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Geometric tolerances of tubular T-joint test-specimens

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Abstract

The objective of present work is estimation of geometric tolerances of fabricated laboratory test-models from 3D CAD models. A set of 7 welded S355 steel specimens with T-joint design have been investigated. The specimens, with nominal dimensions ø114 mm for the brace and ø219 mm for the chord imitate a typical welded T-connection widely met in offshore structures like oil rigs and is to be used for fatigue testing at the UiS lab facilities.

As a result of the study 3D CAD models of the test-specimens were acquired with the use of laser scanning tool “HandyScan 3D” combined with the Creaform CAD software.

This study investigates weld geometry requirements covered in standard AWSD1.1
On the basis of the standard requirements 3D models of reference weld geometry were modelled in Autodesk Inventor CAD application. One model for least material condition (LMC) and another for maximum material condition (MMC) weld profile. Later on the scanned meshes of specimens is compared with reference models resulting in virtual validation reports made in VXelements environment. Geometric tolerances of weld and the assembly are estimated and compared with the values measured during virtual validation.

General conclusion is that the scanned weld geometry of real specimens in every case exceeds the upper limits of allowable weld shape deviation. It is a safe approach from manufacturing side, however it does not provide an optimal fatigue resistant weld profile delivered by the AWSD1.1 standard.

1 Content

2 Acronyms:

AWS	American Welding Society
CAD	Computer Aided Design
CHS	Circular Hollow Section
CJP	Complete Joint Penetration (weld)
CNC	Computer Numerical Control
GD&T	Geometrical Dimensioning and Tolerances
GTAW	Gas Tungsten Arc Welding
HSE	Health Safety and Environment
LED	Light Emitting Diodes
LMC	Least Material Condition (in meaning of ASME Y14.5)
MPI	Magnetic Particle Inspection
NDT	Non Destructive Testing
PJP	Partial Joint Penetration (weld)
PPE	Personal Protective Equipment
RHS	Rectangular Hollow Section
SCF	Stress Concentration Factor
SI	Système international d'unités
SJA	Safe Job Analysis
UT	Ultrasonic Testing

3 Introduction

3.1 Safety

The laser scanning activities took part in Laboratory D-208. The laboratory room is locked for bystanders. Access by safety card is granted only for authorised students and personnel. This mitigates hazard of body injure by specimen or unintended use of laser. Painting booth when used has an ability to lock the doors.

Before commencing the specimens scanning I prepared a SJA (Safe Job Analysis) see Appendix A.

The biggest hazard recognized is activity of handling the test specimen, as it is heavy and there is a potential danger of crushing fingers or toes. The preventive measures taken were PPE as safety shoes and gloves, the specimens were also secured to carriage before transportation.

Figure 1 Method of securing the load - specimens - during transportation on cart. Cargo strap and rachet are used to tie the tubulars tight and prevent them from falling out.

3.2 Stress distribution in welded tubular joints - introduction

Welded tubular joints are widely used in industrial construction, handling cranes, bridges, piping, platforms and especially maritime structures for the offshore oil industry purposes [V]. The tubular sections have inherent properties of minimizing the hydrodynamic forces, and possess high torsional rigidity and higher strength to weight ratio compared to the any other steel sections as well as a better resistance for buckling [VI].

A tubular joint is refereed to connection between two or more tubular sections. For a tubular joint of two pipes of different diameters, the larger diameter pipe is named the **chord** and the smaller one is called the **brace** [VI].

These assemblies are formed by welding the extremities of one or more braces on the side of the chord. Tubular joints are subjects to constant multi-axial loadings, i.e. combined axial force, in-plane bending (IPB) and out-of-plane bending (OPB) caused by dynamic forces of wind, flow, waves or seismic activity. Such loadings induce a large number of stress cycles causing damage by elastic fatigue [VII].

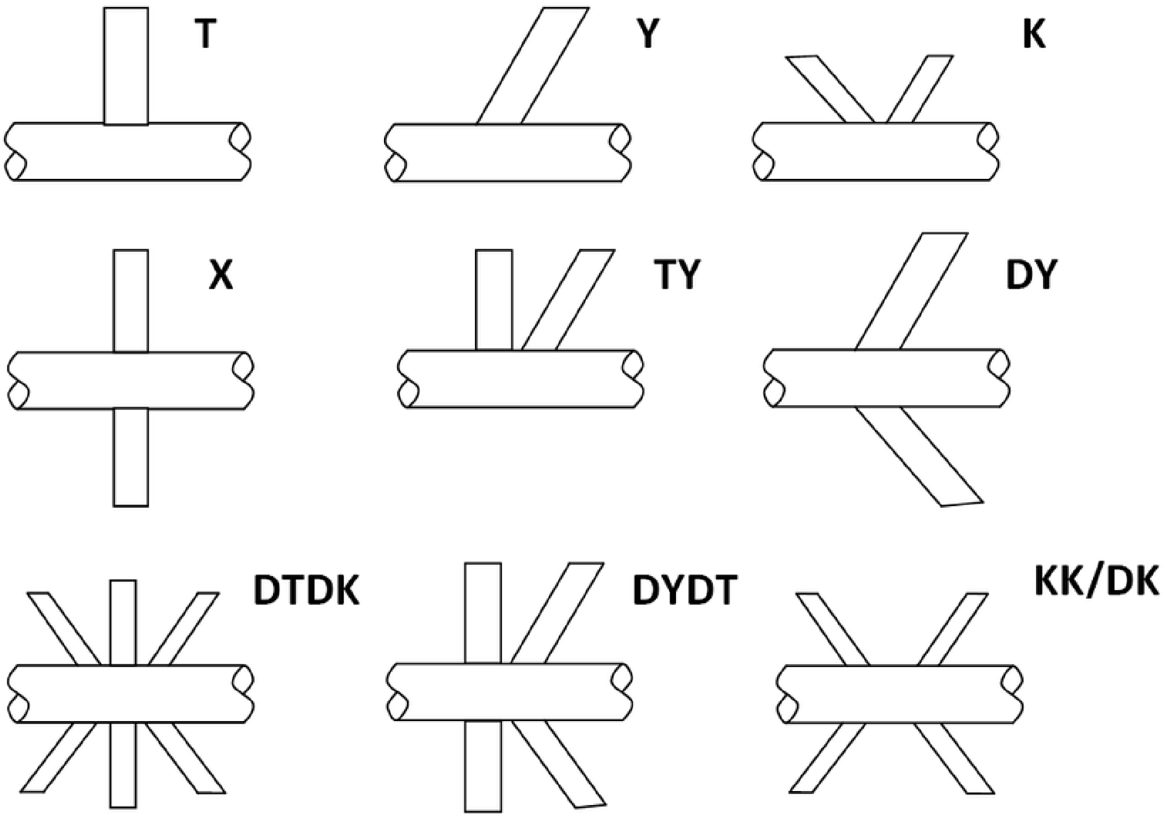


Figure 2 Various types of tubular joints classified according to their shape [VI]

The stress distribution is typically given by the stress concentration factors SCF. According to [XV] the concentration of efforts can result in a maximum stress at the intersection as high as 20 times the nominal force acting in the members.

Definitions:

Geometric Stress:
"*Geometric stress also known as the hot-spot stress/structural stress, is used to calculate the fatigue life of a tubular/non-tubular joints. Due to the difference in deformations between the brace and chord member of a joint, the tube wall tries to bend to maintain the compatibility and therefore, giving rise to geometric stress. This also results in the distribution of the membrane stress*" [VI].

Local Stress:
"*Local stress is caused mainly due to the local notch of the weld toe. It is a function of weld geometry and size. Thus, local stress is mainly dependent on the quality of welding and workmanship and it is quite difficult to incorporate such effects into formulation of stress concentration*" [VI].

This thesis focuses on T-joint connection defined by standard [I] as single side joint of a brace with its main axis inside a 10º tolerance cone from vertical position. Note that this is **not** a definition of manufacturing tolerance range for an angle.

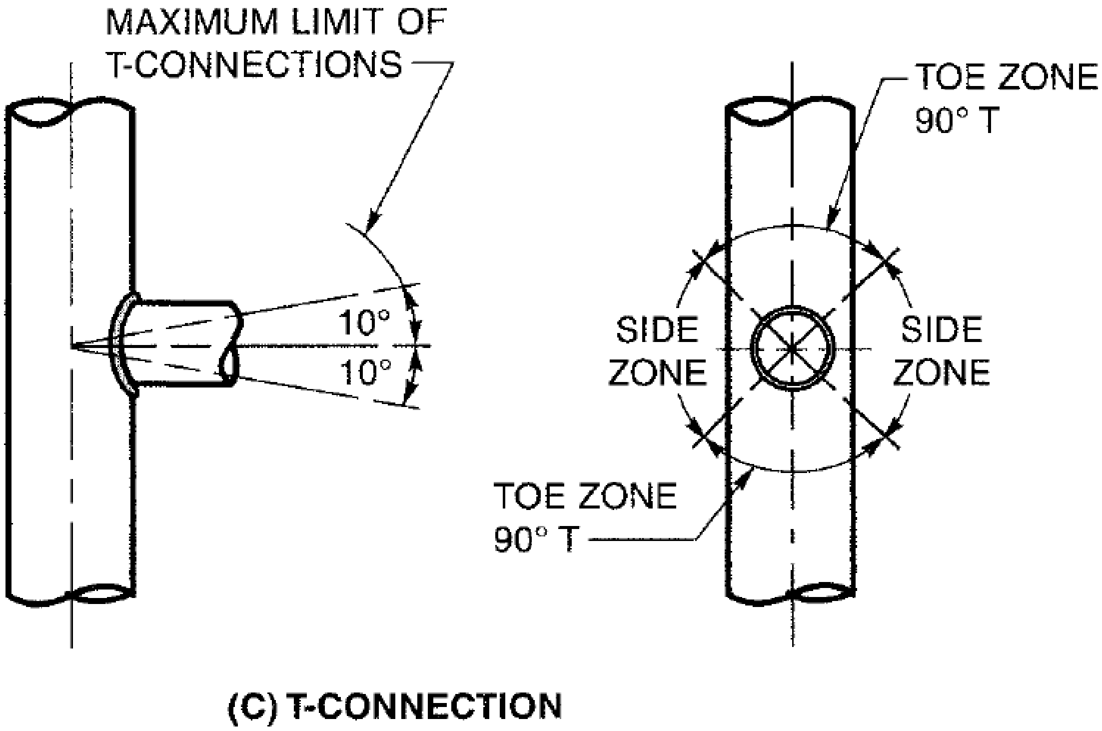


Figure 3 T-connection as defined in AWSD1.1 2010 [I], (figure 2.14)

3.3 Why is this study important:

Several studies have been devoted to determine, how the stress is distributed close to the intersections lines of tubular elements and where the high stress concentrations areas (hot zones) are located [VII].

It may be noted that the local peak stresses are highly influenced by the weld profile [VI].
The hot-spots are the locations at a welded joint where the initiation of cracks is possible under cyclic loading due to increased stress value.

This thesis is a part of larger programme of study offshore welds. Its deliverable is to provide standard acceptance for 3D weld profile and analyse of manufactured specimens weld geometry.

4 Methods

4.1 Specimen

There are 7 specimens of the same design.
They were manufactured by: RPT Production AS, Orstadveien 114, 4353 Klepp St.

Short description:
Half meter tubular section of 114,3 mm diameter (a brace) is orthogonally welded in the middle of 1.3 m tubular of 219,1 mm diameter (a chord). Wall thickness of both items are 8 mm. Tubulars are blinded with round flat bonnets fillet welded externally.
The design is intended to mimic a typical joint oof an offshore structure for test purposes.

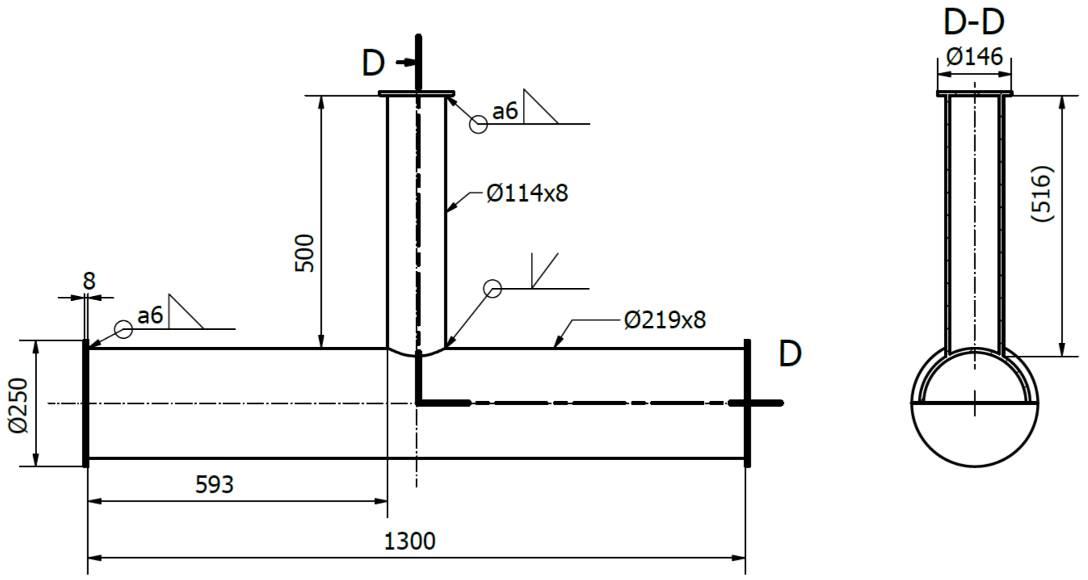


Figure 4 Specimen manufacturing drawing [intellectual property of UiS]

4.2 Serial numbers:

In this entire document reference will be made to scanning sequence number # instead of a full serial number for convenience, the order of scanning was casual.

