.3	FL	2, 4, 6, 8	27.1	0.8
T4214	37.1	FZ	2, 6	22.9	4.0
T4216	36.8	FL	1, 3, 5, 7	26.5	2.1
T4218	34.2	FL	2, 4, 6, 8	23.7	2.1
T4222	37.6	FZ	7	19.7	4.8

Figure D-1. Measured UTS, Failure Location, Yield Strength, and % Elongation for each Tensile Specimen (Continued)

SPECIMEN NUMBER	FAILED THROUGH:			0.2% YS	% EL
	UTS	ZONE	TOES		
T4307	38.8	FZ	3, 7	27.2	4.0
T4309	44.5	FL	1, 3, 5, 7	26.0	5.4
T4312	43.5	FL	1, 3, 5, 7	27.5	4.9
T4314	39.1	FZ	NONE	27.7	3.3
T4318	38.7	FZ	NONE	26.7	3.7
T4320	42.4	FL	1, 3, 5, 7	28.6	4.0
T4502	39.9	FZ	4	26.4	3.3
T4504	43.3	FZ	1, 5	28.6	3.7
T4509	40.1	FZ	2, 6	26.7	3.2
T4511	42.1	FZ	4, 8	28.9	3.2
T4518	39.5	FZ	NONE	27.7	3.4
T4520	42.6	FZ	4, 8	27.8	3.6
T4615	27.9	FZ	3, 7, 5	18.3	1.5
T4617	33.0	FZ	2, 6	18.9	2.4
T4619	28.5	FZ	3, 7	19.5	1.3
T4621	37.2	FZ	3	20.2	3.1
T4623	38.2	FZ	2, 6, 3	18.6	4.6
T4625	34.0	FZ	1, 3, 7	21.0	1.6
T4702	40.3	FZ	3	28.9	2.2
T4704	42.7	FZ	2, 3, 7	28.9	2.8
T4708	42.2	FZ	3, 7	28.0	2.7
T4710	38.7	FZ	2, 6	26.4	3.2
T4720	40.0	FZ	1, 5	26.4	3.8
T4722	42.8	FZ	3, 7	26.1	4.4
T4905	39.6	FZ	8	15.8	•
T4910	39.8	FZ	4	18.6	5.7
T4912	41.1	FZ	1, 5, 4, 8	15.1	•
T4921	39.9	FZ	NONE	15.7	•
T4923	39.6	FZ	1, 5, 4, 8	17.8	5.7

Figure D-1. Measured UTS, Failure Location, Yield Strength, and % Elongation for each Tensile Specimen (Continued)

SPECIMEN NUMBER	FAILED THROUGH:			0.2% YS	% EL
	UTS	ZONE	TOES		
T5005	39.7	FZ	2, 6	16.9	5.0
T5007	32.6	FL	2, 4, 6, 8	17.1	2.0
T5010	40.5	FZ	3, 7	15.7	*
T5012	32.9	FL	2, 4, 6, 8	16.5	2.5
T5019	40.1	FZ	3, 7	17.0	*
T5021	35.4	FL	2, 4, 6, 8	18.2	2.9
T5104	40.6	FZ	2, 6, 3, 7	16.6	6.6
T5106	38.9	FZ	4, 8	14.5	7.3
T5107	38.8	FZ	NONE	17.8	7.5
T5109	40.6	FZ	1, 5, 4, 8	16.2	5.9
T5112	38.0	FZ	2, 6	16.6	7.0
T5114	40.5	FZ	1, 5, 4, 8	15.2	6.5
T5302	44.1	FZ	1, 5, 4, 8	21.3	*
T5304	42.6	FZ	4, 8	21.7	6.6
T5310	43.8	FZ	1, 5, 4, 8	20.2	4.9
T5312	42.2	FZ	1, 5	16.8	7.6
T5320	42.1	FZ	3, 7	18.0	7.3
T5322	43.9	FZ	1, 5, 4, 8	21.4	5.4
T5402	35.7	FZ	1, 5, 4, 8	15.4	4.1
T5404	39.0	FZ	4, 8	13.0	5.9
T5411	38.0	FZ	4, 8	16.2	4.5
T5413	35.3	FL	1, 3, 5, 7	15.5	3.2
T5417	34.3	FL	1, 3, 5, 7	15.0	2.9
T5419	37.8	FZ	1, 5	14.3	5.4
T5501	40.0	FZ	4, 8	16.8	6.2
T5503	41.4	FZ	2, 6, 3, 7	16.3	5.3
T5508	40.9	FZ	4, 8	15.2	6.5
T5510	41.8	FZ	2, 6, 3, 7	17.1	5.4
T5519	41.3	FZ	2, 6, 3, 7	17.3	5.1
T5521	41.7	FZ	2, 6, 3, 7	16.4	6.6

