THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY
12000 Jefferson Avenue
Newport News, VA 23606

PHY MAG REPORT NO.:
PMAG0000-0001-R0002 Rev -0

TITLE: Measurement of Material permeability and Inconel-625

BY: David Kashy
CHK: Eric Sun
APP: P K Ghoshal

DATE: 20th July, 2021

0.0	First Release	Measurement of Material permeability and Inconel_625	Kashy	Sun	Fair	Ghoshal	7/20/2021
REV.	ECO#	DESCRIPTION	BY	CHK.	APP.	APP.	DATE
SUMMARY OF CHANGES FROM PREVIOUS REVISION:							

Inconel 625 Bellows Report

D. Kashy (7/8/21)

A two convolution bellows was purchased by credit card with the main intention of measuring the relative permeability of the material at the cuffs, the convolutions and the weld seam.

The bellows was purchased from Bellows Systems. The product was clean and looked quite nice.

Approximate dimensions: Thickness 0.0625” material

Thickness at weld ~0.0605” (Note the weld looked very nice and possibly plenished to avoid being thicker than the rest of the tube.)

Cuff ID ~10.75”

Min ID ~ 10.35”

Max OD 11.8”

Pitch 0.66” (spacing between convolutions)

Engraved on the surface 8369-049 SN-SO16#04

Permeability measurements:

Instrument/device used *- Ferromaster Permeability Meter [List-Magnetik GmbH, S/N 14633, Certified in April 2021]*

The device was zeroed (set to 1.000) then the 1.36 reference was checked and the read back varied between 1.357 and 1.362

The Cuffs measured 1.001, 1.001

The convolution 1.001 and 1.000

The weld region of the cuff 1.001 and 1.001

The weld region on the convolution 1.001 and 1.002, (but the reading in air had shifted to 1.001

The summary of the permeability measurements is that the bellows has an average value between 1.000 and 1.001

Yet to do is to measure the stiffness (if anyone sees a need). The convolutions of this particular bellows is made of much thicker material than any I've used in the past. I actually wonder what it was designed for (application, cycle life, stroke, other).

INVOICE of bellow purchase

Bellows Systems Inc
11981 FM529 RD
HOUSTON, TX 77041 US
+1 2817212947
rathi.walter@bellows-systems.com
www.bellows-systems.com

Bellows Systems

INVOICE

BILL TO	SHIP TO	
Jefferson Labs 12000 Jefferson Avenue Newport News, Virginia 23606 United States	Jefferson Labs 12000 Jefferson Avenue Newport News, Virginia 23606 United States	INVOICE # 210702003 DATE 07/02/2021 DUE DATE 07/03/2021 TERMS Cash in Advance

SHIP DATE	SHIP VIA	TRACKING NO.	P.O. NUMBER	SALES REP
07/02/2021	UPS Ground	1Z3VX0230734901441	2106-0067	Nikki Hughes

ACTIVITY	DESCRIPTION	QTY	RATE	AMOUNT
BEL1-967-935-8369-49	Expansion Joint	1	1,035.00	1,035.00
FREIGHT OUT	UPS Ground	1	105.00	105.00

Sales Tax: Out of State

PAYMENT 1,140.00
BALANCE DUE **$0.00**

PAID

Please Remit Payments To:
Bellows Systems, Inc
11981 FM 529 Rd,
Houston, Texas 77041.

For ACH Payments:
Bank Name: Iberia Bank
Account Name: Bellows Systems, Inc.
Account Number: 20001908553
Routing Number: 265270413