Table 1 Cross reference table for specimen Serial numbers: and scanning sequence number

Scanning sequence number	Specimen Serial number
#1	S31655-4000-T-03
#2	S21655-4000-T-04
#3	S31655-4000-T-05
#4	S31655-4000-T-01
#5	S31655-4000-T-06
#6	S31655-4000-T-02
#7	S31655-4000-T-07

4.3 Construction material

The S355 is a non-alloy European standard structural steel, most commonly used after S235 where more strength is needed. It got great weldability and machinability. it is an excellent choice for delivering critical components or major structural members [X].

The standard (EN 10025-2) is applicable to steels for offshore structures, designed to operate in the offshore sector however excluding fabrication of subsea pipelines, risers, process equipment, process piping, and other utilities. It is primarily applicable to the North Sea Sector, but can be easily applicable in other areas provided that due consideration is given to local conditions e.g. temperature [XI].

Table 2 Material traceability list [based on internal UiS document FABRICATION RECORD BOOK, Client`s Po No : 312002444, RPT Order No : 31655.SJ – FRB]

Item	Raw material used
a	Pipe Ø 219.1 x 8.2 SCH 40 355 G 14+N
b	Pipe Ø 114.3 x 8.6 SCH 80 355 G 14+N
c	Plate 8 mm VV PL S355J2+N (for type 4000-T)

The steel S355 is named after its minimum yield strength of 355 MPa (N/mm^2). It is worth to be noticed that the yield strength reduces when you go up in thickness above 16 mm for flat products & hollow sections [XII].

According to material standard EN 10225 the Grade S355G14+N

End plates are manufactured of S355 J2+N

"S" stands for Structural,
"(+N)" stands for is normalized formed,
"J2" relates to the minimum impact energy value is 27 J at -20ºC,
"G14" relates to material toughness and indicates steel for offshore use.

The specimen overall dimensions:
1300 mm x 750 mm x 250 mm

4.4 Manufacturing specification

General Notes from manufacturing drawing

1. All steelwork fabrication, inspection and testing shall generally be in accordance with DNV OS-C401.
2. All welds shall be in accordance with DNV OS-C401 approved welding procedure.
3. All structural welds shall be continuous.
4. All tubular joints shall be framed to a common work point at the intersection of the tubular centrelines

5. The following non-destructive testing requirements shall apply to all welded joints at brace-chord intersections:
    a. 100 % VISUAL,
    b. 100 % MPI,
    c. 100 % UT
6. Acceptance criteria for NDT shall be in accordance with DNV OS-C401

4.5 Welding method

The weld between tubulars of our specimen was done using **Gas Tungsten Arc Welding.** Arc welding is one type of fusion welding process where an electric arc is used to supply heat for fusing the faying surfaces of the base materials that are to be joined. In order to weld wide variety of materials in different fashions, there exist several arc welding processes, namely, shielded metal arc welding, gas metal arc welding, gas tungsten arc welding, submerged arc welding, flux cored arc welding, submerged arc welding, stud arc welding, carbon arc welding, etc.

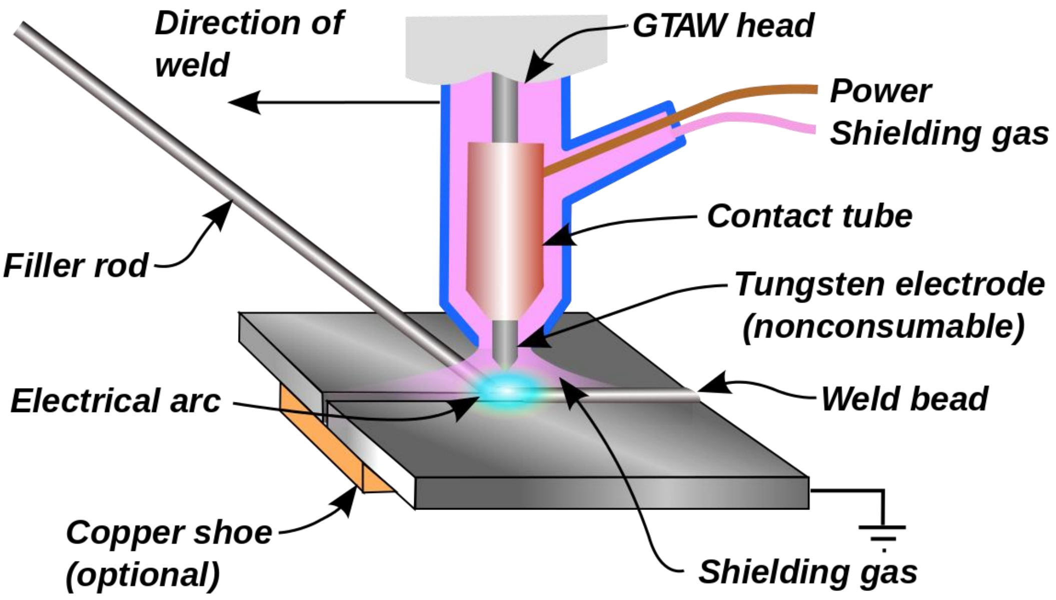


Figure 5 GTAW welding process scheme.

Gas Tungsten Arc Welding **(GTAW),** is known also as Tungsten Inert Gas **(TIG)** welding. In this process an electric arc is established between a non-consumable electrode and the base metals. The welding electrode is made of tungsten (W) usually with some alloying elements. Electrode material is the same regardless of the composition of the base metals joined. The electrode is non-consumable and flux is not required here. The filler metal is supplied additionally by feeding a separate filler rod. An autogenous mode, i.e. joining without using filler metal is possible for TIG. Important part of this technique is inert gas supplied at the welding zone for shielding purpose such as argon, hydrogen, or helium- see Figure 5. TIG welding can be manual or semi-automatic. The advantage of process is lack of spatter formation. TIG welding can offer defect-free sound welding with good weld bead appearance requiring minimum effort [XVI].

4.6 Welding related definitions:

Definitions:

PJP
Groove welds without steel backing, welded from one side, and groove welds welded from both sides, but without backgouging, are considered partial joint penetration groove welds [I, dictionary].

CJP
Complete joint penetration groove weld; A groove weld which has been made from both sides or from one side on a backing having complete penetration and fusion of weld and base metal throughout the depth of the joint.
A complete penetration tubular groove weld made from one side only, without backing, is permitted where the size or configuration, or both, prevent access to the root side of the weld. This is our specimen case [I, dictionary].

Backgouging
The removal of weld metal and base metal from the weld root side of a welded joint to facilitate complete fusion and complete joint penetration upon subsequent welding from that side [I, dictionary].

4.7 Applicable Standards

Table 3 Applicable standards referred in this document

Code	**Title**	**Area**
AWSD1.1	An American National Standard, Structural Welding Code- Steel.	Welding Specification The primary standard used for this thesis
DNV-OS-406	OFFSHORE STANDARDS Fabrication and testing of offshore structures	Offshore structures fabrication
ASME Y14.5	Geometric Dimensioning and Tolerancing, GD&T	Drafting and tolerances
ISO-2553-2019	Welding and allied processes - Symbolic representation on drawings - Welded joints, fifth edition.	Weld symbols on drawings
EN 10225	Weldable structural steels for fixed offshore structures - Technical delivery conditions	Carbon steel products for offshore

4.8 Focus on weld geometry

The weld symbols are in accordance with ISO-2553-2019 standard. The symbol depicts a single-bevel butt weld that is all around the joint between chord and a brace.

Butt welds are full penetration unless otherwise indicated by dimensions on the welding symbol or by reference to other information, for example the WPS [IX]. The WPS of RPT manufacturer does not call for partial penetration.

As defined by the AWSD1.1 standard, the dihedral angle Ψ is an important parameter used to determine the weld thickness.

For T-connection such with our specimens, the local stresses at potential surface of failure through the chord wall may limit the usable strength of the welded joint.
Tubular joints in offshore steel jacket structures are susceptible to fatigue damage being subjected to cyclic wave loading. The number of loading cycles that the structure is able to sustain can be estimated from the corresponding hot-spot stress (HSS) range. The hot-spot stress range can be found using a parameter called the stress concentration factor (SCF). The SCF are the ratio of each maximum geometric stress divided by the maximum nominal stress measured on the braces. The stress distribution along the weld toe for tubular joints is mainly determined by the joint geometry. Usually fatigue induced surface crack initiates from the position of the hot-spot stress [V].

5 Theoretical introduction into Scanning

In a case when there is a very high number of required surface or comparison points to measure on the part, for instance when a surface profile GD&T is required on a part using a high density of measured data points. In this situation, it can be time consuming to use conventional probing devices; scanning technologies should be prioritized. Indeed, 3D scanners help to measure a very high amount of data in a very effective way.

Once the position of object and the scanner have been located with targets, the surface acquisition is completed through the camera. The camera sees, projected on the surface, these two laser lines crossing each other. When the surface is swept over by the laser, data is recorded based on the triangulated position. The output file format is a STL file [VIII].

5.1 Operating principles of optical 3d measuring systems

The configuration of optical 3D measuring systems consists of two or three high frequencies cameras acquiring images simultaneously, to obtain different views on a scene. These systems, make it possible to directly measure or track optical reflectors using triangulation because the distance(s) between the sensors is constant and already known ('Baseline' at Figure 6).
Triangulation is a process of determining the location of a point by measuring angles to it from known points. These points are ends of a fixed baseline. The point can then be found as the third vertex of a triangle with two known angles one known side (the baseline).

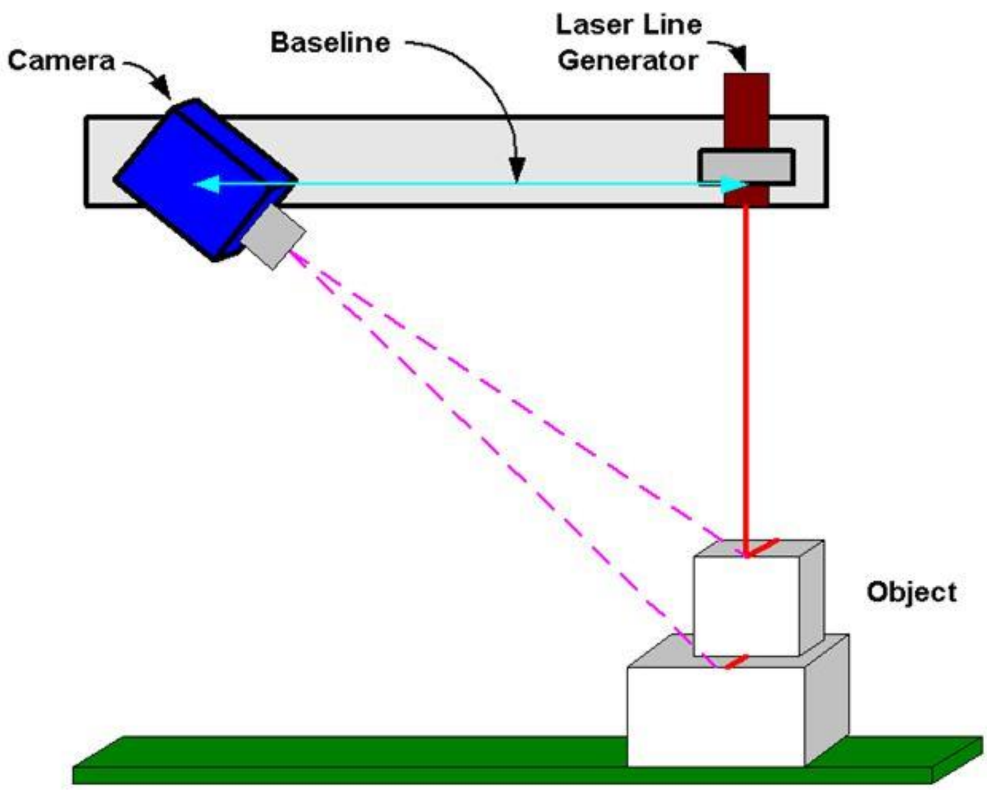


Figure 6 Basic rules of triangulation for a laser scanner [XVII].

5.2 Non-contact technologies (3d scanning)

A 3D scanner is a device analysing a real-world object in order to capture its shape. The collected data is then converted to a digital 3D model. The 3D scanners are mostly used for industrial design, reverse engineering, and prototyping. Also Quality Control (QC) applications require the use of such devices for inspections. Any physical contact on a scanned part is need what is a great advantage in many cases.

Also, applications requiring a high density of measurement data, such as when a surface profile GD&T needs to be computed, should make use of 3D scanners as they allow the measuring of a very high amount of data in a very effective way.

5.3 Metrology software

The main purpose of metrology software is to provide the user with a useful tool to manage the inspection sequence. It also acts as a platform with which measurement data is taken and managed and operations are performed to efficiently report on desired elements.

Whatsoever, some metrology software includes useful tools for reverse engineering applications, such as CAD reconstruction from raw polygonal models. Metrology software generally offers very useful means to manipulate 3D models, particularly regarding the extraction methods of feature types on CAD or polygonal models. Most of the available metrology software on the market perform basic and advanced GD&T calculations. In addition, solutions also use several alignment techniques with powerful

algorithms, which enables users to quickly superimpose data measurements with a reference object and perform comparisons. It is also very convenient and efficient to report the desired elements resulting from an inspection using most types of metrology software.

Typically, an inspection report includes tables of features and comparison points that display tolerances and deviations, along with snapshots, to be able to locate the elements of the tables on the part [III].

5.4 Quality Check and Inspection

The first step of the workflow of any QC process is to understand the main objective of the inspection. In other words: what needs to be measured and why. It is often very important to understand the functional purpose of a part and its main features, particularly if the part is used in a manufacturing process or being manufactured, to make good decisions before undertaking the inspection.

The inspection might require the loading of a 3D CAD model in the inspection program of the metrology software to act as a reference object. For instance, this is necessary when profile or location GD&Ts are required. Indeed, the resulting measured zones, to be compared with the given tolerance zones, are computed by the metrology software with algorithms that use a reference object from a 3D model. Also, importing a CAD is necessary when comparison points have to be used. This is important, for instance, when comparing the deviation between the real part and the CAD in a given alignment—and at specific individual locations on the part. Moreover, some alignment types that use a reference object require a 3D model, such as alignments of type “best-fit.”

