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Report

Measurement of Yield strength, Tensile strength and Fracture toughness of API 5L pipe samples using Instrumented Indentation Testing

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FAST & PRECISE SOLUTIONS FOR QUALITY & RELIABILITY

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Prepared for

GTI

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1. Executive Summary

According to the Gas Mega Rule (PHMSA-2011-0023) proposed by the PHMSA, PHMSA operates the transmission pipelines at pressures below the pipe's yield strength and for the purpose of considering the safety factors of the pipe, PHMSA is seeking to require operators to verify the Maximum Allowable Operating Pressure Determination (MOAP) of Transmission pipe segments without TVC records in the MAOP Verification § 192.624. PHMSA allowed for the verification of yield strength, tensile strength and fracture toughness using the non-destructive test in Material Verification § 192.607.

Instrumented Indentation Testing (IIT) applied FRONTICS AIS2100 can measure yield strength, tensile strength, and fracture toughness in non-destructive way. This technology can be applied directly to in-service and in-situ pipelines so that the test sample can be used after the test. In addition, since the space required for the test is very small, it is also effective in evaluating the weldment.

This test is for the evaluation of the yield and tensile strength of pipes using the IIT included in the DOT Project (DOT Project Number: 729) 'Validating Non-Destructive Tools for Surface to Bulk Correlations of Yield Strength, Toughness, and Chemistry'. In addition, if the test sample included a seam weld, strength and fracture toughness (KJC value) of weldments were also evaluated.

There is a total of 30 test pipe samples.

2. Objective

The objective of this DOT Project is;

"The deliverables of this project will facilitate the use of non-destructive surface testing: micro-indentation, micro-machining, in situ chemistry, and replicate microscopy analysis as accurate, efficient, and cost-effective tools for material property confirmation.

This work will provide benefits to pipeline safety, energy continuity, and integrity assessment programs since the developed techniques and models and validated testing technology will not require a line to be taken out of service or destructively cut out samples from the in-service pipeline. The results of this project will also be applicable to pending DOT/PHMSA regulations that require operators to backfill their material property records for grandfathered pipeline segments and/or those that do not have adequate material records."

The objective of this test is to evaluate the yield strength, tensile strength and fracture toughness using the indentation method, and compare it with destructive test results to validate the technology.

3. Introduction

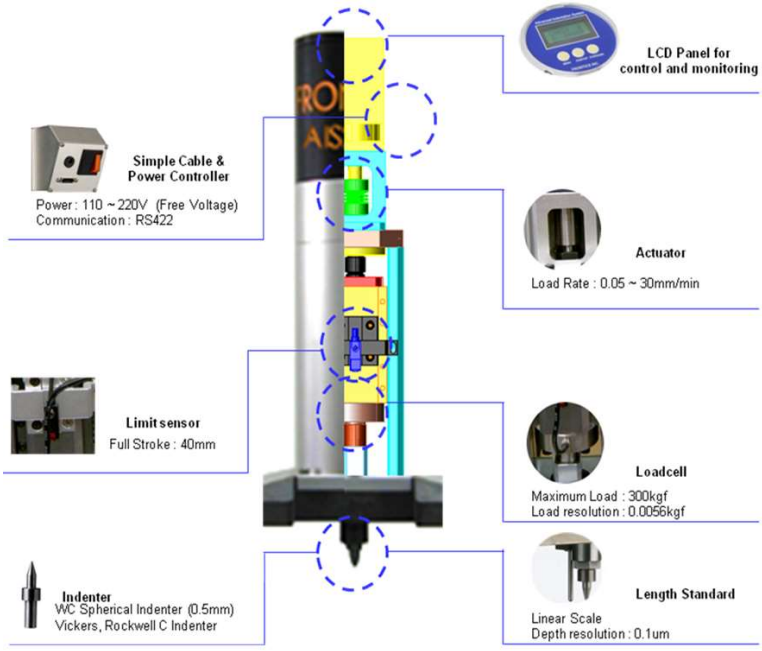
Following is a test report on the yield strength, tensile strength, and fracture toughness measurement on GTI's 30 API pipe samples using the instrumented indentation testing (IIT). The test involved 5 indentation tests at two locations on each pipe samples. AIS2100 of FRONTICS, Inc. was used for this test.

4. Basic operating principles

The Instrumented Indentation Test is a method developed from the conventional hardness test, and is a technology applying load to materials and measuring load-displacement continuously by using a sharp indenter. The Instrumented Indentation Test is a simple test method that does not require shape of a specific sample, compared to the existing uniaxial tensile test, and is a multiscale evaluation method that can assess localized and wide area properties. Also, the Instrumented Indentation Test is an innovative technology that can nondestructively measure real-time field properties of equipment being operated and can assess various properties such as tensile properties, fracture properties and residual stress, etc. through analysis of one load-displacement curve because it leaves only micro indentation marks on the test target.

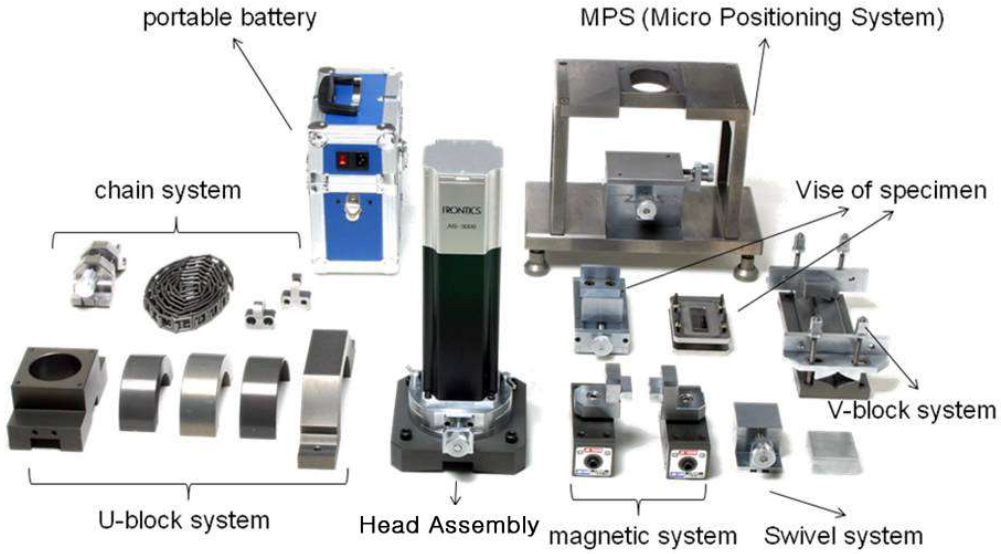
(1) Head Assembly

The AIS series of FRONTICS Company applying the Instrumented Indentation Test guarantee high-level measurement precision and reliability with development know-how and introduction of new technology for more than 10 years. The AIS series of FRONTICS Company have an advantage that can measure conveniently and fast due to improvement of sensor performance, data processing performance as well as characteristics of user-friendly software of the inside of equipment, and have an advantage that can use various attachment devices that the field application to structures among almost all operations is possible.



(2) Various attachments

The power plant and oil refinery equipment are composed of various shaped parts such as Rotor, Shaft, Valve, Casing, and pipe, etc. The various attachment devices should be applied to the test equipment according to these targets. The AIS series have various attachment devices formed based on field experience for more than 10 years.