Internal JLAB Reference –

1. O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\12. Quality Control Documents\Material Permeabilities
2. Added reference to the paper and measurements by Donald Jones donald.jones@temple.edu shared on July 8th, 2021
3. N Wilson and P Bunch, "Magnetic Permeability of SS in Acc beam transport syst", IEEE (PAC1991/2322), Los Alamos (table 1)
4. N Yusa, et al., "Evaluation of the electromagnetic characteristics of type 316L stainless steel welds from the viewpoint of eddy current inspections", Journal of Nuclear Science and Technology, 1881-1248 (2014)
5. Manual Ferromaster 2013 (section 4.4)
6. MOLLER_Ferrous_Materials_Committee_Summary_July 14th 2021 (*M:\JLab_Magnet_Group\12. Documents\Native Document Folders\PMAG0000-0001-R0002 Measurement of Material permeability and Inconel_625*)

Stefan Mayer Instruments

GmbH & Co. KG, Wallstr. 7
D-46535 Dinslaken, Germany
Phone/Fax: +49 2064 479762/3
http://www.stefan-mayer.com
Email: mail@stefan-mayer.com

Permeability Meter FERROMASTER

for easy measurements of the magnetic permeability of materials and workpieces, meas. range μ = 1.001 to 1.999

Features

- Easy use
- Meas. range μ = 1.001 to 1.999
- Permeability test in conformance with ASTM A342 and EN 60404-15
- Calibrated to ref. standards of the National Physical Laboratory, UK
- Calibration material supplied
- $3\,^1/_2$ digit LC display
- Automatic zeroing
- Waterproof enclosure (protection IP65)

Applications

- Quality control of stainless steel
- Non-destructive testing of materials and workpieces
- Material selection for electron-/ion-beam equipment and NMR instruments
- Detection of ferromagnetic inclusions in materials
- Investigation of magnetically anisotropic materials
- Detection of material defects induced by stress

Description

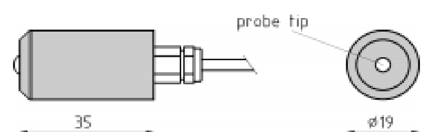
The FERROMASTER is a compact hand-held instrument made for easy measurements of the relative magnetic permeability μ_r of materials and workpieces with μ_r between 1.001 and 1.999. The relative permeability is measured by touching the workpiece with the sensor tip and reading the result from the LC display. Automatic zeroing is performed by simply pressing a button.

The permeability probe contains a small permanent magnet which magnetizes the sample to be investigated in the vicinity of the probe tip. Two sensitive magnetic field sensors in difference connection measure the distortion of the magnetic field introduced by the magnetized sample. The instrument is calibrated to precise standards manufactured by the National Physical Laboratory (NPL, Teddington, UK). The calibration can be easily readjusted. A sample of low permeability material is supplied with each instrument for easy check of the calibration.

As a special feature the FERROMASTER is provided with a robust waterproof case (protection IP65) and is therefore well suited to applications in harsh industrial environments. The built-in battery serves for ~50 hours operating time.

Specifications

Measurement range	μ = 1.001 to 1.999
Resolution	0.001
Accuracy of calibration @ 20 °C	$(\mu - 1)\times 5\%$, ref. to NPL calibration standards, can be readjusted
Operating temperature	0 to 50 °C
Field strength at probe tip	~35 kA/m
Battery	9 V (PP3, Alkaline)
Operation time with one battery	~50 h
Dimensions of electronics unit	151 mm × 82 mm × 33 mm
Environmental protection	IP65
Length of connection cable	1.5 m
Weight of complete instrument	280 g



Dimensions of the permeability probe in mm

Subject to alterations.

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Measurement of Material Magnetic Permeabilities

Meter Used: Ferromaster Permeability Meter [List-Magnetik GmbH, S/N 14633, Cerified in April 2021]

Version No. 1.00

Date: 07.06.21

Engineers Dave Kashy, Ruben Fair, Eric Sun, Probir Ghoshal

sensitivity = (ur_meas-1)/(ur_true-1)
ur_true=((ur_meas-1)/sensitivity)+1

Sensitivity (fit equation) =
MIN(1,(-(-27.724*T^5+1031.4*T^4-15694*T^3+124434*T^2-529102*T+999802)/10^6)+1)

Note: The values in the YELLOW cells have permeability scaled using sensitivity vs thickness variation plot.