It is preferred, for inspections using a 3D CAD model, to load it in a CAD or metrology software at the early stage of preparation, before the inspection is undertaken, to validate its content and ensure it can be used adequately to perform the measurements.

6 Experiments

The following chapter is a report based on a log on scanning activities. With an engineering approach some challenges are indicated, process modifications were tested and some interesting observations made.

6.1 The scanner

The HandySCAN 3D scanner comes with VXelements™, a fully integrated 3D software platform, that powers out entire fleet of 3D scanning and measurement technologies. It gathers all the essential elements and tools into a user-friendly, simplified and sleek working environment. Its real-time visualization provides a simple, enjoyable scanning experience.

The device available at UiS laboratory is HandySCAN700 manufactured by
Creaform Inc. 5825, rue Saint-Georges Lévis, Québec G6V 4L2 Canada
Scanner serial no.:661270.

Figure 7 The scanner head connected to CPU and external power source.

An optimized scan file is automatically created and available upon completion of the data acquisition step, which contributes to greatly shorten your part inspection or design process [XX].

	HandySCAN 300™	HandySCAN 700™
WEIGHT	0.85 kg (1.9 lb)	
DIMENSIONS (LxWxH)	77 x 122 x 294 mm (3.0 x 4.8 x 11.6 in)	
MEASUREMENT RATE	205,000 measurements/s	480,000 measurements/s
SCANNING AREA	225 x 250 mm (8.8 x 9.8 in)	275 x 250 mm (10.8 x 9.8 in)
LIGHT SOURCE	3 laser crosses	7 laser crosses (+1 extra line)
LASER CLASS	2M (eye-safe)	
RESOLUTION	0.100 mm (0.0039 in)	0.050 mm (0.0020 in)
ACCURACY	Up to 0.040 mm (0.0016 in)	Up to 0.030 mm (0.0012 in)
VOLUMETRIC ACCURACY	0.020 mm + 0.100 mm/m (0.0008 in + 0.0012 in/ft)	0.020 mm + 0.060 mm/m (0.0008 in + 0.0007 in/ft)
VOLUMETRIC ACCURACY WITH MaxSHOT Next™	0.020 mm + 0.025 mm/m (0.0008 in + 0.0003 in/ft)	
VOLUMETRIC ACCURACY WITH MaxSHOT Next™|Elite	0.020 mm + 0.015 mm/m (0.0008 in + 0.00018 in/ft)	
STAND-OFF DISTANCE	300 mm (11.8 in)	
DEPTH OF FIELD	250 mm (9.8 in)	
PART SIZE RANGE (RECOMMENDED)	0.1–4 m (0.3–13 ft)	
SOFTWARE	VXelements	
OUTPUT FORMATS	.dae, .fbx, .ma, .obj, .ply, .stl, .txt, .wrl, .x3d, .x3dz, .zpr	
COMPATIBLE SOFTWARE	3D Systems (Geomagic® Solutions), InnovMetric Software (PolyWorks), Dassault Systèmes (CATIA V5 and SolidWorks), PTC (Pro/ENGINEER), Siemens (NX and Solid Edge), Autodesk (Inventor, Alias, 3ds Max, Maya, Softimage).	
CONNECTION STANDARD	1 X USB 3.0	
OPERATING TEMPERATURE RANGE	5-40°C (41-104°F)	
OPERATING HUMIDITY RANGE (NON-CONDENSING)	10 - 90%	
CERTIFICATIONS	EC Compliance (Electromagnetic Compatibility Directive, Low Voltage Directive), IP50, WEEE	

Figure 8 HandySCAN Dataset [XX]

Self-positioning: It uses triangulation on optical reflectors to determine its relative position to the part.

6.2 General scanning session observations

Usually a first action to take on a measuring device is its Calibration. Calibration is made using a known reference, like the calibration glass plate available in the scanner set (Figure 9). Even under normal use, the HandySCAN 3D must be calibrated on a regular basis, typically that is the temperature what affects readings most [VIII].

Figure 9 The calibration board - this equipment is delivered with the set of laser

VXelements™ software optimizes the calibration in order to get back to the initial measuring features. The calibration procedure consists in bringing the scanner to the positions highlighted by the green shadow, see Figure 10, while keeping the laser cross displayed in the white of the calibration plate. The actual position of the scanner is shown in grey colour (Figure 10) [VIII].

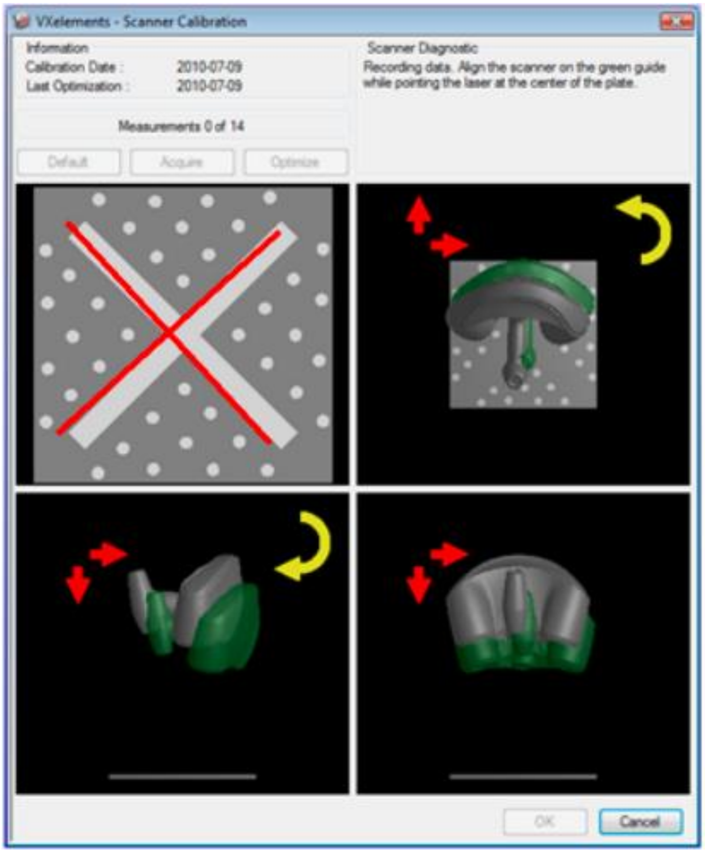


Figure 10 Representation of the calibration procedure

Laser has LED indicating a correct distance of the lens from surface – indicated by green colour. Red means the surface is too close when blue colour means surface is too far for efficient scanning. Scanner projects red thin lines mesh on the surface scanned area (visible on Figure 11 as a ‘pink haze’). Keeping a stable distance in the ‘green’ range requires some experience and good motor skills.

It was found subjectively easier to follow the modelled surface displayed in real-time on the monitor when handling the laser head. Once the surface is not being drawn a correction of distance is needed. Real time generated model enables to quick find poorly gathered surfaces like discontinuities, gaps, holes in mesh or ‘dead targets’(targets that are not contrasting enough to keep being distinguished from the surface). It helps to keep reference tracking too.

Figure 11 A first attempt to scanning the specimen. Green pyramid on the top helps to initiate scanning with its dense targets pattern. It was also used for size references and quick scanner/application checks.

6.3 Spray paint

The system appears to be sensitive to the surface colour and on texture too. It must be caused by different abilities to laser light reflection by a surface.
The surface of specimen is diverse, multi-coloured from white and blue markings through shiny steel surface to multicolour rust tones from bright yellow and orange up to dark brown. The rusted surface is visibly matte, it diffuses light less than the not corroded steel surface. See Figure 13.

The laser acquires very well the white areas of marking (original pipe manufacturer white painted letters all long the specimen #1). It works well on a healthy steel surface. I have not encountered any issues with glare from a shiny surface.
It works actually poor on a corroded, dark stains, they are usually interpreted as discontinuities (holes) in the surface of generated model.
The scanner cannot see blue surface. Some straight lines are painted on the smaller diameter tubular (looking like the manufacturer marking)

Solution in use is a dedicated white flat spray paint. It is odourless, nontoxic* and the coat disappear (sublimates) in several minutes. This feature is an disadvantage as it limits the measurement time.

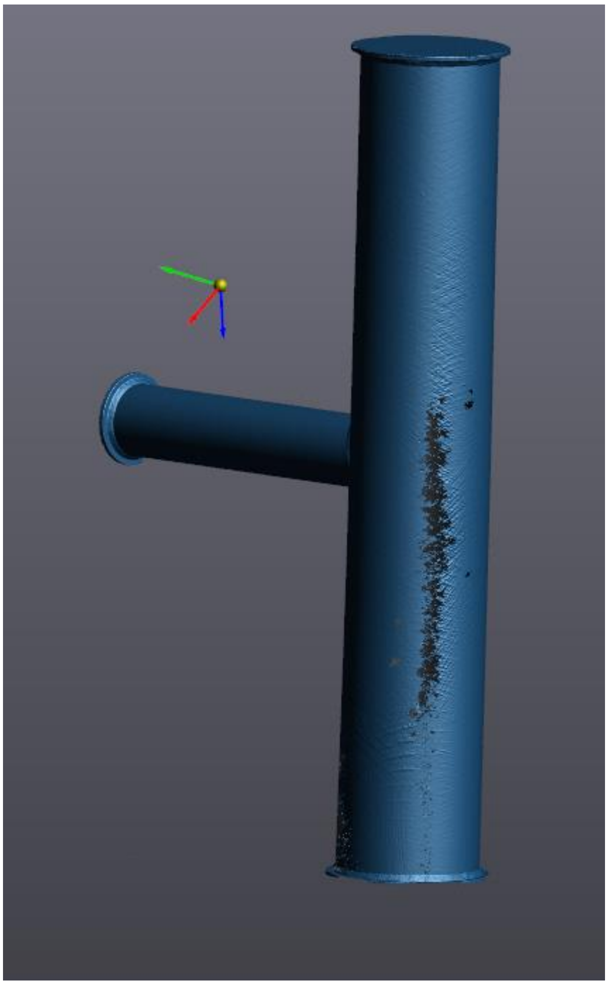


Figure 12 The mesh of specimen number 2 with a huge portion of missing surface. There was a blue paint stain in this position on the real specimen.

The visible long gap in surface is an effect of blue paint on the specimen, please compare Figure 12 with Figure 13. The area was ignored by scanner reading despite covering with generous portion of temporary spray.

Figure 13 Not painted specimen. Visible the targets for reference patterns, stains, manufacturer markings and numbers of different colours - making difficulties on surface gathering.

The paint used is AESAN Blue manufactured by ‘Scanningspray Vertriebs GmbH’.

Relevant hazard statements [XXIII]:

- H222 Extremely flammable aerosol.
- H229 Pressurised container: May burst if heated.
- H336 May cause drowsiness or dizziness.
- H412 Harmful to aquatic life with long lasting effects

The uniform white surface is acquired quick and seamlessly, I cannot of course provide any quantitative description on that.

6.4 Lighting

As stated in manual, the Infrared light-emitting diodes are seen by the camera(s) through filters providing resilience to ambient lighting [VIII]. Based on that factors such lighting intensity in the lab cannot differentiate the measurement results. However a proper lighting condition has a major impact on the operator (me): First I scanned at daylight of a cloudy day in the laboratory and then at paint booth with an appropriate artificial radiation what was not without an impact on the activity effectiveness.

6.5 Targets

The HandySCAN 3D is positioned relatively to the object with reflective targets. These targets (sometime called markers) should be positioned in an organized fashion in order to ensure that the surface is free of blank spots and that the scanner will be well positioned all time. This is true even if randomization is necessary to create unique feature patterns [VIII].

The reference targets are very important for the result. Sticky paper dots are of 8 mm diameter, black circle with white ring outside. Targets are manually attached to the specimen after painting. The targets recycling is limited. A dot covered with white paint is not recognised by laser, it is interpreted as the scanned surface. Even a thin layer of paint on a fragmentary surface of black circle makes the marker useless (invisible for scanner). Therefore it is important to remove all the remaining targets before painting the specimen again.
There need to be 3 targets [VIII] in the current scanning area to let the application continuously acquire the surface points. Interruptions and missing the reference are common for unskilled operators. Then it is need to return to the previous 'known' (recognized) pattern to continue scanning. It was noticed the density of the targets per area were not sufficient.

It was tested that targets of smaller black dot diameter (4mm) were not recognized by the scanner, hence they could not be used.

The following rules are recommended by Creaform (the scanner supplier) at targets application [VIII]:

- Average distance between targets: from 2 to 10 cm (0.7 to 4 in).
- Shorten the distance between targets on high-curvature areas.
- Avoid damaged, greasy, dusty, dirty or hidden targets.
- Avoid to align targets too perfectly (doesn't allow proper triangulation).
- Do not put targets close to edges and/or detailed areas: >5mm (0.2 in) from the edge.
- Apply a regular density of targets; do not create isolated groups of targets.
- Triangulation implies at least 3 targets seen at once: the targets pattern needs to take this parameter into consideration.

Observation:
It used to be difficult to obtain scan of flat surfaces at the tubular ends. That was due to their perpendicularity to the cylindrical surfaces covered with targets. In laser head position facing the end plate the reference pattern was usually not seen in scanning area. Attaching the targets on edges (of end caps) facilitates smoother transition of scanned surfaces. It is not

recommended practice as the stickers disturbs the edge curve, but this edge is not a focus of the experiment.