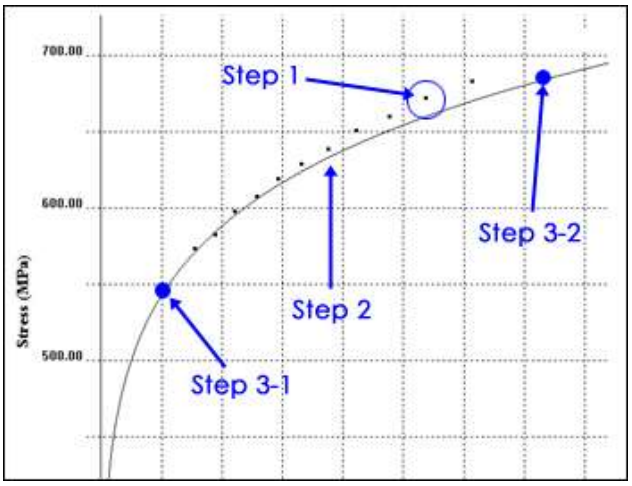
Model		**AIS2100**
Size	Driving Unit	4.0 x 4.0 x 13.9 inch (Cylinder structure)
	Horizontal moving Unit	5.5 x 5.5 x 1.7 inch (two-story dovetail slider structure)
	Base Unit	7 x 7 x 1.6 inch (V block structure)
Maximum load		660 lbf (300 kgf)
Load / Depth resolution		**5.6 gf / 0.1 um**
Maximum stroke		1.57 inch (40 mm)
Loading rate		0.1 ~ 30 mm/min
Communication method		RS-422
Power supply		**AC 110 ~ 220V (free voltage)**
Analysis equipment		Laptop PC (w/SW)
Indenter		Spherical Indenter (Dia. 0.5 mm)

(3) Analysis algorithms

AIS2100 has revised its S/W for more accurate and reliable data results:

- Revision of contact area determination procedure considering pile-up effect dependent on indentation depth and materials' work-hardening characteristics

- Revision of yield strength determination procedure based on indentation-derived elastic modulus



Step 0 Determination of **contact area**

a → a_c

Step 1 Derivation of **stress-strain points**

$$\sigma = \frac{L}{\pi a^2}\frac{1}{\psi}, \quad \varepsilon = \frac{\alpha}{\sqrt{1-(a/R)^2}}\frac{a}{R} = \alpha \tan\gamma$$

Step 2 Determination of **flow curve**

$\sigma = K\varepsilon^n$ for Hollomon-type materials

$\sigma = A + E_r\varepsilon$ for FCC materials

Step 3 Determination of **yield strength** (3-1) and **tensile strength** (3-2)

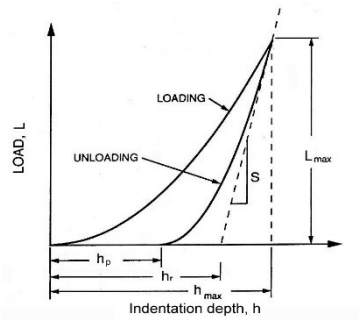
$\sigma_y = K(\varepsilon_y + b)^n$ yield strength

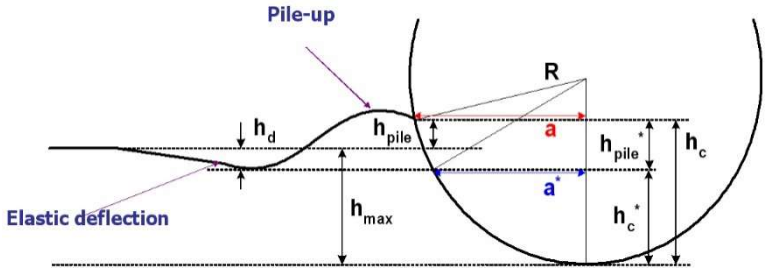
$\sigma_{UTS} = Kn^n$ tensile strength

<Details>

Step 0 Calibration of contact area

: Change in contact depth by **elastic deflection** and **plastic pile-up/sink-in** at maximum indentation load





(0-1) elastic deflection

$$h_c^* = h_{\max} - h_d = h_{\max} - 0.75\frac{L_{\max}}{S}$$

(0-2) plastic pile-up

$$\frac{h_{pile}^*}{h_c^*} = f(n, \frac{a_{\max}}{R})$$

$h_c = h_c^* + h_{pile}^* = h_{\max} - h_d + h_{pile}^*$ and $A_c = f(h_c)$.

Step 1 Determination of stress-strain points

(1-1) Definitions of stress and strain

$$\sigma = \frac{L}{\pi a^2}\frac{1}{\psi}, \quad \varepsilon = \frac{\alpha}{\sqrt{1-(a/R)^2}}\frac{a}{R} = \alpha\tan\gamma$$

(1-2) Selection of constants (α, ψ)

(α=0.14 and ψ=3.0)

Step 2 Flow curve determination

(2-1) Determination of fitting type

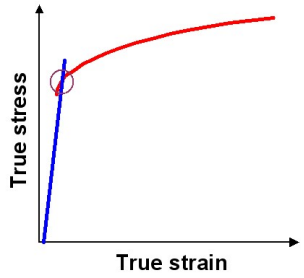
$\sigma = K\varepsilon^n$ for Hollomon-type materials

$\sigma = A + E_r\varepsilon$ for FCC materials

Step 3 Strength determination

(3-1) Yield strength

: using Intercept point of elastic line and plastic flow curve



$K\varepsilon_y^n = E\left(\varepsilon_y - 0.002\right)$ ➔ εy determination

$\sigma_y = K(\varepsilon_y + b)^n$

(3-1-1) Elastic modulus

: Using initial slope of unloading curve reflecting elastic recovery of material

: Unloading curve can be expressed in a power law relation as

$L = k(h - h_f)^m$, where m and K = fitting constants.

$$S = \left(\frac{dL}{dh}\right)_{h=h_{\max}} = km(h_{\max} - h_f)^{m-1} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A_c},$$

where

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}$$

and subscript, *i* indicates indenter.

(3-2) Tensile strength

: Using the fact that tensile strain is same as work-hardening exponent

$\sigma_{UTS} = Kn^n$

5. Test conditions

(1) Samples

- Pipe: API 5L pipe samples 30EA
- Test location: Total 60 locations

pipe #	OD (in)
3	12
5	24
6	24
12	12
13	16
24	12
26	18
27	18
29	16
32	26
33	16
34	8
35	12
37	12
40	30
44	26
50	24

pipe #	OD (in)
111	4
123	10
125	10
126	10
127	10
132	12
137	6
141	8
143	25
146	10
148	8
165	10
169	12

(2) The test location

The test involved 5 indentation tests at two locations on each pipe samples.