Thk (mm)	Fitted sensi
2	0.671

from sheet Plot sec4.4, row 73-80; D. Kashy extracted function

TED2504: 07.06.21 / 11:10am

[Probe zeroed before start of measurements]

#	Material	thk (mm)	#1 μr	#2 μr	#3 μr	Average μr (meas)	Average μr (true or actual)
1	Corrosion-Resistant 316 Stainless Steel Sheet, 6" x 6", 0.03" Thick	0.762	1.001	1.001	1.001	1.001	1.003
2	Multipurpose 304 Stainless Steel Sheet, 6" x 6", 0.03" Thick	0.762	1.002	1.002	1.002	1.002	1.006
3	Marine-Grade 5083 Aluminum, 1/8" Thick, 6" x 6	3.175	1.000	1.000	1.000	1.000	1.000
4	Easy-to-Form Marine-Grade 5086 Aluminum, 0.063" Thick, 6" x 6"	1.6002	1.000	1.000	1.000	1.000	1.000
5	Multipurpose 6061 Aluminum Sheet, 0.032" Thick, 6" x 6"	0.8128	1.000	1.000	1.000	1.000	1.000
6	High-Strength 625 Nickel Sheet, 0.032" Thick x 6" Wide x 6" Long	0.8128	1.000	1.000	1.000	1.000	1.000
7	Tungsten Copper 85W15Cu, 0.090 x 3.75 x 5.75, - Midwest Tungsten Service	2.286	1.000	1.000	1.000	1.000	1.000
8	HD Tungsten Alloy EA18 95W3.5Ni1.5Cu, 0.1x1x1 (brazed to copper) Eagle Alloys	2.54	1.000	1.000	1.000	1.000	1.000
9	Plumbing copper		1.000	1.000	1.000	1.000	
10	High-Strength 625 Nickel Sheet, 0.032" Thick x 6" Wide x 6" Long (LIGHT WELD - just put an arc on it))						
11	High-Strength 625 Nickel Sheet, 0.032" Thick x 6" Wide x 6" Long (HEAVY WELD - just put an arc on it))						

TED2504: 07.06.21 / 11:24am
[Probe zeroed before measurement start;
Calibration sample supplied with instrument, Cal Std #2111: relative permeability = 1.36

Starting reading on calibration sample = 1.362, End reading on calibration sample = 1.362]

#	#1 μr	#2 μr	#3 μr	Average μr (meas)	Average μr (true or actual)
1	1.002	1.002	1.002	1.002	1.006
2	1.002	1.002	1.003	1.0023	1.007
3	1.001	1.001	1.001	1.001	1.001
4	1.001	1.001	1.001	1.001	1.002
5	1.001	1.001	1.001	1.001	1.003
6	1.001	1.001	1.001	1.001	1.003
7	1.001	1.001	1.002	1.0013	1.002
8	1.001	1.001	1.001	1.001	1.001
9	1.001	1.001	1.001	1.001	
10	1.000	1.000	1.000	1.000	
11	1.000	1.000	1.000	1.000	

#	Treatment	thk (mm)	Weld bead w 316L rod (meas)	Weld bead w 316L rod (actual)	Peened (meas)	Peened (Actual)	Bent 4x (meas)	Bent 4x (Actual)	Sheared * (meas)	Sheared * (Actual)
12	Corrosion-Resistant 316 Stainless Steel Sheet, 6" x 6", 0.03" Thick		1.17		1.003		1.003		1.004	
	Corrosion-Resistant 316 Stainless Steel Sheet, 6" x 6", 0.03" Thick		1.2		1.003		1.003		1.005	
	Corrosion-Resistant 316 Stainless Steel Sheet, 6" x 6", 0.03" Thick		1.177		1.003		1.003		1.004	
	Corrosion-Resistant 316 Stainless Steel Sheet, 6" x 6", 0.03" Thick (average)	0.762	**1.182**	1.540	**1.003**	1.009	**1.003**	1.009	**1.004**	1.013