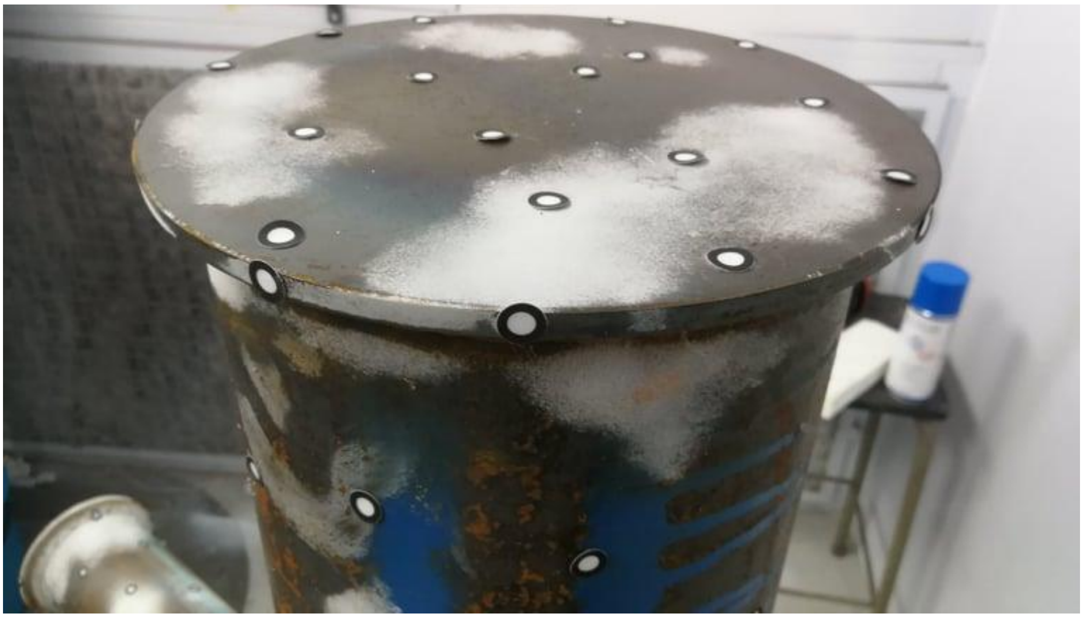


Figure 14 Attaching targets on edges of top plate enables smooth transition of scanned surfaces.

6.6 Process modifications applied to scanning sessions

Modification #1:

A plywood pad with a dense targets pattern added under the specimen. This was for two reasons:

- Adhesive targets are difficult to be removed from the laboratory lino floor.
- Dense targets pattern under specimen facilitates scanner position recognition.
-

Result:

Both the objectives were met.

Modification #2

More contrast paint was sprayed on specimen comparing to previous session. Approximately 1 (one) can per one specimen.

Result::

The AESUB spray is not able to cover the original white or blue paint on the steel tubular to the level where the surface is visually homogeneous. Extensive use of spray was not only irritating for the other laboratory workers but was found not effective too. There still remains a few stains interpreted as discontinuities of surface.

Figure 15 Specimen #1 painted white. The manufacturer markings are still visible under the AESUB coat.

<u>Modification #3:</u>

I tested the density of targets pattern influence on the scanner position recognition. I expected the denser pattern (the targets closer each other) will enable smoother transition of scanned surface. The distances are close to these recommended by Creaform.

Tabell 1 Targets pattern density test

Specimen number	**Average distance between closest targets**	**Distances dispersion [mm] (tolerance 10mm)**
#1	105	80-130
#2	70	60-80
#3	90	80-100

Result:

The effect was perceptible. However, placing targets reveals to be the most time taking task of specimen preparation. Moreover the duration of contrast spray paint persistence is limited (circa 20-30 minutes from application) and the positive effect of higher number of targets was dismissed by vanishing contrast.

Figure 16 Specimen #2 with concentrated targets count on surface. Average distance 6cm.

6.7 Scanning in dedicated paint booth

Scanning took place in a dedicated paint booth at UiS campus workshop. The new premise provides far better lighting and - what was the direct reason for changing location - mechanical ventilation. However the available space in paint booth is limited.
Mechanical ventilation and heating in the painting booth (temperature set to 25ºC) causes quicker vaporisation of the contrast spray paint (approximately 20 minutes). Despite moderate time to attach targets on specimens #6 and #7 the coat disappeared on some, painted earliest areas and re-applying was needed before continuation of scanning.

Figure 17 Specimen #5 in the university paint booth before preparation (paint and targets). The main mechanical ventilation inlet filters visible in the background.

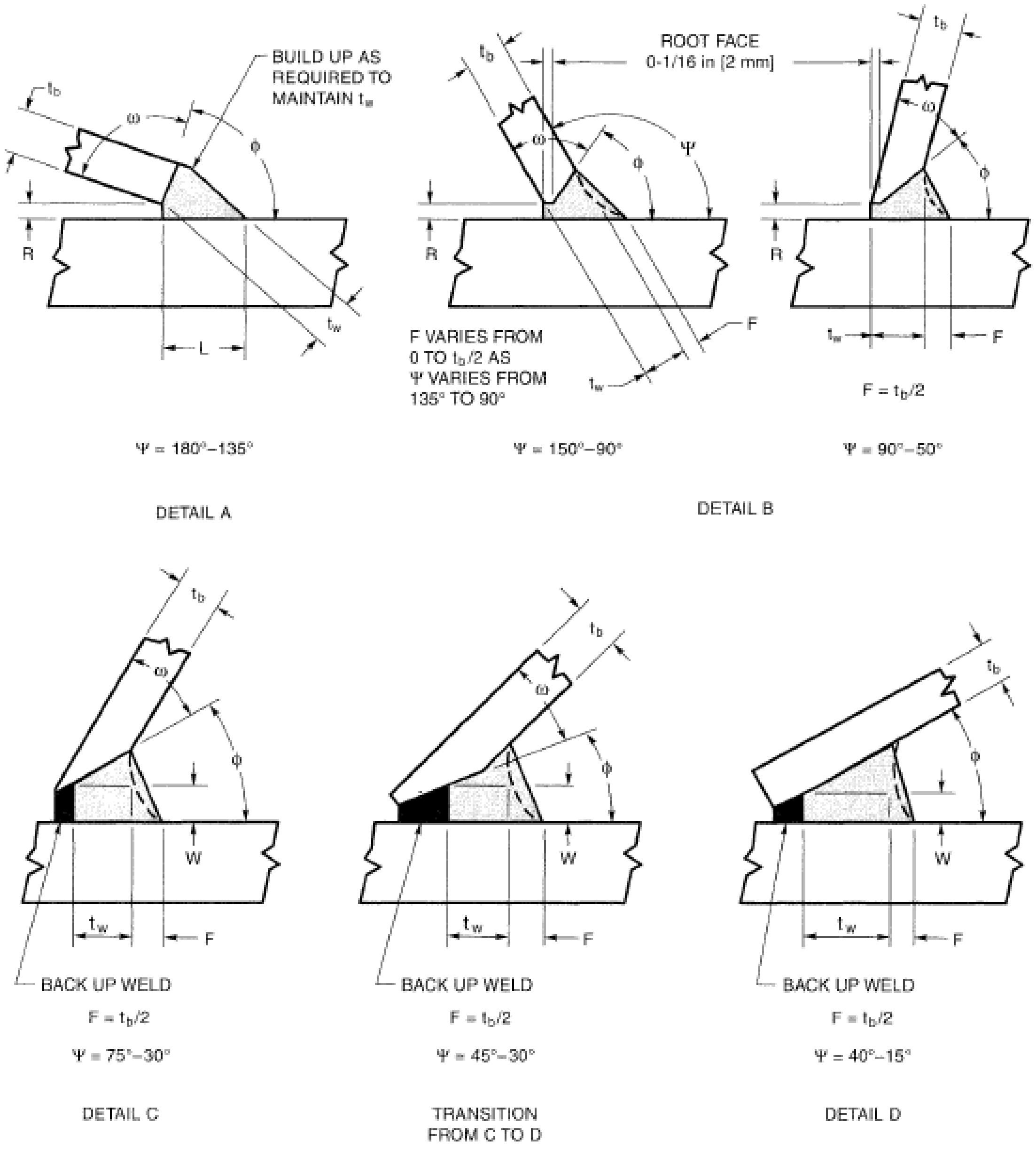
6.8 End conclusion after scanning

The most interesting for this thesis surface of weld is gathered well. There is no excessive rust or contamination stains in this area. Moreover due to shape of specimen, the main weld sew is easily accessible by laser operator.

Figure 18 Special attention was paid on scanning the weld surrounding. Mesh is not interrupted in this area.

7 Weld profile geometry according to AWSD1.1

The detail B on Figure 57 clearly specifies dimensioning of pre-weld preparation shape (grinding typically) however the external geometry of weld is not given implicit. A concave is not clearly specified; a radius is acceptable as well as a straight transition – a chamfer. Let's look closer at the AWSD1.1 requirements:



Notes:
1. See Table 3.6 for dimensions t_w, L, R, W, ω, ϕ.
2. Minimum standard flat weld profile shall be as shown by solid line.
3. A concave profile, as shown by dashed lines, shall also be applicable.
4. Convexity, overlap, etc. shall be subject to the limitations of 5.24.
5. Branch member thickness, t_b, shall be subject to limitations of 2.21.6.7.

Figure 19 AWSD1.1 2010 figure 3.8 Prequalified Joint Details for Complete Joint Penetration Groove Welds in Tubular T -, Y -, and K-Connections-Standard Flat Profiles for Limited Thickness.

As noted in Figure 19 “DETAIL B”, the location of the weld toe on the chord member along the tubular joint intersection is defined by the parameter “F” which varies in length from 0 to “$t_b/2$”as the dihedral angle Ψ varies from 135º to 90º, where “t_b” is the thickness of the brace member and in this analysis “t_b”=8 mm according to the tubulars specification.

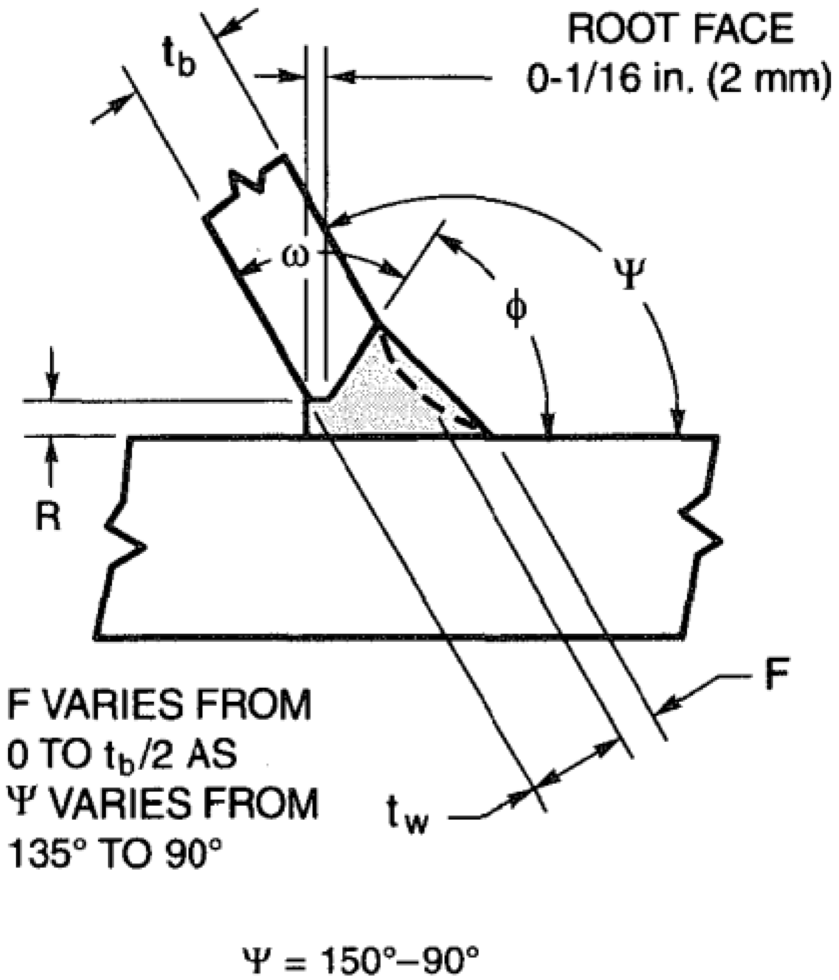


Figure 20 AWSD1-1 2010 [I] figure 3.8 Detail B adequate for the dihedral angle range on T-joint- Standard Flat Profiles for Limited Thickness

The dihedral angle Ψ is to be measured in a relevant sections. Its value of 90º at the crown is obvious in the main axis section, as shown in the manufacturing drawing main view - Figure 4. In any other point however a section of the cylindrical chord is ellipse. With a one special case for saddles section, when the ellipse is degenerated to a circle.