Figure D-1. Measured UTS, Failure Location, Yield Strength, and % Elongation for each Tensile Specimen (Concluded)

SPECIMEN NUMBER	UTS	FAILED THROUGH: ZONE	FAILED THROUGH: TOES	0.2% YS	% EL
**T4109	41.7	FL	2, 4, 6, 8	26.9	1.5
**T4110	40.0	FL	2, 4, 6, 8	30.8	1.1
**T4114	39.7	FL	2, 4, 6, 8	30.8	1.2
**T4115	41.1	FL	1, 3, 5, 7	30.6	1.3
**T4207	32.2	FL	2, 4, 6, 8	24.5	0.7
**T4208	31.6	FL	2, 4, 6, 8	24.8	0.9
**T4506	40.4	FZ	1, 5	27.6	1.4
**T4507	42.4	FZ	1, 5	29.3	2.0
***T4903	***	FZ	1, 5, 4, 8	***	***

*Stress-Strain Curves for These Specimens did not Enable these Measurements to be made
**Counter-peaking rotation trial specimens
***Test equipment malfunctioned, destroying specimen before any mechanical properties obtained

APPENDIX E

Table E-1. 'C' Code Used For Calculating Theory Predictions

```
*============================================
*       calculate UTS for a single corner of joint
*
*       Parameters:
*               corner - corner number being calculated
*               tp     - pointer of toe stress information return structure
*               kp     - pointer of geometry constants structure
*               dp     - pointer of geometry variable structure
*
*       NOTE:   negative peaking angles - lowers resulting UTS
*               positive mismatch       - lowers resulting UTS
*/
void UTS_func( int corner, UTS_toe *tp, rGeoHdr *kp, rGeoData *dp )
{
        /* mismatch and peaking sign table for each of the 8 weld corners */
        static Real m_sign[8] = { 1, -1, -1, 1, 1, -1, -1, 1 };
        static Real p_sign[8] = { 1, 1, -1, -1, 1, 1, -1, -1 };
        static int crown_flag[8] = { 1, 1, 0, 0, 1, 1, 0, 0 };

        Real fusion_line_uts;
        Real mismatch_stress;
        Real peaking_stress;
        Real width;
        Real sigma_w_const;

        sigma_w_const = crown_flag[corner] ? kp->Sigma_Kt_Crown : kp->Sigma_Kt_R
        width         = crown_flag[corner] ? dp->Crown_Width    : dp->Root_Width
        /*
         * Compute fusion line strength.
         */
        fusion_line_uts = sigma_w_const /
                SQUARE( COS( dp->Fusion_angle[corner] ));
        fusion_line_uts -= sigma_w_const;

        if( fline_enable == 1 )         /* INCREASE WITH FUSION LINE ANGLE */
                fusion_line_uts = sigma_w_const + fusion_line_uts;
        else if( fline_enable == -1 )   /* DECREASE WITH FUSION LINE ANGLE */
                fusion_line_uts = sigma_w_const - fusion_line_uts;
        else                            /* ignore FUSION ANGLE */
                fusion_line_uts = sigma_w_const;

        /*
         * compute additional stress due to mismatch
         */
        mismatch_stress = kp->Work_Hardening *
                SQUARE(dp->Thickness / width) * ((m_sign[corner] * dp->Mismatch)
        if( ! mismatch_enable )
                mismatch_stress = 0.0;
        /*
         * compute additional stress due to peaking
         */
        peaking_stress = 0.5 * (M_PI / 180.0) *
                kp->Work_Hardening * (dp->Thickness / width) * -(dp->Peaking * p
        if( ! peaking_enable )
                peaking_stress = 0.0;
        /*
         * enter return information into toe stress structure
         */
        tp->sigma_w      = sigma_w_const;
        tp->fusion_line  = fusion_line_uts;
        tp->mismatch     = -mismatch_stress;
        tp->peaking      = -peaking_stress;
        tp->UTS          = fusion_line_uts - mismatch_stress - peaking_stress;

        }
```