	Treatment	thk (mm)	Weld bead w 308L rod (meas)	Weld bead w 308L rod (actual)	Peened (meas)	Peened (Actual)	Bent 4x (meas)	Bent 4x (Actual)	Sheared * (meas)	Sheared * (Actual)
13	Multipurpose 304 Stainless Steel Sheet, 6" x 6", 0.03" Thick		1.2		1.007		1.005		1.011	
	Multipurpose 304 Stainless Steel Sheet, 6" x 6", 0.03" Thick		1.211		1.006		1.006		1.012	
	Multipurpose 304 Stainless Steel Sheet, 6" x 6", 0.03" Thick		1.223		1.008		1.007		1.013	
	Multipurpose 304 Stainless Steel Sheet, 6" x 6", 0.03" Thick (average)	0.762	**1.211**	1.626	**1.007**	1.021	**1.006**	1.018	**1.012**	1.036

* Thin sheets so hard to make measurements on the edge.

Permeability (engineeringtoolbox.com)

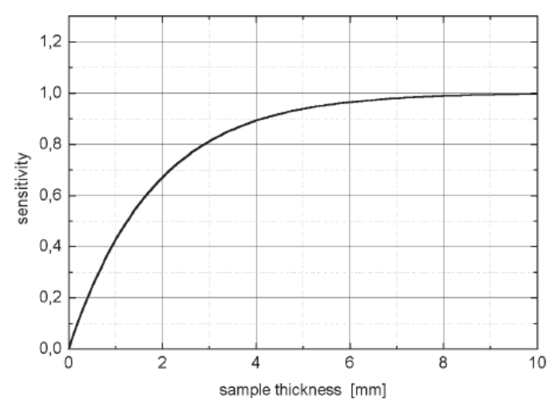
Medium	Permeability - μ - (H/m)	Relative permeability - μ / μ_0 -
Air	$1.25663753 \cdot 10^{-6}$	1.00000037
Aluminum	$1.256665 \cdot 10^{-6}$	1.000022
Austenitic stainless steel[1)]	$1.260 \cdot 10^{-6}$ - $8.8 \cdot 10^{-6}$	1.003 – 7
Bismuth	$1.25643 \cdot 10^{-6}$	0.999834
Carbon Steel	$1.26 \cdot 10^{-4}$	100
Cobalt-Iron (high permeability strip material)	$2.3 \cdot 10^{-2}$	18000
Copper	$1.256629 \cdot 10^{-6}$	0.999994
Ferrite (nickel zinc)	$2.0 \cdot 10^{-5}$ – $8.0 \cdot 10^{-4}$	16 – 640
Ferritic stainless steel (annealed)	$1.26 \cdot 10^{-3}$ - $2.26 \cdot 10^{-3}$	1000 – 1800
Hydrogen	$1.2566371 \cdot 10^{-6}$	1
Iron (99.8% pure)	$6.3 \cdot 10^{-3}$	5000
Iron (99.95% pure Fe annealed in H)	$2.5 \cdot 10^{-1}$	200000
Martensitic stainless steel (annealed)	$9.42 \cdot 10^{-4}$ - $1.19 \cdot 10^{-3}$	750 – 950
Martensitic stainless steel (hardened)	$5.0 \cdot 10^{-5}$ - $1.2 \cdot 10^{-4}$	40 – 95
Nanoperm	$1.0 \cdot 10^{-1}$	80000
Neodymium magnet	$1.32 \cdot 10^{-6}$	1.05
Nickel	$1.26 \cdot 10^{-4}$ - $7.54 \cdot 10^{-4}$	100 – 600
Permalloy	$1.0 \cdot 10^{-2}$	8000
Platinum	$1.256970 \cdot 10^{-6}$	1.000265
Sapphire	$1.2566368 \cdot 10^{-6}$	0.99999976
Superconductors	0	0
Teflon	$1.2567 \cdot 10^{-6}$	1
Vacuum (μ_0)	**$4\pi \cdot 10^{-7}$**	**1**
Water	$1.256627 \cdot 10^{-6}$	0.999992
Wood	$1.25663760 \cdot 10^{-6}$	1.00000043