Table 4 Joint and grove dimensions requirements AWSD1.1 2010 [I] Table 3.6

Table 3.6
Prequalified Joint Dimensions and Groove Angles for Complete Joint Penetration Groove Welds in Tubular T-, Y-, and K-Connections Made by Shielded Metal Arc, Gas Metal Arc (Short Circuiting Transfer)[3] and Flux Cored Arc Welding (see 3.13.4)

		Detail A Ψ = 180° – 135°		Detail B Ψ = 150° – 50°		Detail C Ψ = 75° – 30°**	Detail D Ψ = 40° – 15°**
End preparation (ω)	max			90°*		*	
	min			10° or 45° for Ψ > 105°		10°	
Fit-up or root opening (R)		FCAW-S SMAW (1)	GMAW-S FCAW-G (2)	FCAW-S SMAW (1)	GMAW-S FCAW-G (2)	***	
	max	3/16 in. (5 mm)	3/16 in. (5 mm)	1/4 in. (6 mm)	1/4 in. (6 mm) for ϕ > 45° 5/16 in. (8 mm) for ϕ ≤ 45°	W max. / ϕ FCAW-S SMAW (1): 1/8 in. (3 mm) 25°–40° 3/16 in. (5 mm) 15°–25°	
	min	1/16 in. (2 mm) No min for ϕ > 90°	1/16 in. (2 mm) No min for ϕ > 120°	1/16 in. (2 mm)	1/16 in. (2 mm)	GMAW-S FCAW-G (2): 1/8 in. (3 mm) 30°–40° 1/4 in. (6 mm) 25°–30° 3/8 in. (10 mm) 20°–25° 1/2 in. (12 mm) 15°–20°	
Joint included angle ϕ	max	90°		60° for Ψ ≤ 105°		40°; if more use Detail B	
	min	45°		37-1/2°; if less use Detail C		1/2 Ψ	
Completed weld	t_w	≥ t_b		≥ t_b for Ψ > 90° ≥ t_b/sin Ψ for Ψ < 90°		≥ t_b/sin Ψ but need not exceed 1.75 t_b	≥ 2t_b
	L	≥ t_b/sin Ψ but need not exceed 1.75 t_b				Weld may be built up to meet this	

*Otherwise as needed to obtain required ϕ
**Not prequalified for groove angles (ϕ) under 30°
***Initial passes of back-up weld discounted until width of groove (W) is sufficient to assure sound welding; the necessary width of weld groove (W) provided by back-up weld

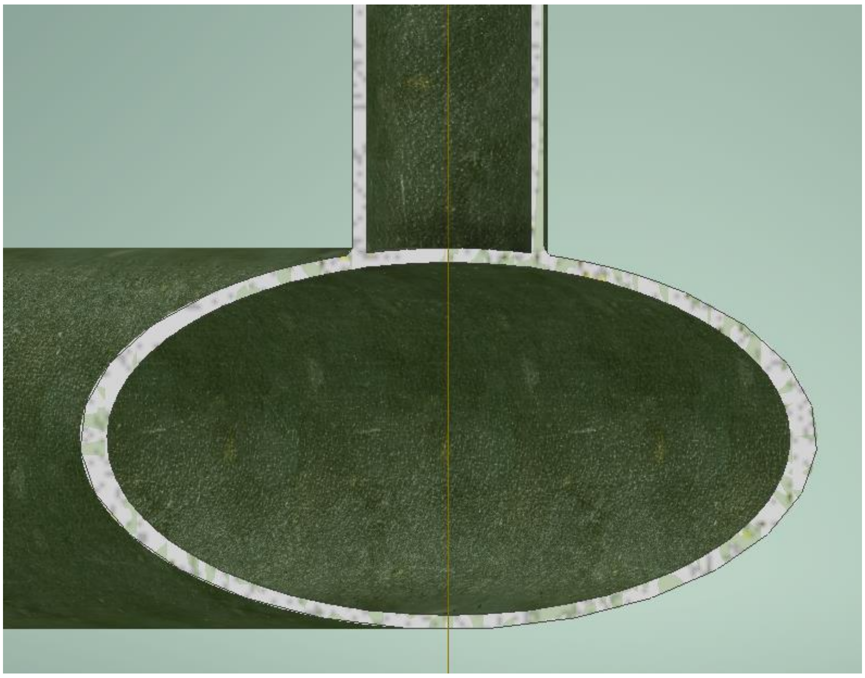


Figure 21 Any cross section of the chord containing the brace axis presents an ellipse. Example above is for γ=60°.

The minor axis of the ellipse is all the time diameter of chord 'M' where the major semi-axis length varies according to the below:

Equation 1

$$a = \frac{M}{sin\gamma}$$

a - major semi-axis, (where 'a' ∈<M ; ∞), hence it is not defined for $sin\gamma=0 \Leftrightarrow \gamma=0^o, 180^o$ i.e.: the function is not defined for crown points, however, the angle Ψ and size F is defined well according to [I] – see Figure 19. M is outer radius of the chord (Symbol 'M' is used to not be confused with 'R' standing for fit up or root opening as in Table 4, p30)

Where γ is an angle arbitrarily measured from the chord main axis – as indicated on Figure 22:

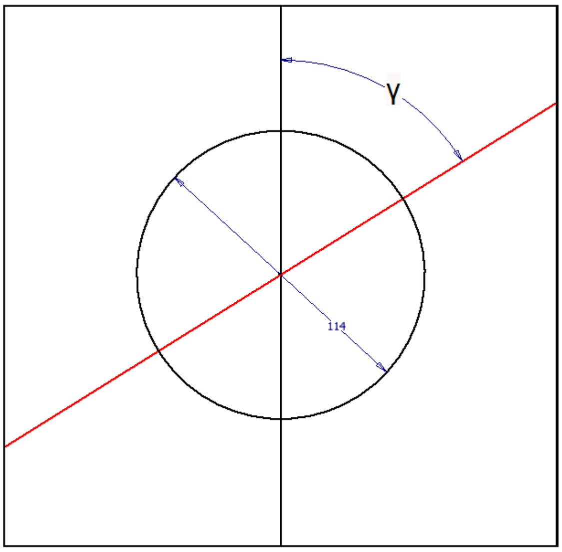


Figure 22 Top view on specimen brace showing the angle γ – a sketch

Note the radius 'r' of the brace is included in each sections defines as such and is constant. All the ellipse parameters vary on the angle γ:

a=mayor semi-axis length

b=minor semi axis length

Note the radius 'r' of the brace is included in each sections defines as such and is constant. All the ellipse parameters vary on the angle γ:

Equation 2

$$b=M=\text{const.}$$

c=focus distances from the centre of the ellipse

Equation 3

$$c = \sqrt{a^2 - b^2}$$

e=eccentricity

Equation 4

$$e = \frac{c}{a}$$

|PD1| and |PD2| are distances from the point of tangency to one of the ellipse 'directrix' D – vertical lines satisfying the Equation 5:

Equation 5

$$D = \frac{a^2}{c}$$

According to Figure 23 we see some geometrical dependencies:
Distance from a point of ellipse to any of its directrix is given be the below:

Equation 6

$$|PD_1| = \frac{a^2}{c} - r$$

Equation 7

$$|PD_2| = \frac{a^2}{c} + r$$

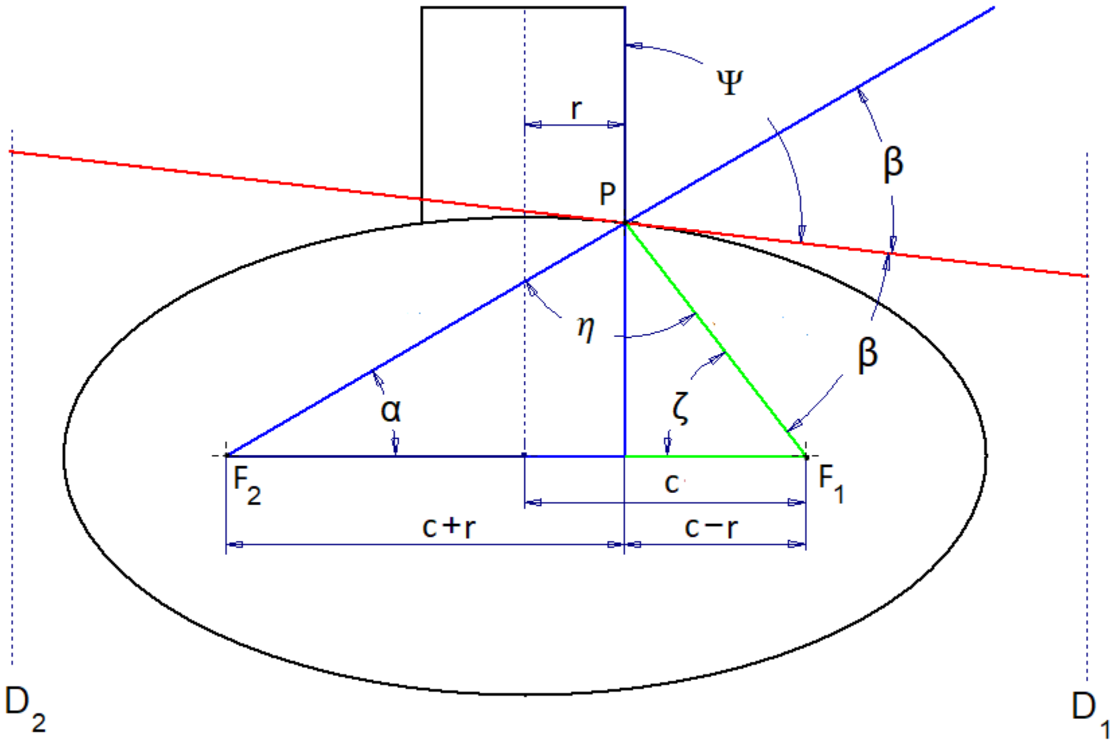


Figure 23 A sketch for calculation of dihedral angle in one of a considered cross sections.

The triangle sides |PF2| and |PF1| are distances from each of focus to the tangency point. They are given by definition [XIX] as:

Equation 8

$$|PF_1| = e|PD_1| = e \cdot \left(\frac{a^2}{c} - r\right) = \frac{c}{a} \cdot \left(\frac{a^2}{c} - r\right) = a - er$$

Equation 9

$$|PF_2| = e|PD_2| = e \cdot \left(\frac{a^2}{c} + r\right) = a + er$$

From the sketch (Figure 23) we can see also how the Ψ can be found:

Equation 10

$$\Psi = \pi - \left(\beta + \frac{\pi}{2} - \zeta\right)$$

Equation 11

$$\Psi = \frac{\pi}{2} - \beta + \zeta$$

Considering the theorem of ellipse tangent that the tangent bisects the supplementary angle of the angle between the lines to the foci we introduce the β as:

Equation 12

$$2\beta + \eta = \pi$$

Equation 13

$$\beta = \frac{\pi - \eta}{2}$$

We can express dependencies of angles in triangle as follows:

Equation 14

$$\alpha + \zeta + \eta = \pi$$

To find η:

Equation 15

$$\eta = \pi - \alpha - \zeta$$

The α and ζ values can be found knowing the two rectangular triangles dimensions:

Equation 16

$$\cos \alpha = \frac{c - r}{a - er}$$

Equation 17

$$\alpha = acos\left(\frac{c - r}{a - er}\right)$$

Equation 18

$$\cos \zeta = \frac{c + r}{a + er}$$

Equation 19

$$\zeta = acos\left(\frac{c + r}{a + er}\right)$$

Considering the equations Equation 11, Equation 13 and Equation 15:

Equation 20

$$\Psi = \frac{\pi}{2} + \zeta - \frac{\pi - \omega}{2}$$

Eventually the dihedral angle Ψ is found from an equation:

Equation 21

$$\Psi = 0.5(\zeta - \alpha) + \frac{\pi}{2}$$

For consistency we can deduct the Ψ=f(γ, r, R):

Equation 22

$$\Psi = 0.5\left(acos\left(\frac{c+r}{a+er}\right) - acos\left(\frac{c-r}{a-er}\right)\right) + \frac{\pi}{2}$$

Equation 23

$$\Psi = 0.5\left(acos\left(\frac{\sqrt{a^2-b^2}+r}{a+\frac{\sqrt{a^2-b^2}}{a}r}\right) - acos\left(\frac{\sqrt{a^2-b^2}-r}{a-\frac{\sqrt{a^2-b^2}}{a}r}\right)\right) + \frac{\pi}{2}$$

Remembering that $a = \frac{R}{sin\gamma}$ (The minor axis of the ellipse is all the time diameter of chord 'M' where the major semi-axis length varies according to the below:
Equation 1) & b=M we have:

a=mayor semi-axis length

b=minor semi axis length

Note the radius 'r' of the brace is included in each sections defines as such and is constant. All the ellipse parameters vary on the angle γ:

Equation 24

$$\Psi=0.5\left(\mathrm{acos}\left(\frac{\sqrt{\left(\frac{\mathrm{M}}{\sin\gamma}\right)^2-\mathrm{M}^2}+\mathrm{r}}{\frac{\mathrm{M}}{\sin\gamma}+\frac{\sqrt{\left(\frac{\mathrm{M}}{\sin\gamma}\right)^2-\mathrm{M}^2}}{\mathrm{M}}\mathrm{r}\cdot\sin\gamma}\right)-\mathrm{acos}\left(\frac{\sqrt{\left(\frac{\mathrm{M}}{\sin\gamma}\right)^2-\mathrm{M}^2}-\mathrm{r}}{\frac{\mathrm{M}}{\sin\gamma}-\frac{\sqrt{\left(\frac{\mathrm{M}}{\sin\gamma}\right)^2-\mathrm{M}^2}}{\mathrm{M}}\mathrm{r}\cdot\sin\gamma}\right)\right)+\frac{\pi}{2}$$

Equation 25

$$\Psi=0.5\left(\mathrm{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+\mathrm{r}}{\frac{\mathrm{M}}{\sin\gamma}+\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}}{\mathrm{M}}\mathrm{r}\cdot\sin\gamma}\right)-\mathrm{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}-\mathrm{r}}{\frac{\mathrm{M}}{\sin\gamma}-\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}}{\mathrm{M}}\mathrm{r}\cdot\sin\gamma}\right)\right)+\frac{\pi}{2}$$

Equation 26

$$\Psi=0.5\left(\mathrm{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+\mathrm{r}}{\frac{\mathrm{M}}{\sin\gamma}+\sqrt{1\text{-}sin^2\gamma}\cdot\mathrm{r}}\right)\text{-}\mathrm{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}\text{-}\mathrm{r}}{\frac{\mathrm{M}}{\sin\gamma}\text{-}\sqrt{1\text{-}sin^2\gamma}\cdot\mathrm{r}}\right)\right)+\frac{\pi}{2}$$

When populating numerical values [mm] and with angles value in degrees:

Equation 27

$$\Psi=0.5\left(\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+57.15}{\frac{109{,}55}{\sin\gamma}+57.15\sqrt{1\text{-}sin^2\gamma}}\right)\text{-}\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}\text{-}57.15}{\frac{109{,}55}{\sin\gamma}\text{-}57.15\sqrt{1\text{-}sin^2\gamma}}\right)\right)+90°$$

Minimum fillet weld size 'F' – as shown in Figure 19 - F varies in length from 0 to "$t_b/2$"as the dihedral angle Ψ varies from 135º to 90º [I]. As the standard [I] does not specify this relation any closer I hereby assume a linear function F(Ψ) expressed by Equation 28 for the Ψ angle (expressed in degrees). In other words F is normalized to fit control points at 90º and 135º (see the comment under Figure 20.)