(3) Sample images

#003

#005

#006

#012

#013

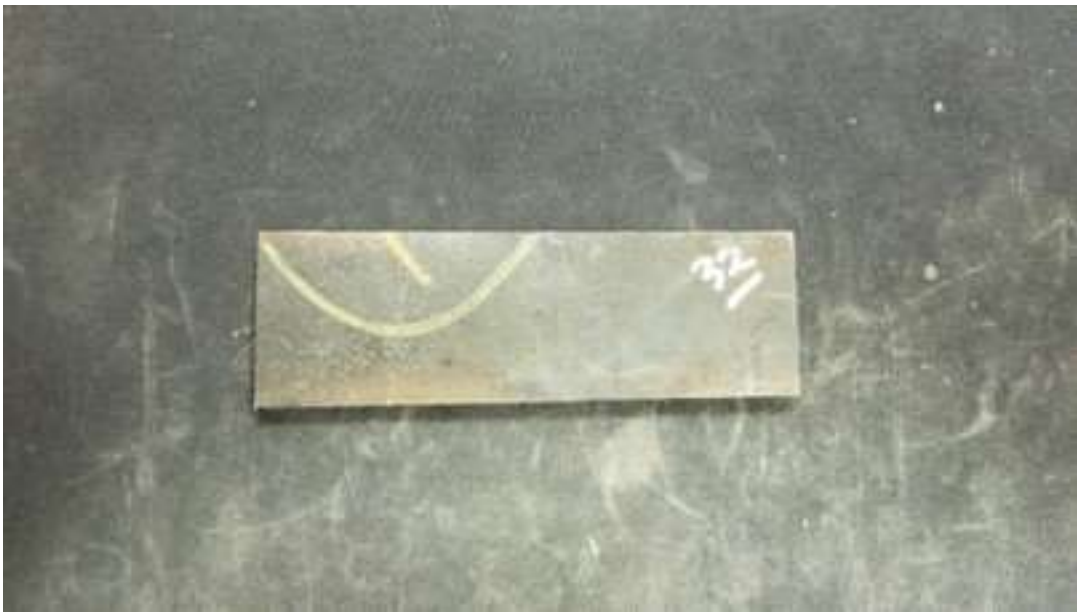
#024

#026

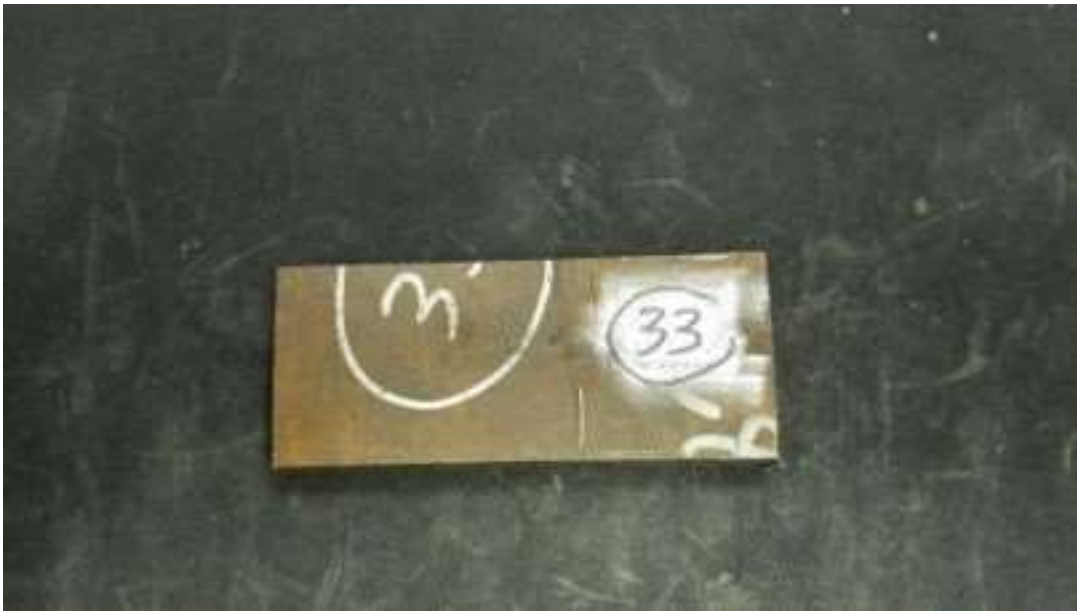
#027

#029

#032



#033



#034

#035

#037

#040

#044

#050

#111

#123

125

#126

#0127

#132

#137

#141

#143

#146

#148

#165

#169

6. Test procedures

(1) Surface grinding of sample

- Surfaces of specimens were polished up to #800 grit using hand-polisher

(2) Position of sample

- The Sample is placed on the MPS (Micro Positioning System)

7. Results

Figure below shows locations of the test from AIS 2100. The appendix shows all the detail measured results.

(1) Analysis results of base metal (average data)

Pipe #	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
#003	62.74	81.87	323.94
#005	51.49	69.66	240.61
#006	52.61	71.36	267.80
#012	47.03	68.71	292.04
#013	55.82	74.46	307.15
#024	55.06	67.08	247.93
#026	60.24	84.65	388.80
#027	66.76	85.48	405.07
#029	48.08	70.62	314.79
#032	51.07	67.87	306.72
#033	57.42	77.51	340.65
#034	38.34	55.94	205.03
#035	40.45	57.26	183.89
#037	54.51	70.07	253.93
#040	65.07	82.00	388.53
#044	58.58	77.46	335.14
#050	61.24	83.07	344.16
#111	46.54	65.49	285.86
#123	58.06	78.73	342.98

Pipe #	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
#125	59.73	81.58	320.50
#126	55.87	79.74	342.41
#127	63.21	80.60	390.05
#132	56.75	76.31	353.75
#137	53.62	69.01	263.91
#141	59.01	80.92	358.07
#143	55.75	68.94	275.55
#146	36.64	53.57	195.75
#148	52.58	69.75	307.90
#165	49.23	67.05	287.20
#169	55.56	66.84	280.20