Reference to plot:

Stefan Mayer, "Ferromaster Permeability Meter, Stefan Mayer Instruments Instruction Manual", Page 7, Feb 2013, Germany

4.4 Dimensions of the sample

For small samples the result of the permeability measurement depends on the dimensions of the sample. For example, the sensitivity of the instrument increases with increasing sample thickness. The sensitivity is independent of the dimensions for samples which are more than ~5 mm thick and have a lateral diameter of more than 2 cm. The sensitivity as a function of the sample thickness is shown in the following diagram. The sensitivity is defined as $(\mu_r \text{ measured} - 1)/(\mu_r \text{true} - 1)$.



Thick Sample Permeability Measurements

DHK **7/15/2021**

Thk (mm)	Fitted sensi
2	0.671

from sheet Plot sec4.4, row 73-80; D. Kashy extracted function

ur_true=((ur_meas-1)/sensitivity)+1

Note: The values in the YELLOW cells have permeability scaled using sensitivity vs thickness variation plot.

Aero to 1.000 Cal @1.359 1.36 reference

			dim (inches)				Central measurements			Edge measurements				PKG with recalculated factor with sensitivity (D Kashy extracted function)		
Number of order	Material	McM #	length	width	thickness	thickness (mm)	#1	#2	#3	#1	#2	#3	Avg central	Actual or true (central)	Average edge	Actual or True (edge)
1	Inconel 625	8786K104	6	6	0.375	9.525	1.000	1.000	1.001	1.007	1.001	1.001	1.0003	1.000	1.0030	1.003
2	AL 6061-T6	9246K483	6	6	0.4375	11.1125	1.000	1.000	1.000	1.000	1.000	1.000	1.0000	1.000	1.0000	1.000
3	AL 5083	4058T74	6	6	0.375	9.525	0.999	0.999	1.000	0.999	0.999	0.999	0.9993	0.999	0.9990	0.999
4	AL 5086	5865T76	6	6	0.375	9.525	1.000	1.000	1.000	1.000	1.000	1.000	1.0000	1.000	1.0000	1.000
5	303 SST	9084K45	1.25	6	0.375	9.525	1.005	1.004	1.005	1.011	1.009	1.008	1.0047	1.005	1.0093	1.009
6	304 SST	8983K212	6	6	0.375	9.525	1.089	1.086	1.099	1.573	1.831	1.874	1.0913	1.092	1.7593	1.762
7	316 SST	4816T53	3	3	0.375	9.525	1.010	1.008	1.009	1.068	1.059	1.049	1.0090	1.009	1.0587	1.059
8	AL 7075	8885K911	6	6	0.375	9.525	1.000	1.000	1.000	1.000	1.000	1.000	1.0000	1.000	1.0000	1.000
9	AL 2024	89215K114	2	6	0.5	12.7	1.000	1.000	1.000	0.999	0.999	0.999	1.0000	1.000	0.9990	0.999
10	AL 7075	9055K11	1	6	0.5	12.7	1.000	1.000	1.000	1.000	1.000	1.000	1.0000	1.000	1.0000	1.000
11	410 SST Round bar 1 inch dia	86705K12	6	NA	NA	NA	>1.999	>1.999	>1.999	>1.999	>1.999	>1.999	>1.999	Geometry doesn't match the scaling factor	>1.999	Geometry doesn't match the scaling factor
12	Silicon Bronze Bolt 1/2-UNC 6.5 lg	93516A176	6.5	NA	NA	NA	1.000	1.000	1.000	1.000	1.000	1.000	1.0000		1.0000	
13	Silicon Bronze Nut Wide 1/2-UNC	92049A032	NA	NA	NA	NA	1.000	1.000	1.000	1.000	1.000	1.000	1.0000		1.0000	

NOTE: **Line 7 the material 316 SST and 316L (D Jines Email) are essentially the same and vendors do not differentiate the JLab measurement.**
The values matches well to the values provided below by Donald Jones at a value of ~1.06 on 7.9.2021 email.