Equation 28

$$F=\frac{t_b}{2}\cdot\left(\frac{135°-\Psi°}{135°-90°}\right)=\frac{t_b}{2}\cdot\frac{135°-\Psi°}{45°}$$

Equation 29

$$\mathrm{F}=\frac{t_b}{90°}\cdot\left(45°-0.5\left(\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+57.15}{\frac{109{,}55}{\sin\gamma}+57.15\sqrt{1\text{-}sin^2\gamma}}\right)\text{-}\mathrm{acos}\left(\frac{\frac{109{,}5}{\sin\gamma}5\sqrt{1\text{-}sin^2\gamma}\text{-}57.15}{\frac{109{,}55}{\sin\gamma}\text{-}57.15\sqrt{1\text{-}sin^2\gamma}}\right)\right)\right)$$

Equation 30

$$\mathrm{F}=\frac{t_b}{2}-\frac{t_b}{180°}\left(\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+57.15}{\frac{109{,}55}{\sin\gamma}+57.15\sqrt{1\text{-}sin^2\gamma}}\right)\text{-}\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}\text{-}57.15}{\frac{109{,}55}{\sin\gamma}\text{-}57.15\sqrt{1\text{-}sin^2\gamma}}\right)\right)$$

Equation 31

$$\mathrm{F}=4-\frac{2}{45°}\left(\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+57.15}{\frac{109{,}55}{\sin\gamma}+57.15\sqrt{1\text{-}sin^2\gamma}}\right)\text{-}\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}\text{-}57.15}{\frac{109{,}55}{\sin\gamma}\text{-}57.15\sqrt{1\text{-}sin^2\gamma}}\right)\right)$$

The above Equation 31 is then implemented to create 3D curve determining the weld boundary in space. It is described in

The toe length can be found from a straightforward trigonometry:

Equation 32

$$toe = \frac{F}{\sin\left(\pi - \Psi\right)}$$

Equation 33

$$toe = \frac{F}{\sin\Psi}$$

The result of computed calculations is shown in the table below:

Table 5 Computation results for dihedral angle Ψ and Minimum fillet weld size F

γ[º]	Ψ[º]	F[mm]
0	90,000	4,000
10	90,905	3,920
20	93,549	3,685
30	97,694	3,316
40	102,887	2,854
50	108,467	2,358
60	113,681	1,895
70	117,857	1,524
80	120,529	1,286
90	121,445	1,205
100	120,529	1,286
110	117,857	1,524
120	113,681	1,895
130	108,467	2,358
140	102,887	2,854
150	97,694	3,316
160	93,549	3,685
170	90,905	3,920
180	90,000	4,000

The results obtained for Ψ in Table 5 can be compared with positive results with the AWSD1.1 data, see Figure 24. The graph (Figure 22) confirms that for T-joint (θ =90º) and r/R ratio of 0.52 (our specimen case) the dihedral angle is in range of 90º to 120º.

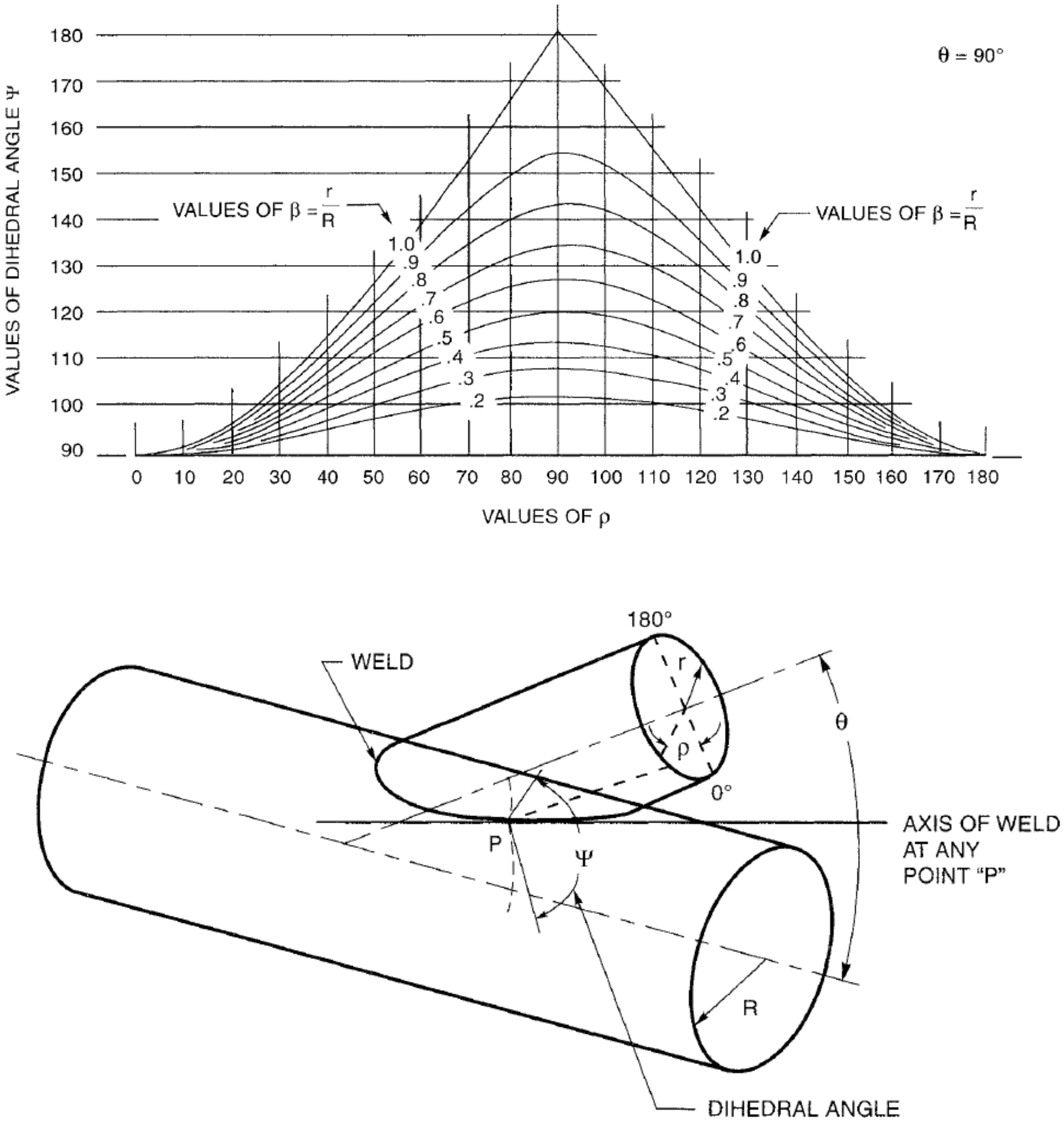


Figure 24 Local dihedral angle between crowns (0 and 180), saddle point is q=90. According to AWSD1-1 2020 informative Annex P. The graph confirms that for T-joint (θ=90) and r/R ratio of about 0.5 the dihedral angle is in range of 90° to120°.

3D model check also confirms the correctness of above algorithm used.

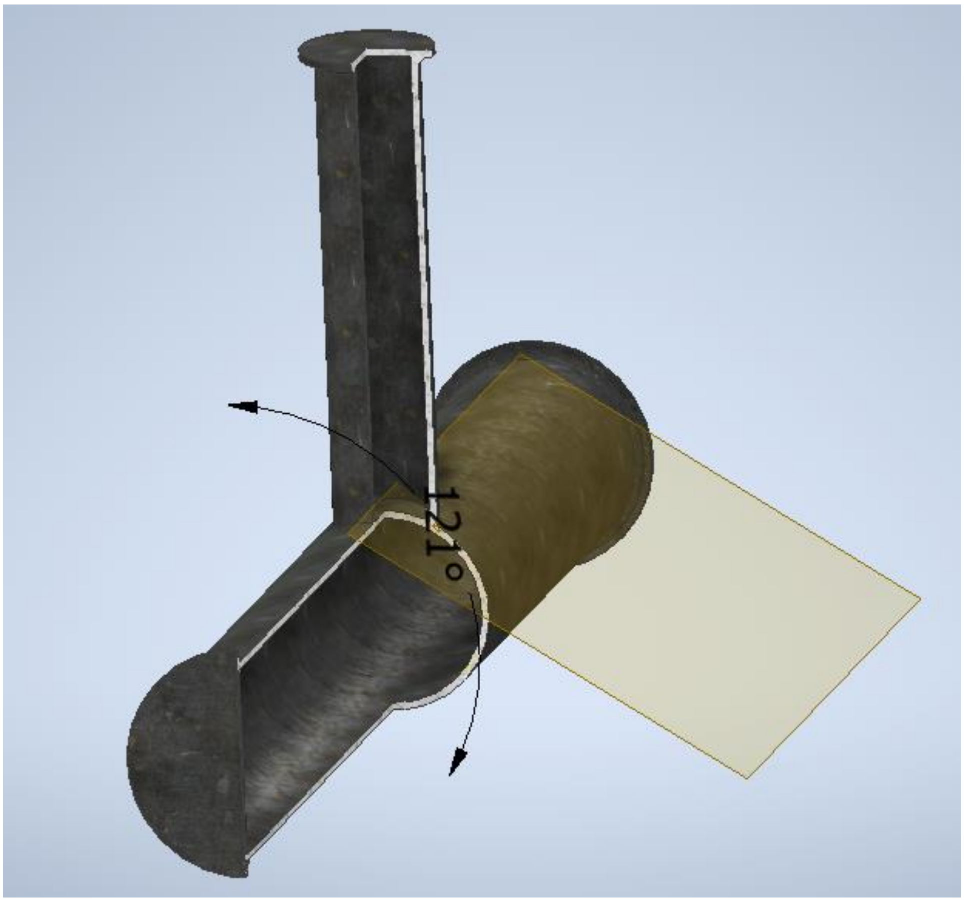


Figure 25 Defining maximum Psi (Ψ) angle for weld geometry

These values of Table 5 are combined in a single chart – blue for angle and orange for fillet size:

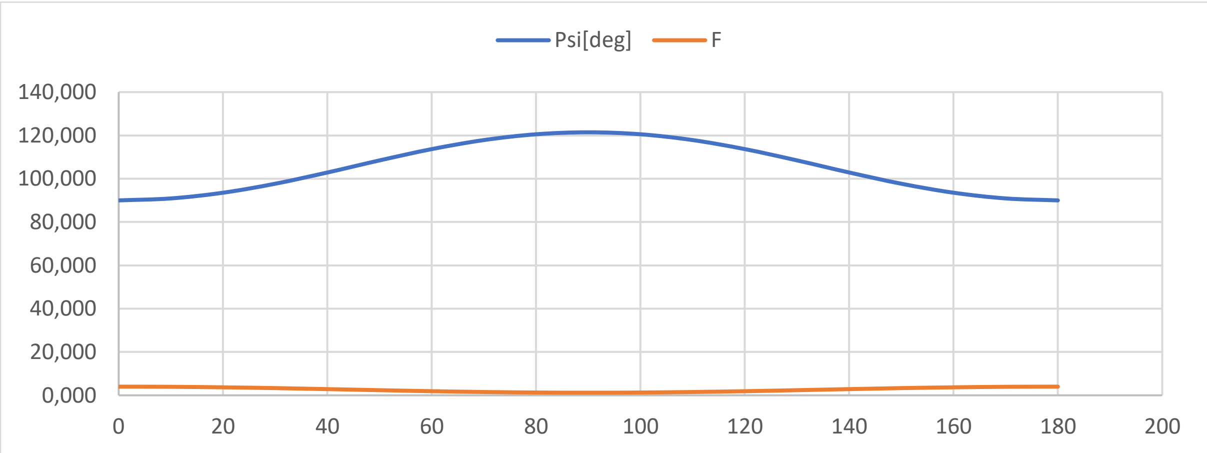


Figure 26 A combined chart of weld thickness F -orange and Ψ-blue in function of mapping angle γ.

Much better understanding can be achieved when presenting results in polar coordinate system (a radar chart n Excel):

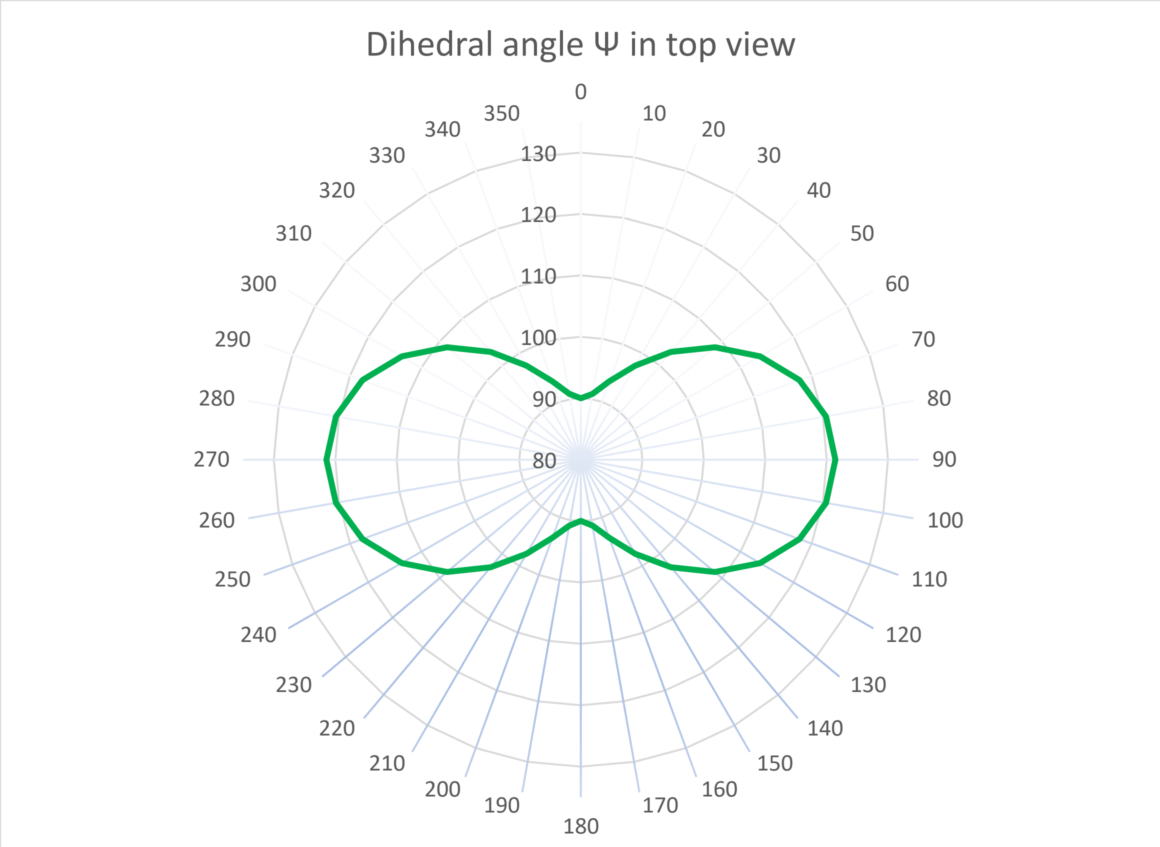


Figure 27 Radar chart of Dihedral angle Ψ in function of γ angle.