(2) Detail testing results

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#003	L1	1	61.62	76.24	294.53
		2	61.46	77.95	286.08
		3	61.13	80.31	334.91
		4	64.06	83.20	349.57
		5	63.58	82.69	354.70
		Avg. L1	**62.37**	**80.08**	**323.96**
	L2	1	58.81	81.90	333.50
		2	60.95	82.82	352.68
		3	66.03	85.43	301.51
		4	65.31	84.20	321.86
		5	64.49	83.99	310.02
		Avg. L2	**63.12**	**83.67**	**323.91**
	Total	**Avg. Total**	**62.74**	**81.87**	**323.94**
		Stdev.	**2.29**	**2.89**	**25.03**
#005	L1	1	53.76	71.07	218.82
		2	52.79	69.60	268.77
		3	51.87	70.20	242.99
		4	50.82	70.57	212.01
		5	50.24	69.65	255.02
		Avg. L1	**51.90**	**70.22**	**239.52**
	L2	1	51.61	68.67	253.20
		2	51.87	69.69	231.99
		3	48.92	69.49	237.30
		4	51.62	69.88	257.30
		5	51.44	67.74	228.73
		Avg. L2	**51.09**	**69.09**	**241.71**
	Total	**Avg. Total**	**51.49**	**69.66**	**240.61**
		Stdev.	**1.33**	**0.93**	**18.14**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#006	L1	1	50.83	69.47	216.66
		2	51.76	70.43	291.33
		3	52.36	71.50	280.55
		4	52.42	71.52	283.16
		5	59.79	73.77	306.83
		Avg. L1	**53.43**	**71.34**	**275.71**
	L2	1	54.17	71.95	281.50
		2	49.43	70.80	238.69
		3	55.05	72.81	317.16
		4	48.70	71.06	210.43
		5	51.62	70.33	251.66
		Avg. L2	**51.79**	**71.39**	**259.89**
	Total	**Avg. Total**	**52.61**	**71.36**	**267.80**
		Stdev.	**3.17**	**1.26**	**36.69**
#012	L1	1	46.71	68.95	309.09
		2	45.28	68.01	298.57
		3	43.60	66.56	253.84
		4	44.22	66.79	232.41
		5	46.23	69.15	305.61
		Avg. L1	**45.21**	**67.89**	**279.90**
	L2	1	48.61	70.94	340.29
		2	47.44	67.88	306.07
		3	49.87	70.08	296.36
		4	49.44	69.84	270.71
		5	48.88	68.95	307.41
		Avg. L2	**48.85**	**69.54**	**304.17**
	Total	**Avg. Total**	**47.03**	**68.71**	**292.04**
		Stdev.	**2.20**	**1.41**	**31.21**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#013	L1	1	55.83	73.17	324.99
		2	56.14	72.78	287.74
		3	56.65	74.53	328.21
		4	56.62	73.96	268.10
		5	55.95	74.03	284.69
		Avg. L1	**56.24**	**73.70**	**298.74**
	L2	1	57.22	74.87	328.61
		2	55.19	75.38	322.37
		3	54.35	74.84	274.02
		4	53.53	75.32	325.11
		5	56.76	75.71	327.64
		Avg. L2	**55.41**	**75.22**	**315.55**
	Total	**Avg. Total**	**55.82**	**74.46**	**307.15**
		Stdev.	**1.16**	**0.96**	**25.16**
#024	L1	1	54.57	66.37	237.28
		2	57.05	66.89	277.81
		3	53.63	65.98	251.83
		4	56.61	66.93	272.27
		5	54.87	66.97	233.38
		Avg. L1	**55.34**	**66.63**	**254.51**
	L2	1	51.44	67.19	198.39
		2	53.01	68.80	198.57
		3	55.99	66.99	269.99
		4	55.95	67.43	246.01
		5	57.45	67.29	293.82
		Avg. L2	**54.77**	**67.54**	**241.36**
	Total	**Avg. Total**	**55.06**	**67.08**	**247.93**
		Stdev.	**1.92**	**0.74**	**32.17**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#026	L1	1	58.22	80.67	332.91
		2	59.52	84.27	391.04
		3	60.21	85.27	395.93
		4	63.48	85.99	367.39
		5	59.42	84.96	407.80
		Avg. L1	**60.17**	**84.23**	**379.01**
	L2	1	60.18	84.80	400.63
		2	61.74	86.03	413.52
		3	59.59	84.46	385.59
		4	59.90	84.52	389.44
		5	60.14	85.56	403.76
		Avg. L2	**60.31**	**85.07**	**398.59**
	Total	**Avg. Total**	**60.24**	**84.65**	**388.80**
		Stdev.	**1.44**	**1.53**	**23.53**
#027	L1	1	67.80	85.10	396.46
		2	68.77	87.16	413.97
		3	67.61	87.61	445.92
		4	61.65	86.77	354.99
		5	65.02	80.82	324.43
		Avg. L1	**66.17**	**85.49**	**387.15**
	L2	1	66.19	80.16	415.20
		2	67.43	79.93	381.42
		3	68.51	86.86	426.57
		4	68.06	89.35	456.73
		5	66.54	91.06	435.02
		Avg. L2	**67.35**	**85.48**	**422.99**
	Total	**Avg. Total**	**66.76**	**85.48**	**405.07**
		Stdev.	**2.12**	**3.92**	**41.53**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#029	L1	1	49.17	69.46	305.11
		2	48.50	70.75	323.22
		3	48.41	71.46	337.06
		4	47.37	70.57	311.44
		5	47.32	69.04	298.36
		Avg. L1	**48.15**	**70.25**	**315.04**
	L2	1	47.32	71.07	314.64
		2	47.45	71.41	315.72
		3	48.55	70.35	303.30
		4	48.02	69.74	305.40
		5	48.73	72.34	333.65
		Avg. L2	**48.01**	**70.98**	**314.54**
	Total	**Avg. Total**	**48.08**	**70.62**	**314.79**
		Stdev.	**0.68**	**1.01**	**12.99**
#032	L1	1	51.30	71.11	334.09
		2	45.72	66.33	200.59
		3	48.72	66.63	291.41
		4	49.11	66.62	304.73
		5	55.85	67.93	321.62
		Avg. L1	**50.14**	**67.72**	**290.49**
	L2	1	51.59	66.53	301.12
		2	52.02	67.65	338.16
		3	52.98	68.36	334.19
		4	51.18	68.29	312.00
		5	52.22	69.29	329.30
		Avg. L2	**51.99**	**68.02**	**322.95**
	Total	**Avg. Total**	**51.07**	**67.87**	**306.72**
		Stdev.	**2.73**	**1.50**	**40.53**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#033	L1	1	57.61	75.39	342.23
		2	57.32	77.18	355.10
		3	58.81	78.04	353.38
		4	56.72	77.99	340.61
		5	58.26	78.04	333.81
		Avg. L1	**57.74**	**77.33**	**345.03**
	L2	1	56.68	78.14	355.67
		2	58.44	77.51	334.36
		3	56.20	77.29	310.42
		4	57.30	77.81	353.09
		5	56.83	77.68	327.79
		Avg. L2	**57.09**	**77.69**	**336.27**
	Total	**Avg. Total**	**57.42**	**77.51**	**340.65**
		Stdev.	**0.86**	**0.82**	**14.60**
#034	L1	1	37.06	55.39	204.18
		2	36.18	54.61	168.76
		3	37.50	56.20	215.23
		4	36.11	55.31	191.31
		5	39.16	56.02	220.69
		Avg. L1	**37.20**	**55.51**	**200.03**
	L2	1	39.81	55.36	210.37
		2	39.75	56.61	220.12
		3	39.37	56.47	217.18
		4	39.63	56.74	186.05
		5	38.85	56.68	216.45
		Avg. L2	**39.48**	**56.37**	**210.03**
	Total	**Avg. Total**	**38.34**	**55.94**	**205.03**
		Stdev.	**1.48**	**0.73**	**17.47**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#035	L1	1	42.29	55.94	212.25
		2	42.07	57.88	167.24
		3	41.88	58.11	210.55
		4	40.43	57.56	210.34
		5	40.57	57.63	153.07
		Avg. L1	**41.45**	**57.42**	**190.69**
	L2	1	41.68	59.20	155.36
		2	41.39	57.63	218.17
		3	38.79	56.55	200.87
		4	37.44	56.31	149.29
		5	37.92	55.78	161.81
		Avg. L2	**39.44**	**57.10**	**177.10**
	Total	**Avg. Total**	**40.45**	**57.26**	**183.89**
		Stdev.	**1.78**	**1.08**	**28.68**
#037	L1	1	56.48	69.72	264.29
		2	52.68	69.51	221.58
		3	56.37	71.61	295.59
		4	53.08	72.54	272.07
		5	53.11	70.47	240.89
		Avg. L1	**54.34**	**70.77**	**258.88**
	L2	1	54.05	70.17	243.24
		2	55.09	69.41	253.46
		3	55.65	68.53	270.49
		4	56.23	69.15	266.86
		5	52.39	69.59	210.83
		Avg. L2	**54.68**	**69.37**	**248.98**
	Total	**Avg. Total**	**54.51**	**70.07**	**253.93**