Table E-1. 'C' Code Used For Calculating Theory Predictions (Continued)

```
*=============================================
*       calculate one specimen's UTS values
*
*       Parameters:
*               jp - pointer of joint/toe stress return structure
*               kp - pointer of geometry constants structure
*               dp - pointer of geometry variable structure
*
*       Return value:
*               Char pointer of error message when it is a non-null
*               pointer.
*
*/
char *UTS_calculate( UTS_joint *jp, rGeoHdr *kp, rGeoData *dp )

        int i;

        if( dp->Thickness == 0 ) {
                return( "Thickness is zero" );
                }
        if( dp->Crown_Width == 0 ) {
                return( "Crown_Width is zero" );
                }
        if( dp->Root_Width == 0 ) {
                return( "Root_Width is zero" );
                }

        UTS_func( 0, &jp->toe[0], kp, dp );
        UTS_func( 1, &jp->toe[1], kp, dp );
        UTS_func( 2, &jp->toe[2], kp, dp );
        UTS_func( 3, &jp->toe[3], kp, dp );
        UTS_func( 4, &jp->toe[4], kp, dp );
        UTS_func( 5, &jp->toe[5], kp, dp );
        UTS_func( 6, &jp->toe[6], kp, dp );
        UTS_func( 7, &jp->toe[7], kp, dp );

        jp->min_toe = 0;
        jp->min_UTS = jp->toe[0].UTS;

        for( i = 0; i < 8; ++i ) {
                if( jp->toe[i].UTS < jp->min_UTS ) {
                        jp->min_toe = i;
                        jp->min_UTS = jp->toe[i].UTS;
                        }
                }

        return (char *) 0;
        }
```

Table E-1. 'C' Code Used For Calculating Theory Predictions (Concluded)

```
_ypedef struct UTS_toe {
        Real UTS;
        Real sigma_w;
        Real fusion_line;
        Real peaking;
        Real mismatch;
        } UTS_toe;

typedef struct UTS_joint {
        int     min_toe;
        Real    min_UTS;
        UTS_toe toe[8];
        } UTS_joint;
```

Report Documentation Page

NASA
National Aeronautics and Space Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

An Investigation Into Geometry and Microstructural Effects Upon the Ultimate Tensile Strengths of Butt Welds

5. Report Date

2/5/92

6. Performing Organization Code

7. Author(s)

STEPHEN S. GORDON

8. Performing Organization Report No.

10. Work Unit No.

9. Performing Organization Name and Address

Nichols Research Corporation
4040 South Memorial Parkway
Huntsville, AL 35802

11. Contract or Grant No.

NAS8-38671

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

13. Type of Report and Period Covered

Final

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A mathematical theory, developed by Dr. Arthur Nunes, Jr., NASA/MSFC, was evaluated empirically. This theory predicts weld ultimate tensile strength based on material properties and fusion line angles, mismatch, peaking, and weld widths. Welds were made on 1/4" and 1/2" aluminum 2219-T87, their geometries were measured, they were tensile tested, and these results were compared to theoretical predictions. Statistical analysis of results was performed to evaluate correlation of theory to results for many different categories of weld geometries.

17. Key Words (Suggested by Author(s))

Ultimate Tensile Strength, Weld Geometry, Predictions, fusion line angle, peaking, mismatch, weld width

18. Distribution Statement

Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
N/A	N/A		