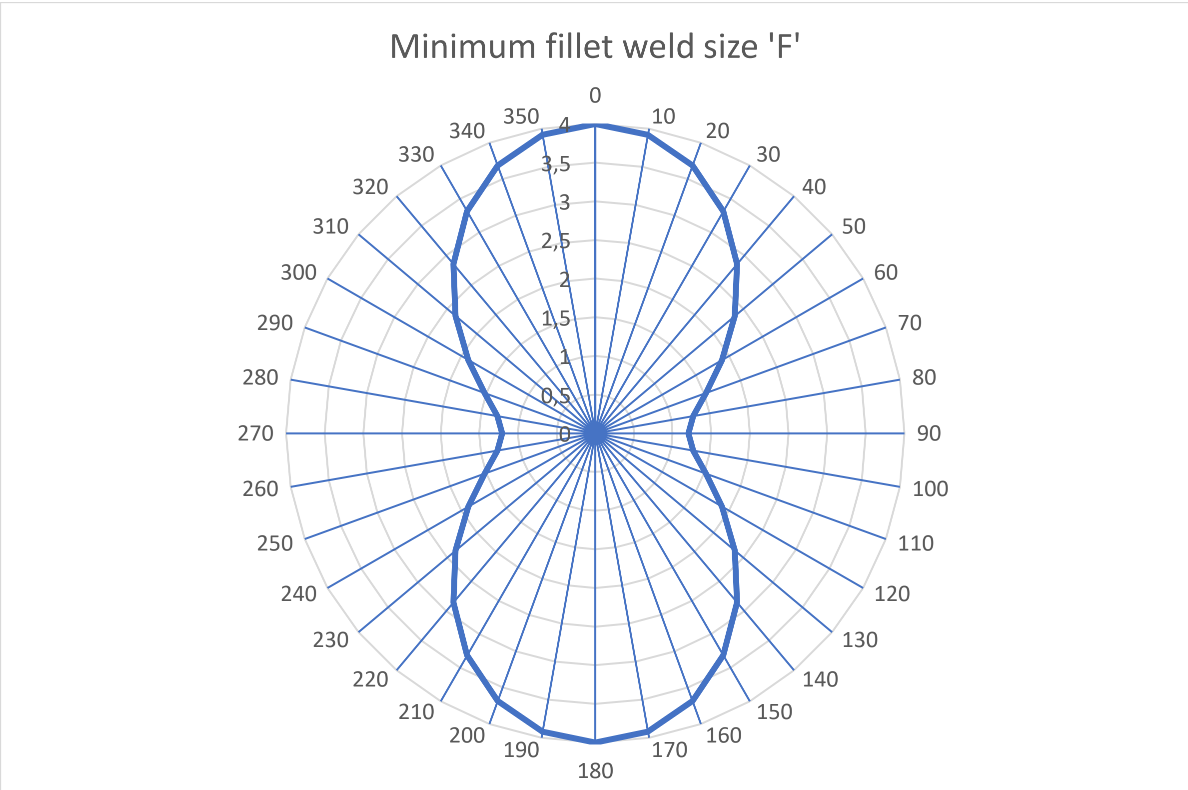


Figure 28 Radar chart of F size in function of γ angle.

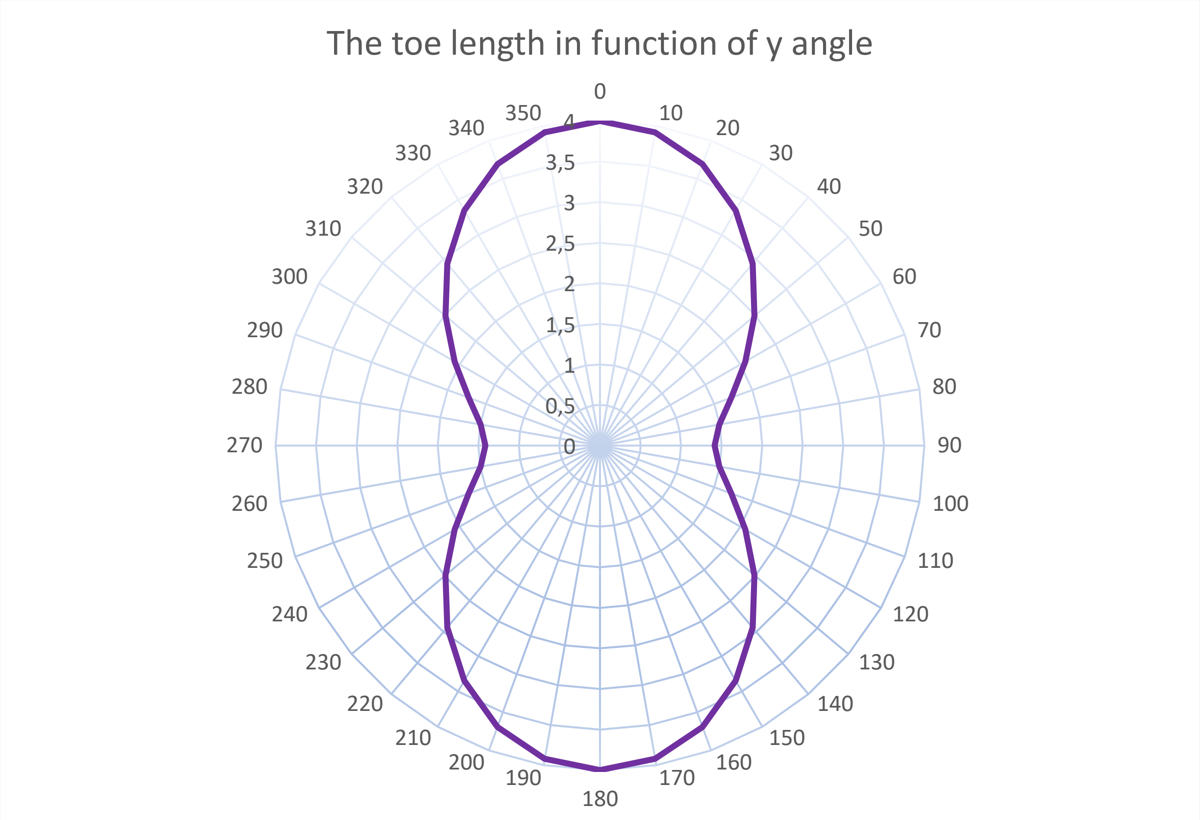


Figure 29 Radar chart of toe size in function of γ angle.

What is interesting, the toe length is only slightly bigger than the F size – because sinγ decreases while F decreases too. The toe length will be further interpreted as projection of F function onto cylindrical surface of chord.
The shape of weld depends on the difference in tubulars diameters mostly. In extreme case of welding a tubular vertically to a plate, imagined as tubular of infinite diameter, F is constant all around and $F=t_b/2$, and Ψ=90º. This is intuitive and can be directly explained using simplifies what ensures me the calculations are correct.

Returning to Equation 27

$$(\Psi=0.5\left(\operatorname{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+r}{\frac{M}{\sin\gamma}+\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}}{M}r\cdot\sin\gamma}\right)\text{-}\operatorname{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}\text{-}r}{\frac{M}{\sin\gamma}\text{-}\frac{\frac{M}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}}{M}r\cdot\sin\gamma}\right)\right)+\frac{\pi}{2})$$

After trigonometry conversions we re-arrange to below:

Equation 34

$$\Psi=0.5\left(\operatorname{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{cos^2\gamma}+r}{\frac{M}{\sin\gamma}+r\sqrt{cos^2\gamma}}\right)\text{-}\operatorname{acos}\left(\frac{\frac{M}{\sin\gamma}\sqrt{cos^2\gamma}\text{-}r}{\frac{M}{\sin\gamma}\text{-}r\sqrt{cos^2\gamma}}\right)\right)+90°$$

Equation 35

$$\Psi=0.5\left(\text{acos}\left(\frac{\frac{M}{\sin\gamma}\,cos\gamma+\text{r}}{\frac{M}{\sin\gamma}+\text{r}cos\gamma}\right)\text{-acos}\left(\frac{\frac{M}{\sin\gamma}\,cos\gamma\text{-r}}{\frac{M}{\sin\gamma}\text{-r}cos\gamma}\right)\right)+90°$$

Equation 36

$$\Psi=0.5\left(\text{acos}\left(\frac{M\cdot ctg\gamma+\text{r}}{\frac{M}{\sin\gamma}+\text{r}cos\gamma}\right)\text{-acos}\left(\frac{M\cdot ctg\gamma\text{-r}}{\frac{M}{\sin\gamma}\text{-r}cos\gamma}\right)\right)+90°$$

When M goes to high value:

Equation 37

$$\lim_{M\to\infty}\Psi=90°$$

And hence also:

Equation 38

$$\text{F}(\Psi)=\text{F}(90°)=\frac{t_b}{2}$$

8 3D modelling

8.1 3D environment used

The CAD application used for creating reference model:
Autodesk® Inventor® Professional 2022, 64-bit edition
Built 153, Release: 2022, Date: Tue 02/16/2021

8.2 Types of 3D files format used in this scope

8.2.1 STEP

STEP files are commonly used in computer-aided design (CAD) and 3D printing to contain three-dimensional model data for a wide variety of design tasks.
STEP stands for Standard for the Exchange of Product Data and is also known as ISO 10303.
As a common file format used for 3D modelling and printing, these files are an ISO standard exchange format.
This means that STEP files can read and save the complete body of a 3D model — not just the basic geometries — which is necessary for high levels of accuracy.
Along with improving cross-platform compatibility, STEP files hold all the detail and body of a 3D model with unparalleled precision. Some earlier file formats only held the basic geometries, which made sharing, opening, and editing less accurate [XIII].

8.2.2 IGES

A file with *.iges extension is designed to exchange a 2D or 3D design information between computer-aided design (CAD) applications. IGES stands for Initial Graphics Exchange Specifications. IGES is used in traditional engineering drawings, 3D models analysis, and manufacturing functions. IGES files can be opened with several CAD applications such as Autodesk, CADSoftTools, ABViewer. IGES files are saved in ASCII text format and can be opened in any text editor to view the contents of the file. Textual information in an IGES file is represented in format called “Hollerith”. A common IGES file can contain even thousands of lines [XIV].
The IGES format is required for the reference model geometry by VXelements™ application.

8.3 Manufacturing drawing analysis

Figure 30 3D model obtained in Autodesk Inventor showing cross-section of weldment to illustrate different tangency angles depending on location.

The dihedral angle Ψ (Greek letter 'Psi') ranges from 90º to 121º. It means that only Weld Type A2 is applicable – as per weldment specification drawings, Figure 31.

The weld profile radius 'R' is a welded shape and does not call for surface grinding, unless specified on design drawings. It is confirmed moreover that the specimens were delivered to laboratory in as welded state, without any machining performed on the welding seam.

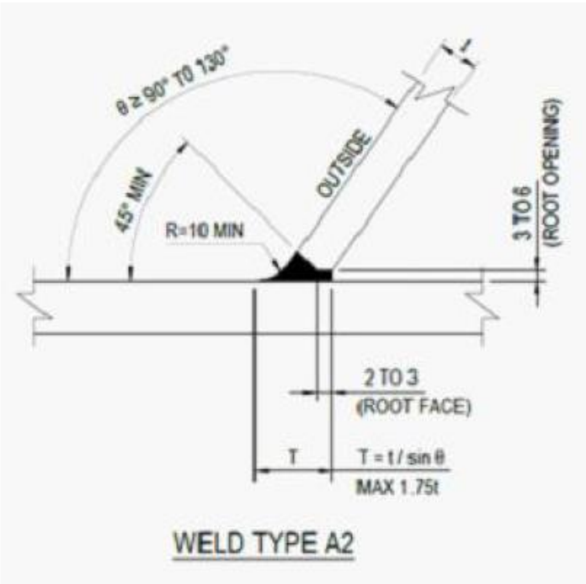


Figure 31 Weld type A2 as per specification.

The root opening is accessible only from inside of the brace, it cannot be verified from scanned geometry.
It is worth to notice that the weld specification in the manufacturing documentation Figure 31 is very similar to the geometry specified by AWSD1.1 in Figure 20. There are however differences in the details; The manufacturing drawing calls for a weld toe radius of minimum

10 mm (this feature was eventually not machined on any of specimen), the joint included angle is set to be minimum 45º,what is a simplification of AWSD1.1 requirements. Also Root openings and root faces acceptable dimensions differs slightly.\
In the next chapters only the standard [I] geometry will be analysed – as per scope of this thesis.
The manufacturing drawing does not call any tolerance on the angular position between chord and brace. The angle nominal 90º is not dimensioned even, however it is implicit from the drawing according to ASME Y14.5. Proposed improvement to this documentation is to dimension the end cap centre (the nose) of brace referring to one end of the specimen chord or/and add a tolerance of position symbol on the brace axis with required value. Suggested tolerance field of ø3.2 mm. The tolerance field in this case is a cylinder of given diameter where the measured axis of brace tubular shall be included.