		Stdev.	**1.63**	**1.20**	**25.39**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#040	L1	1	64.75	78.85	391.55
		2	64.99	78.81	385.87
		3	66.09	79.31	389.47
		4	63.60	79.66	328.28
		5	66.86	82.43	397.22
		Avg. L1	**65.26**	**79.81**	**378.48**
	L2	1	64.32	82.30	375.46
		2	65.64	83.84	413.49
		3	64.33	83.29	371.35
		4	63.84	84.53	407.75
		5	66.29	86.96	424.91
		Avg. L2	**64.88**	**84.18**	**398.59**
	Total	**Avg. Total**	**65.07**	**82.00**	**388.53**
		Stdev.	**1.10**	**2.77**	**26.88**
#044	L1	1	59.38	77.85	353.60
		2	55.95	77.82	321.41
		3	58.16	78.37	329.72
		4	58.39	78.66	345.35
		5	59.67	79.29	354.38
		Avg. L1	**58.31**	**78.40**	**340.89**
	L2	1	58.72	78.50	326.35
		2	56.37	77.83	324.24
		3	59.37	78.50	356.51
		4	59.53	74.97	320.68
		5	60.29	72.79	319.12
		Avg. L2	**58.85**	**76.52**	**329.38**
	Total	**Avg. Total**	**58.58**	**77.46**	**335.14**
		Stdev.	**1.43**	**2.00**	**15.46**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#050	L1	1	63.90	83.63	292.89
		2	61.68	83.19	355.54
		3	61.73	83.71	366.60
		4	59.32	82.28	324.20
		5	59.94	83.07	339.19
		Avg. L1	**61.32**	**83.18**	**335.68**
	L2	1	60.38	82.55	334.60
		2	62.19	83.33	370.57
		3	60.70	82.90	353.80
		4	60.58	82.59	336.63
		5	62.01	83.49	367.53
		Avg. L2	**61.17**	**82.97**	**352.63**
	Total	**Avg. Total**	**61.24**	**83.07**	**344.16**
		Stdev.	**1.33**	**0.49**	**23.97**
#111	L1	1	46.99	67.22	300.28
		2	44.24	65.78	282.75
		3	46.49	66.85	300.26
		4	44.48	64.56	260.15
		5	44.87	66.35	269.95
		Avg. L1	**45.42**	**66.15**	**282.68**
	L2	1	46.91	66.65	282.16
		2	48.00	64.66	303.24
		3	46.02	63.54	279.97
		4	49.41	64.97	297.80
		5	47.99	64.35	282.04
		Avg. L2	**47.67**	**64.83**	**289.04**
	Total	**Avg. Total**	**46.54**	**65.49**	**285.86**
		Stdev.	**1.68**	**1.24**	**14.32**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#123	L1	1	59.96	78.86	374.25
		2	58.37	77.47	321.88
		3	55.59	76.64	298.03
		4	57.89	79.10	348.71
		5	58.75	80.36	376.13
		Avg. L1	**58.11**	**78.49**	**343.80**
	L2	1	59.12	80.23	369.30
		2	57.60	80.31	354.97
		3	54.01	78.56	274.01
		4	59.85	77.84	358.50
		5	59.48	77.88	354.01
		Avg. L2	**58.01**	**78.96**	**342.16**
	Total	**Avg. Total**	**58.06**	**78.73**	**342.98**
		Stdev.	**1.92**	**1.29**	**34.21**
#125	L1	1	60.74	80.98	337.37
		2	59.14	80.86	303.31
		3	57.13	81.19	306.83
		4	59.97	81.44	345.99
		5	59.31	81.94	330.68
		Avg. L1	**59.26**	**81.28**	**324.84**
	L2	1	59.70	81.66	337.05
		2	59.79	81.38	327.94
		3	59.63	81.25	306.01
		4	60.18	81.70	290.26
		5	61.67	83.35	319.57
		Avg. L2	**60.19**	**81.87**	**316.17**
	Total	**Avg. Total**	**59.73**	**81.58**	**320.50**
		Stdev.	**1.17**	**0.71**	**18.18**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#126	L1	1	55.60	79.09	316.17
		2	54.26	78.90	327.33
		3	55.86	79.88	340.67
		4	54.95	79.64	349.31
		5	55.77	78.90	326.20
		Avg. L1	**55.29**	**79.28**	**331.94**
	L2	1	56.64	80.44	361.27
		2	56.62	80.47	369.55
		3	56.38	79.97	353.95
		4	54.44	78.99	310.19
		5	58.23	81.16	369.50
		Avg. L2	**56.46**	**80.21**	**352.89**
	Total	**Avg. Total**	**55.87**	**79.74**	**342.41**
		Stdev.	**1.18**	**0.78**	**21.67**
#127	L1	1	62.96	78.88	393.51
		2	63.14	78.43	379.55
		3	60.38	78.42	355.93
		4	60.71	78.98	335.76
		5	61.41	78.77	371.59
		Avg. L1	**61.72**	**78.70**	**367.27**
	L2	1	64.38	82.92	432.88
		2	65.89	83.62	415.32
		3	63.19	81.30	385.66
		4	64.45	81.71	401.30
		5	65.63	82.98	429.01
		Avg. L2	**64.71**	**82.50**	**412.84**
	Total	**Avg. Total**	**63.21**	**80.60**	**390.05**
		Stdev.	**1.93**	**2.11**	**31.11**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#132	L1	1	53.46	77.96	344.48
		2	53.17	77.65	339.65
		3	53.32	78.14	344.65
		4	56.83	73.60	337.15
		5	56.20	73.07	332.27
		Avg. L1	**54.60**	**76.08**	**339.64**
	L2	1	55.46	73.45	342.81
		2	62.43	77.91	392.76
		3	57.51	74.95	355.48
		4	59.89	76.70	364.70
		5	59.19	79.64	383.56
		Avg. L2	**58.90**	**76.53**	**367.86**
	Total	**Avg. Total**	**56.75**	**76.31**	**353.75**
		Stdev.	**3.09**	**2.35**	**20.43**
#137	L1	1	53.20	67.17	277.59
		2	51.88	66.93	208.18
		3	52.37	66.49	207.21
		4	54.41	65.59	281.72
		5	55.29	66.40	277.65
		Avg. L1	**53.43**	**66.52**	**250.47**
	L2	1	55.91	70.13	337.61
		2	54.72	73.23	211.03
		3	52.68	70.93	259.44
		4	55.54	73.02	306.73
		5	50.17	70.21	271.94
		Avg. L2	**53.80**	**71.51**	**277.35**
	Total	**Avg. Total**	**53.62**	**69.01**	**263.91**
		Stdev.	**1.86**	**2.84**	**43.67**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#141	L1	1	59.24	79.87	386.96
		2	58.09	80.22	377.21
		3	59.36	81.00	375.56
		4	60.40	81.60	381.48
		5	56.84	81.32	261.81
		Avg. L1	**58.79**	**80.80**	**356.60**
	L2	1	55.74	79.13	277.22
		2	59.70	82.47	393.09
		3	59.44	81.62	371.23
		4	63.52	82.06	392.57
		5	57.79	79.91	363.58
		Avg. L2	**59.24**	**81.04**	**359.54**
	Total	**Avg. Total**	**59.01**	**80.92**	**358.07**
		Stdev.	**2.13**	**1.09**	**47.70**
#143	L1	1	57.87	69.87	304.86
		2	56.13	67.92	292.20
		3	56.79	69.17	301.21
		4	57.55	69.06	302.46
		5	51.47	68.30	262.58
		Avg. L1	**55.96**	**68.86**	**292.66**
	L2	1	58.76	70.76	258.99
		2	53.33	68.06	260.15
		3	54.18	68.28	253.78
		4	59.06	69.29	313.71
		5	52.33	68.64	205.58
		Avg. L2	**55.53**	**69.01**	**258.44**
	Total	**Avg. Total**	**55.75**	**68.94**	**275.55**
		Stdev.	**2.74**	**0.89**	**33.37**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#146	L1	1	34.10	53.93	196.14
		2	36.32	54.40	199.54
		3	36.11	54.47	198.76
		4	35.26	54.60	194.98
		5	37.55	55.37	219.98
		Avg. L1	**35.87**	**54.55**	**201.88**
	L2	1	36.91	52.37	190.63
		2	37.68	52.73	197.24
		3	36.04	52.58	171.99
		4	38.47	52.96	200.96
		5	37.97	52.31	187.26
		Avg. L2	**37.41**	**52.59**	**189.62**
	Total	**Avg. Total**	**36.64**	**53.57**	**195.75**
		Stdev.	**1.34**	**1.10**	**12.04**
#148	L1	1	55.66	70.24	312.72
		2	54.36	69.00	340.53
		3	52.46	68.98	307.30
		4	51.27	69.69	298.63
		5	51.28	70.28	311.94
		Avg. L1	**53.00**	**69.64**	**314.22**
	L2	1	54.46	71.34	295.13
		2	51.46	69.43	299.60
		3	49.37	69.13	297.05
		4	53.59	70.76	331.47
		5	51.95	68.67	284.63
		Avg. L2	**52.17**	**69.87**	**301.58**
	Total	**Avg. Total**	**52.58**	**69.75**	**307.90**
		Stdev.	**1.90**	**0.87**	**17.12**