Conclusion (JLAB):

JLab measured many metal samples. Inconel 625 always measured 1.000 or 1.001. Silicon Bronze also measure 1.000 so it should be a good bolting option for Moller.
JLab measurement quality seems to be good agreement with the values reported for 316/316L (sheared) as referenced by D. Jones

From: Donald Jones <donald.jones@temple.edu>
Sent: Thursday, July 8, 2021 12:13 PM
To: David Kashy <kashy@jlab.org>; Ruben Fair <rfair@jlab.org>; James Fast <jfast@jlab.org>
Subject: [EXTERNAL] 316L

Hi Folks,
A colleague of mine recently had some 316L plate machined and he wanted to make sure their permeability was low enough for his application so I took advantage of the situation to add to our database of measurements. Here is a link to the spreadsheet of measurements, which are summarized in the plot below. He had a rough ~30" square by 1/2" plate with a 24" circle cut out of it. From the cutout a 2' annular disc was machined. Briefly
Original 1/2" thick unmachined ~30" square plate (4 measurements on flat sections near corners)
1.010 stdev 0.004 stderr 0.002

Measurements taken on the 1/2" shear edge of the original 30" square plate (9 measurements)
1.061 stdev 0.026 stderr 0.009

These are consistent with the Los Alamos paper (see table 1) that suggested 316L is <1.01. However, they claim welding can take it to 1.6. Another paper on 316L deals specifically with welds. Jeff, let me know if these links don't work.

Flat machined annulus surface (16 measurements around annulus)
1.016 stdev 0.004 stderr 0.001

Machined annulus inner and outer 1/2" edges (16 measurements)
1.035 stdev 0.014 stderr 0.004