(Continues)

Pipe #	Location	No.	Yield strength	Tensile strength	Fracture toughness
			ksi	ksi	MPa·m^1/2
#165	L1	1	50.84	65.38	301.17
		2	50.26	68.21	313.03
		3	48.76	68.70	299.70
		4	48.69	67.07	286.16
		5	49.50	67.86	306.71
		Avg. L1	**49.61**	**67.44**	**301.36**
	L2	1	48.72	65.49	263.96
		2	49.89	66.19	281.42
		3	48.72	66.46	269.92
		4	48.98	67.21	285.49
		5	47.91	67.92	264.39
		Avg. L2	**48.84**	**66.65**	**273.04**
	Total	**Avg. Total**	**49.23**	**67.05**	**287.20**
		Stdev.	**0.88**	**1.15**	**17.63**
#169	L1	1	56.68	66.95	310.69
		2	57.49	67.72	283.99
		3	55.15	66.11	302.37
		4	54.05	65.78	288.89
		5	54.65	66.83	269.40
		Avg. L1	**55.61**	**66.68**	**291.07**
	L2	1	60.51	70.78	258.36
		2	54.37	66.41	296.10
		3	54.69	66.50	241.19
		4	52.42	64.55	254.73
		5	55.63	66.77	296.25
		Avg. L2	**55.52**	**67.00**	**269.33**
	Total	**Avg. Total**	**55.56**	**66.84**	**280.20**
		Stdev.	**2.23**	**1.62**	**23.06**

< Appendix 1 >

Details of Measured Results

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	003
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	62.37	80.08	323.96
L2	63.12	83.67	323.91

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	61.62	76.24	294.53
	2	61.46	77.95	286.08
	3	61.13	80.31	334.91
	4	64.06	83.20	349.57
	5	63.58	82.69	354.70
	1	58.81	81.90	333.50
	2	60.95	82.82	352.68
	3	66.03	85.43	301.51
	4	65.31	84.20	321.86
	5	64.49	83.99	310.02

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	005
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	51.90	70.22	239.52
L2	51.09	69.09	241.71

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	53.76	71.07	218.82
	2	52.79	69.60	268.77
	3	51.87	70.20	242.99
	4	50.82	70.57	212.01
	5	50.24	69.65	255.02
	1	51.61	68.67	253.20
	2	51.87	69.69	231.99
	3	48.92	69.49	237.30
	4	51.62	69.88	257.30
	5	51.44	67.74	228.73

* Analysis result is engineering value

Remark

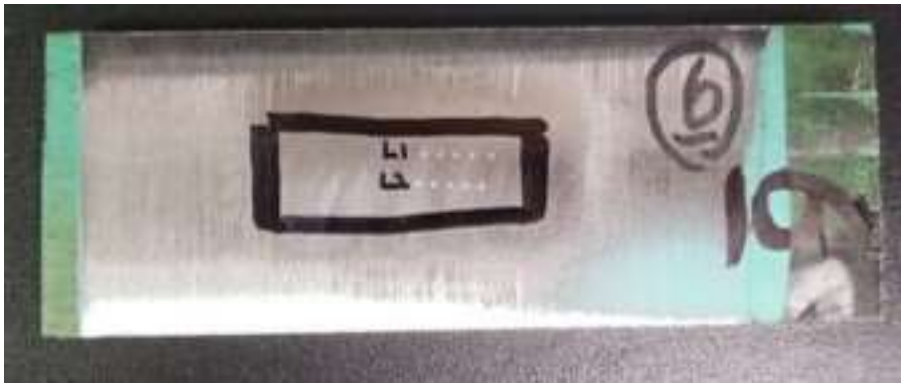
Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	006
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample



Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	53.43	71.34	275.71
L2	51.79	71.39	259.89

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	50.83	69.47	216.66
	2	51.76	70.43	291.33
	3	52.36	71.50	280.55
	4	52.42	71.52	283.16
	5	59.79	73.77	306.83
	1	54.17	71.95	281.50
	2	49.43	70.80	238.69
	3	55.05	72.81	317.16
	4	48.70	71.06	210.43
	5	51.62	70.33	251.66

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	012
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	45.21	67.89	279.90
L2	48.85	69.54	304.17

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	46.71	68.95	309.09
	2	45.28	68.01	298.57
	3	43.60	66.56	253.84
	4	44.22	66.79	232.41
	5	46.23	69.15	305.61
	1	48.61	70.94	340.29
	2	47.44	67.88	306.07
	3	49.87	70.08	296.36
	4	49.44	69.84	270.71
	5	48.88	68.95	307.41

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	013
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	56.24	73.70	298.74
L2	55.41	75.22	315.55

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	55.83	73.17	324.99
	2	56.14	72.78	287.74
	3	56.65	74.53	328.21
	4	56.62	73.96	268.10
	5	55.95	74.03	284.69
	1	57.22	74.87	328.61
	2	55.19	75.38	322.37
	3	54.35	74.84	274.02
	4	53.53	75.32	325.11
	5	56.76	75.71	327.64

* Analysis result is engineering value

Remark

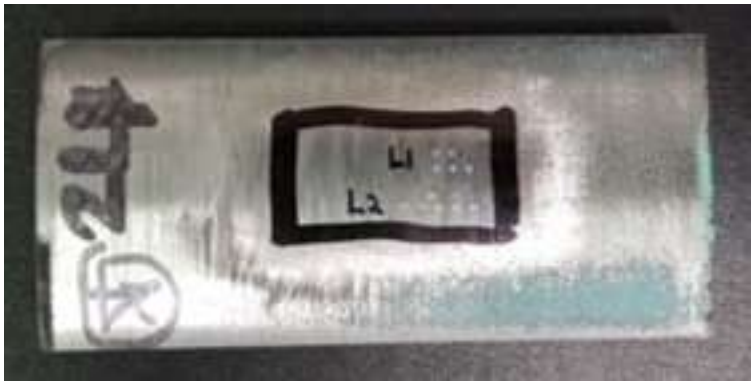
Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	024
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample



Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	55.34	66.63	254.51
L2	54.77	67.54	241.36

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	54.57	66.37	237.28
	2	57.05	66.89	277.81
	3	53.63	65.98	251.83
	4	56.61	66.93	272.27
	5	54.87	66.97	233.38
	1	51.44	67.19	198.39
	2	53.01	68.80	198.57
	3	55.99	66.99	269.99
	4	55.95	67.43	246.01
	5	57.45	67.29	293.82

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	026
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	60.17	84.23	379.01
L2	60.31	85.07	398.59

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	58.22	80.67	332.91
	2	59.52	84.27	391.04
	3	60.21	85.27	395.93
	4	63.48	85.99	367.39
	5	59.42	84.96	407.80
	1	60.18	84.80	400.63
	2	61.74	86.03	413.52
	3	59.59	84.46	385.59
	4	59.90	84.52	389.44
	5	60.14	85.56	403.76

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	027
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	66.17	85.49	387.15
L2	67.35	85.48	422.99

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	67.80	85.10	396.46
	2	68.77	87.16	413.97
	3	67.61	87.61	445.92
	4	61.65	86.77	354.99
	5	65.02	80.82	324.43
	1	66.19	80.16	415.20
	2	67.43	79.93	381.42
	3	68.51	86.86	426.57
	4	68.06	89.35	456.73
	5	66.54	91.06	435.02

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	029
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	48.15	70.25	315.04
L2	48.01	70.98	314.54

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	49.17	69.46	305.11
	2	48.50	70.75	323.22
	3	48.41	71.46	337.06
	4	47.37	70.57	311.44
	5	47.32	69.04	298.36
	1	47.32	71.07	314.64
	2	47.45	71.41	315.72
	3	48.55	70.35	303.30
	4	48.02	69.74	305.40
	5	48.73	72.34	333.65

* Analysis result is engineering value

Remark

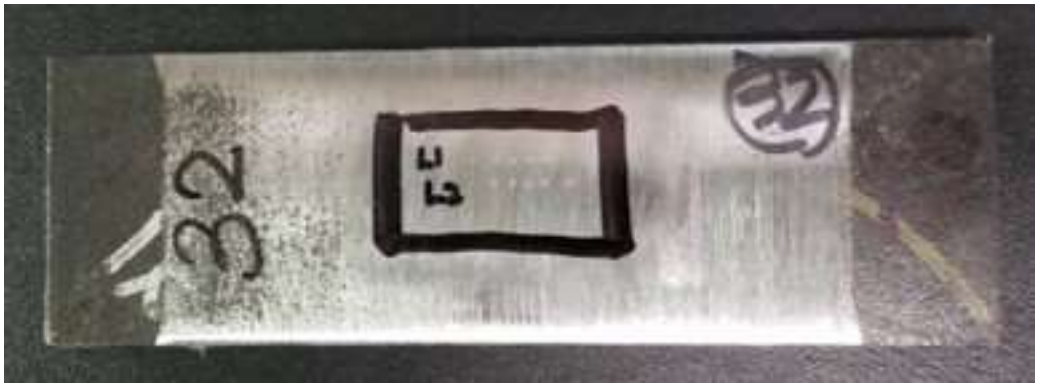
Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	032
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample



Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	50.14	67.72	290.49
L2	51.99	68.02	322.95

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	51.30	71.11	334.09
	2	45.72	66.33	200.59
	3	48.72	66.63	291.41
	4	49.11	66.62	304.73
	5	55.85	67.93	321.62
	1	51.59	66.53	301.12
	2	52.02	67.65	338.16
	3	52.98	68.36	334.19
	4	51.18	68.29	312.00
	5	52.22	69.29	329.30

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	033
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	57.74	77.33	345.03
L2	57.09	77.69	336.27

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	57.61	75.39	342.23
	2	57.32	77.18	355.10
	3	58.81	78.04	353.38
	4	56.72	77.99	340.61
	5	58.26	78.04	333.81
	1	56.68	78.14	355.67
	2	58.44	77.51	334.36
	3	56.20	77.29	310.42
	4	57.30	77.81	353.09
	5	56.83	77.68	327.79

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	034
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	37.20	55.51	200.03
L2	39.48	56.37	210.03

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	37.06	55.39	204.18
	2	36.18	54.61	168.76
	3	37.50	56.20	215.23
	4	36.11	55.31	191.31
	5	39.16	56.02	220.69
	1	39.81	55.36	210.37
	2	39.75	56.61	220.12
	3	39.37	56.47	217.18
	4	39.63	56.74	186.05
	5	38.85	56.68	216.45

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	035
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	41.45	57.42	190.69
L2	39.44	57.10	177.10

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	42.29	55.94	212.25
	2	42.07	57.88	167.24
	3	41.88	58.11	210.55
	4	40.43	57.56	210.34
	5	40.57	57.63	153.07
	1	41.68	59.20	155.36
	2	41.39	57.63	218.17
	3	38.79	56.55	200.87
	4	37.44	56.31	149.29
	5	37.92	55.78	161.81

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	037
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	54.34	70.77	258.88
L2	54.68	69.37	248.98

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	56.48	69.72	264.29
	2	52.68	69.51	221.58
	3	56.37	71.61	295.59
	4	53.08	72.54	272.07
	5	53.11	70.47	240.89
	1	54.05	70.17	243.24
	2	55.09	69.41	253.46
	3	55.65	68.53	270.49
	4	56.23	69.15	266.86
	5	52.39	69.59	210.83

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	040
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	65.26	79.81	378.48
L2	64.88	84.18	398.59

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	64.75	78.85	391.55
	2	64.99	78.81	385.87
	3	66.09	79.31	389.47
	4	63.60	79.66	328.28
	5	66.86	82.43	397.22
	1	64.32	82.30	375.46
	2	65.64	83.84	413.49
	3	64.33	83.29	371.35
	4	63.84	84.53	407.75
	5	66.29	86.96	424.91

* Analysis result is engineering value

Remark

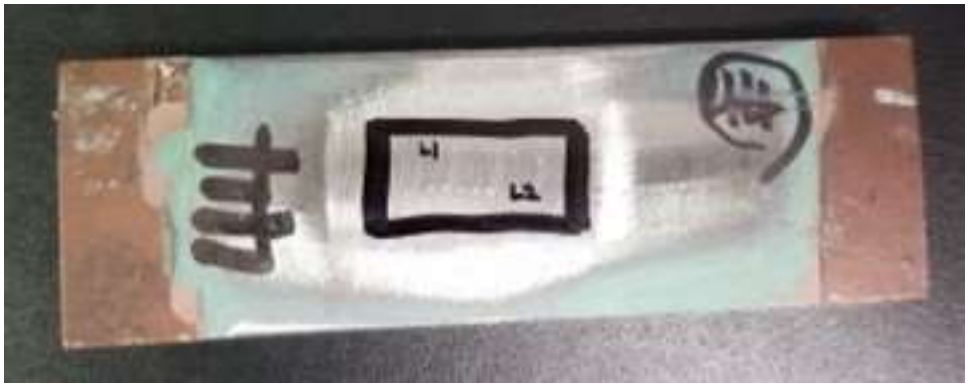
Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	044
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample



Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	58.31	78.40	340.89
L2	58.85	76.52	329.38

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	59.38	77.85	353.60
	2	55.95	77.82	321.41
	3	58.16	78.37	329.72
	4	58.39	78.66	345.35
	5	59.67	79.29	354.38
	1	58.72	78.50	326.35
	2	56.37	77.83	324.24
	3	59.37	78.50	356.51
	4	59.53	74.97	320.68
	5	60.29	72.79	319.12

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	050
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	61.32	83.18	335.68
L2	61.17	82.97	352.63

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	63.90	83.63	292.89
	2	61.68	83.19	355.54
	3	61.73	83.71	366.60
	4	59.32	82.28	324.20
	5	59.94	83.07	339.19
	1	60.38	82.55	334.60
	2	62.19	83.33	370.57
	3	60.70	82.90	353.80
	4	60.58	82.59	336.63
	5	62.01	83.49	367.53

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	111
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	45.42	66.15	282.68
L2	47.67	64.83	289.04

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	46.99	67.22	300.28
	2	44.24	65.78	282.75
	3	46.49	66.85	300.26
	4	44.48	64.56	260.15
	5	44.87	66.35	269.95
	1	46.91	66.65	282.16
	2	48.00	64.66	303.24
	3	46.02	63.54	279.97
	4	49.41	64.97	297.80
	5	47.99	64.35	282.04

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	123
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	58.11	78.49	343.80
L2	58.01	78.96	342.16

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	59.96	78.86	374.25
	2	58.37	77.47	321.88
	3	55.59	76.64	298.03
	4	57.89	79.10	348.71
	5	58.75	80.36	376.13
	1	59.12	80.23	369.30
	2	57.60	80.31	354.97
	3	54.01	78.56	274.01
	4	59.85	77.84	358.50
	5	59.48	77.88	354.01

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	125
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	59.26	81.28	324.84
L2	60.19	81.87	316.17

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	60.74	80.98	337.37
	2	59.14	80.86	303.31
	3	57.13	81.19	306.83
	4	59.97	81.44	345.99
	5	59.31	81.94	330.68
	1	59.70	81.66	337.05
	2	59.79	81.38	327.94
	3	59.63	81.25	306.01
	4	60.18	81.70	290.26
	5	61.67	83.35	319.57

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	126
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	55.29	79.28	331.94
L2	56.46	80.21	352.89

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	55.60	79.09	316.17
	2	54.26	78.90	327.33
	3	55.86	79.88	340.67
	4	54.95	79.64	349.31
	5	55.77	78.90	326.20
	1	56.64	80.44	361.27
	2	56.62	80.47	369.55
	3	56.38	79.97	353.95
	4	54.44	78.99	310.19
	5	58.23	81.16	369.50