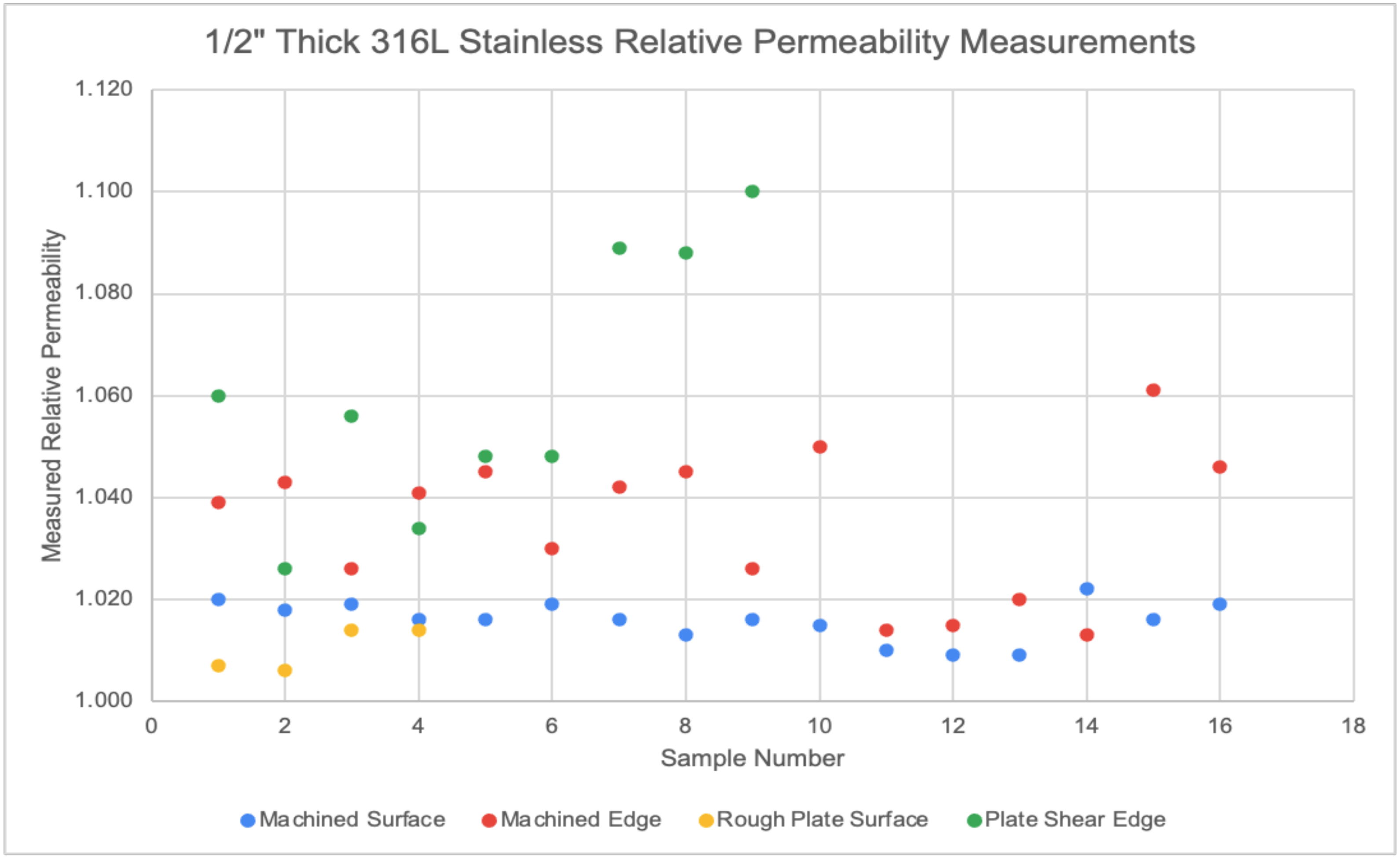
So machining gives a modest increase in permeability but the sheared edge shows the largest increase and has large changes from position to position. Welding is expected to have a much larger effect perhaps by a factor of 10. It basically confirms what we thought that 316L has too large of a permeability (and uncertainty) for us unless it is annealed after working.

Approved: 07/21/2021; E-Sign ID: 444325; Signed By: Reviewer 1: D. Kashy; Reviewer 2: E. Sun; DCG Quality Check: T. Fuell

email from Donald Jones, July 8th, 2021

316L permeability measurements for Jeff Martoff
These were done on a machined annulus approximately 2' in diameter and 2" in width and 1/2" in thickness.

	16 points around on the flat machined surface of the annulus	16 points around the inner and outer machined edges i.e. on the 1/2" thick inner and outer edges	4 points on the flat section of the original unmachined plate the disc was cut from	9 points around sheared edge of original unmachined plate	1.007
1.000	1.020	1.039	1.007	1.060	1.006
2.000	1.018	1.043	1.006	1.026	1.014
3.000	1.019	1.026	1.014	1.056	1.014
4.000	1.016	1.041	1.014	1.034	1.060
5.000	1.016	1.045	average	1.048	1.026
6.000	1.019	1.03	1.010	1.048	1.056
7.000	1.016	1.042	standard deviation	1.089	1.034
8.000	1.013	1.045	0.004	1.088	1.048
9.000	1.016	1.026	standard error	1.100	1.048
10.000	1.015	1.05	0.002	average	1.089
11.000	1.010	1.014		1.061	1.088
12.000	1.009	1.015		standard deviation	1.100
13.000	1.009	1.02		0.026	1.020
14.000	1.022	1.013		standard error	1.018
15.000	1.016	1.061		0.009	1.019
16.000	1.019	1.046			1.016
	average	average			1.016
	1.016	1.035			1.019
	standard deviation	standard deviation			1.016
	0.004	0.014			1.013
	standard error	standard error			1.016
	0.001	0.004			1.015
					1.010
					1.009
					1.009
					1.022
					1.016
					1.019



Conclusion (JLAB):

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