* Analysis result is engineering value

Remark

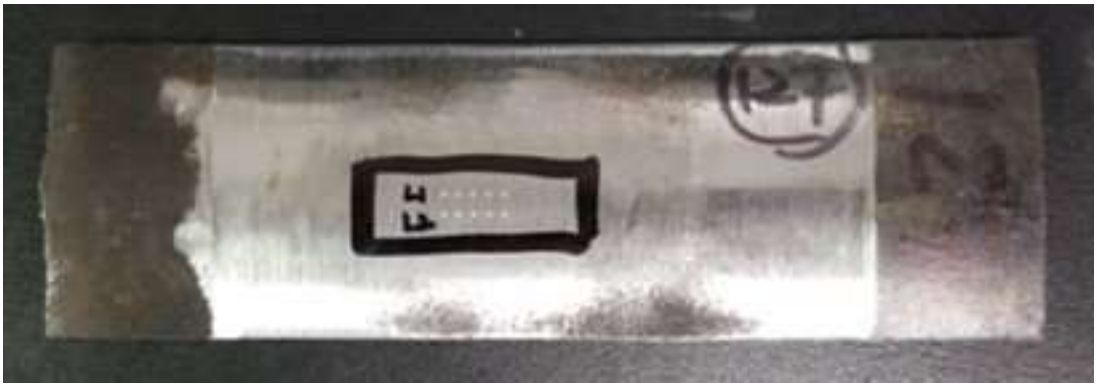
Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	127
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample



Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	61.72	78.70	367.27
L2	64.71	82.50	412.84

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	62.96	78.88	393.51
	2	63.14	78.43	379.55
	3	60.38	78.42	355.93
	4	60.71	78.98	335.76
	5	61.41	78.77	371.59
	1	64.38	82.92	432.88
	2	65.89	83.62	415.32
	3	63.19	81.30	385.66
	4	64.45	81.71	401.30
	5	65.63	82.98	429.01

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	132
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	54.60	76.08	339.64
L2	58.90	76.53	367.86

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	53.46	77.96	344.48
	2	53.17	77.65	339.65
	3	53.32	78.14	344.65
	4	56.83	73.60	337.15
	5	56.20	73.07	332.27
	1	55.46	73.45	342.81
	2	62.43	77.91	392.76
	3	57.51	74.95	355.48
	4	59.89	76.70	364.70
	5	59.19	79.64	383.56

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	137
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	53.43	66.52	250.47
L2	53.80	71.51	277.35

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	53.20	67.17	277.59
	2	51.88	66.93	208.18
	3	52.37	66.49	207.21
	4	54.41	65.59	281.72
	5	55.29	66.40	277.65
	1	55.91	70.13	337.61
	2	54.72	73.23	211.03
	3	52.68	70.93	259.44
	4	55.54	73.02	306.73
	5	50.17	70.21	271.94

* Analysis result is engineering value

Remark

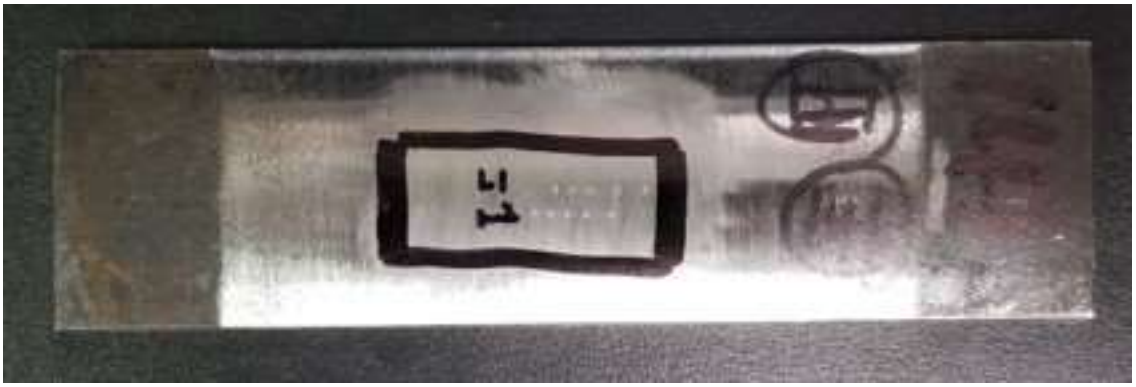
Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	141
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample



Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	58.79	80.80	356.60
L2	59.24	81.04	359.54

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	59.24	79.87	386.96
	2	58.09	80.22	377.21
	3	59.36	81.00	375.56
	4	60.40	81.60	381.48
	5	56.84	81.32	261.81
	1	55.74	79.13	277.22
	2	59.70	82.47	393.09
	3	59.44	81.62	371.23
	4	63.52	82.06	392.57
	5	57.79	79.91	363.58

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	143
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	55.96	68.86	292.66
L2	55.53	69.01	258.44

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	57.87	69.87	304.86
	2	56.13	67.92	292.20
	3	56.79	69.17	301.21
	4	57.55	69.06	302.46
	5	51.47	68.30	262.58
	1	58.76	70.76	258.99
	2	53.33	68.06	260.15
	3	54.18	68.28	253.78
	4	59.06	69.29	313.71
	5	52.33	68.64	205.58

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	146
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	35.87	54.55	201.88
L2	37.41	52.59	189.62

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	34.10	53.93	196.14
	2	36.32	54.40	199.54
	3	36.11	54.47	198.76
	4	35.26	54.60	194.98
	5	37.55	55.37	219.98
	1	36.91	52.37	190.63
	2	37.68	52.73	197.24
	3	36.04	52.58	171.99
	4	38.47	52.96	200.96
	5	37.97	52.31	187.26

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	148
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	53.00	69.64	314.22
L2	52.17	69.87	301.58

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	55.66	70.24	312.72
	2	54.36	69.00	340.53
	3	52.46	68.98	307.30
	4	51.27	69.69	298.63
	5	51.28	70.28	311.94
	1	54.46	71.34	295.13
	2	51.46	69.43	299.60
	3	49.37	69.13	297.05
	4	53.59	70.76	331.47
	5	51.95	68.67	284.63

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	165
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	49.61	67.44	301.36
L2	48.84	66.65	273.04

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	50.84	65.38	301.17
	2	50.26	68.21	313.03
	3	48.76	68.70	299.70
	4	48.69	67.07	286.16
	5	49.50	67.86	306.71
	1	48.72	65.49	263.96
	2	49.89	66.19	281.42
	3	48.72	66.46	269.92
	4	48.98	67.21	285.49
	5	47.91	67.92	264.39

* Analysis result is engineering value

Remark

Instrumented Indentation Test (IIT) Results

- Yield strength, Tensile strength and Fracture toughness

Test Information

Customer	GTI	Pipe #	169
Location	FRONTICS AMERICA	Pipe size (in)	12
Test date	11/9/2020	Testing location #	2
Operator	Dongseong Ro	Max. testing depth	150 μm
Equipment	AIS2100	Indenter #	K05352

Sample

Results

Test location	Yield strength	Tensile strength	Fracture toughness
	ksi	ksi	MPa·m^1/2
L1	55.61	66.68	291.07
L2	55.52	67.00	269.33

* Analysis result is engineering value

Detail Results

Test location	No.	Yield strength	Tensile strength	Fracture toughness
		ksi	ksi	MPa·m^1/2
	1	56.68	66.95	310.69
	2	57.49	67.72	283.99
	3	55.15	66.11	302.37
	4	54.05	65.78	288.89
	5	54.65	66.83	269.40
	1	60.51	70.78	258.36
	2	54.37	66.41	296.10
	3	54.69	66.50	241.19
	4	52.42	64.55	254.73
	5	55.63	66.77	296.25

* Analysis result is engineering value

Remark