8.4 The model of weld in LMC

I began the weld geometry modelling from defining a 2D curve outlining the weld thickness – indicated F on the figures. Based on the former chapter' Equation 31;

$$F=4-\frac{2}{45^\circ}\left(\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}+57.15}{\frac{109{,}55}{\sin\gamma}+57.15\sqrt{1\text{-}sin^2\gamma}}\right)\text{-}\mathrm{acos}\left(\frac{\frac{109{,}55}{\sin\gamma}\sqrt{1\text{-}sin^2\gamma}\text{-}57.15}{\frac{109{,}55}{\sin\gamma}\text{-}57.15\sqrt{1\text{-}sin^2\gamma}}\right)\right)$$

Trying to record the above in Inventor 'Equation Curve' I followed the required syntax:

- γ=a : polar angle parameter,
- r(a)=r+F : radius in a polar coordinate system
- acos() = arcus cosines
- deg = angular degrees, a unit, required due to acos() output is in degrees where the radius of the curve shall remain in length unit – millimetres.

Equation 39

r(a)=57.15+4-2*(acos(((109,55*sqrt(1-(sin(a))^2))/sin(a)+57.15)/(109,55/sin(a)
+57.15*(sqrt(1-(sin(a))^2))))
-acos(((109,55*sqrt(1-(sin(a))^2))/sin(a)-57.15)/(109,55/sin(a)-57*(sqrt(1-(sin(a))^2)))
))/45deg

Note: Unfortunately, the application pre-checks any equation entered in real time, what resulted in multiple runtime errors of type: 'Zero division' or 'Negative root argument'. The equation needed a slight arithmetic transformation to be successfully computed.

Eventually, the equation used for 2D curve describing the thickness of weld took the following form:

Equation 40

r(a)= 61,15-acos((109,55*(sqrt (1- (sin(a)) ^2)) /sin(a)+57,15) / (109,55/sin(a)+57,15* (sqrt (1-(sin(a))^2))))/22.5deg +
acos((109,55*(sqrt (1- (sin(a)) ^2)) /sin(a)-57,15) / (109,55/sin(a)-57,15* (sqrt (1-(sin(a))^2))))/22.5deg

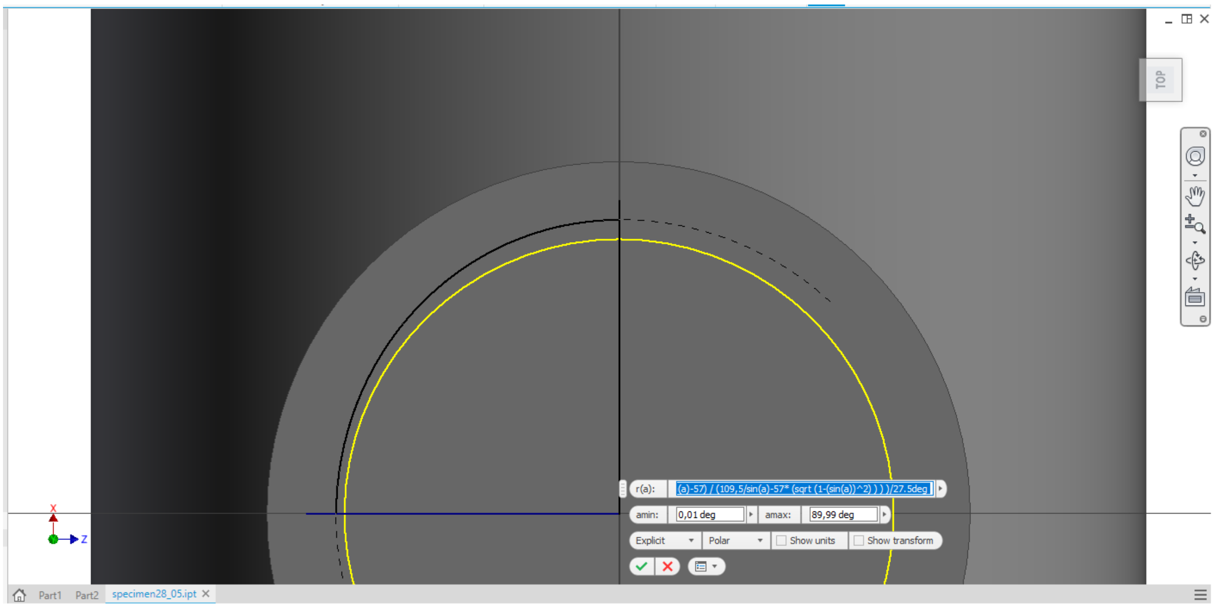


Figure 32 Visualization of analytical curve in Inventor sketch (one quarter of full domain)

The function domain was limited to 0.001º - 1799.999º. Then the missing sections around singular points of the function (k*180º, k=0, 1, 2…) are approximated with a sketched straight line. Note that such simple approximation is subject to an error below 10^{-7}mm (less than computational accuracy in application). It is important to remind here that the overall accuracy of HandyScan 3D system is not better than 0.03 mm.

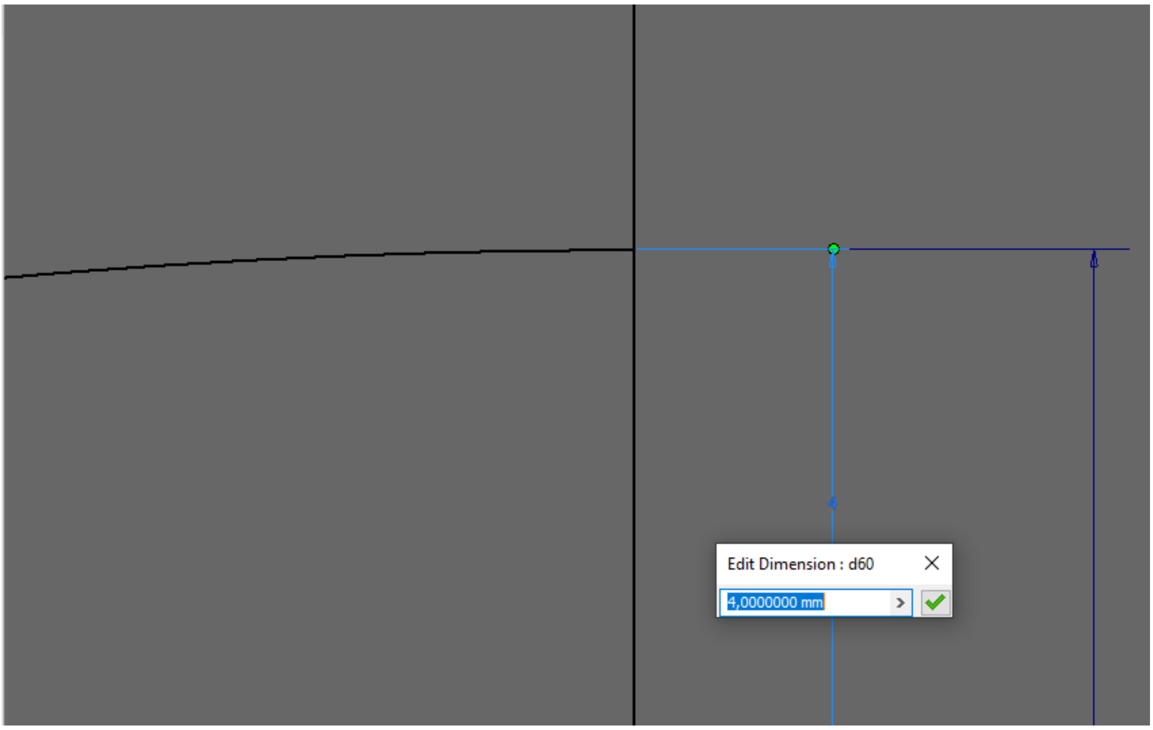


Figure 33 Upper crown of weld sketch - it is one of singular point of analytical curve. However straight line approximation is satisfactory being below computational accuracy; F =4 mm is theoretical size in the crown point.

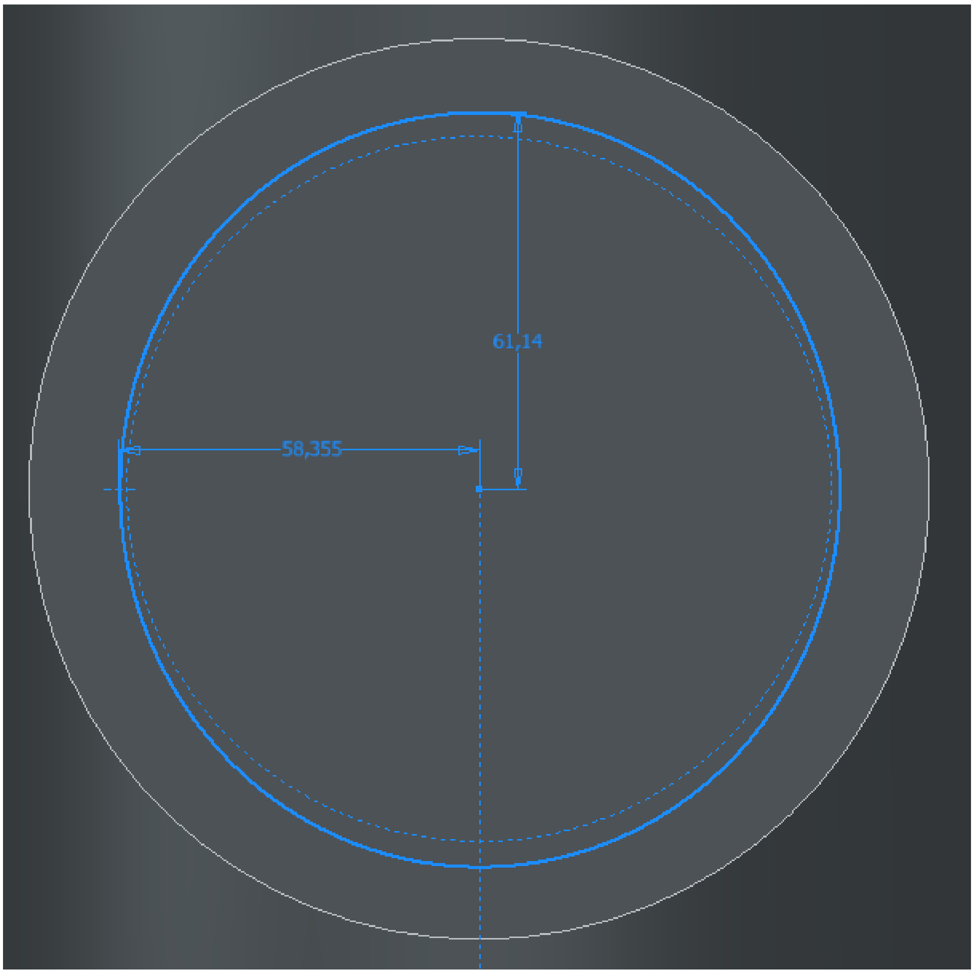


Figure 34 Two segments of curve bridged at its singular points (blue dashed construction line is a projection of the brace outer diameter 114.3 mm).

Next step is to create a 3D weld model per [I] specification. The model will be parametrized for minimum thickness (LMC) to became a lower boundary for shape tolerance.

The roots openings R are cut on model using revolve – this ensures constant distance from the chord OD.

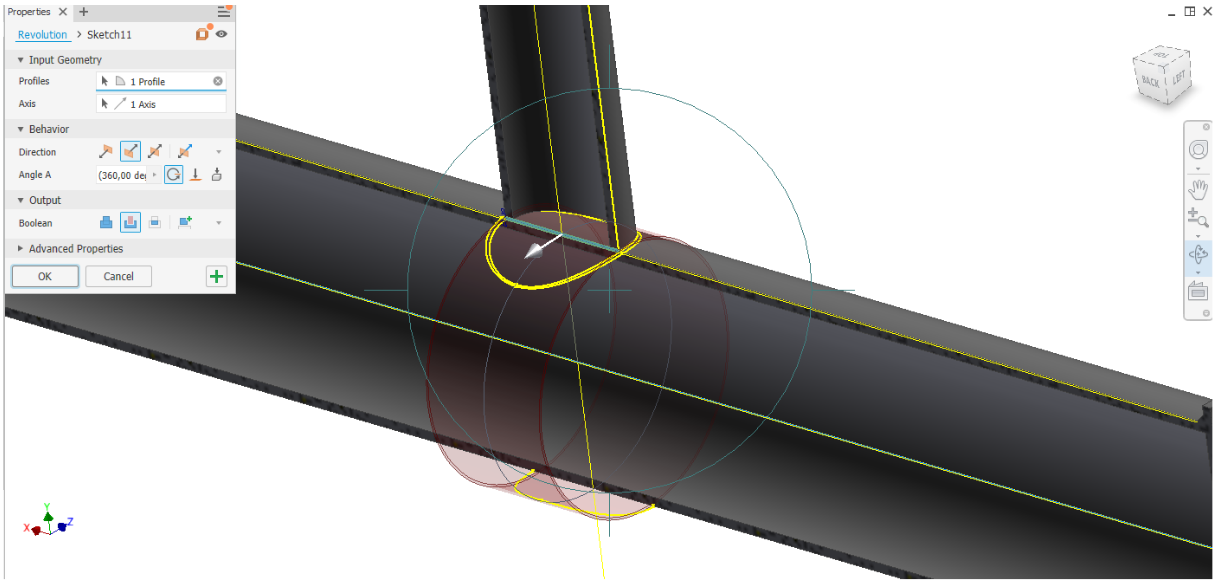


Figure 35 A method for modelling the Root openings of weld.

Minimum value for root openings R=2 mm according to Joint and grove dimensions requirements AWSD1.1 2010 [I] Table 3.6 (Table 4, page 30).

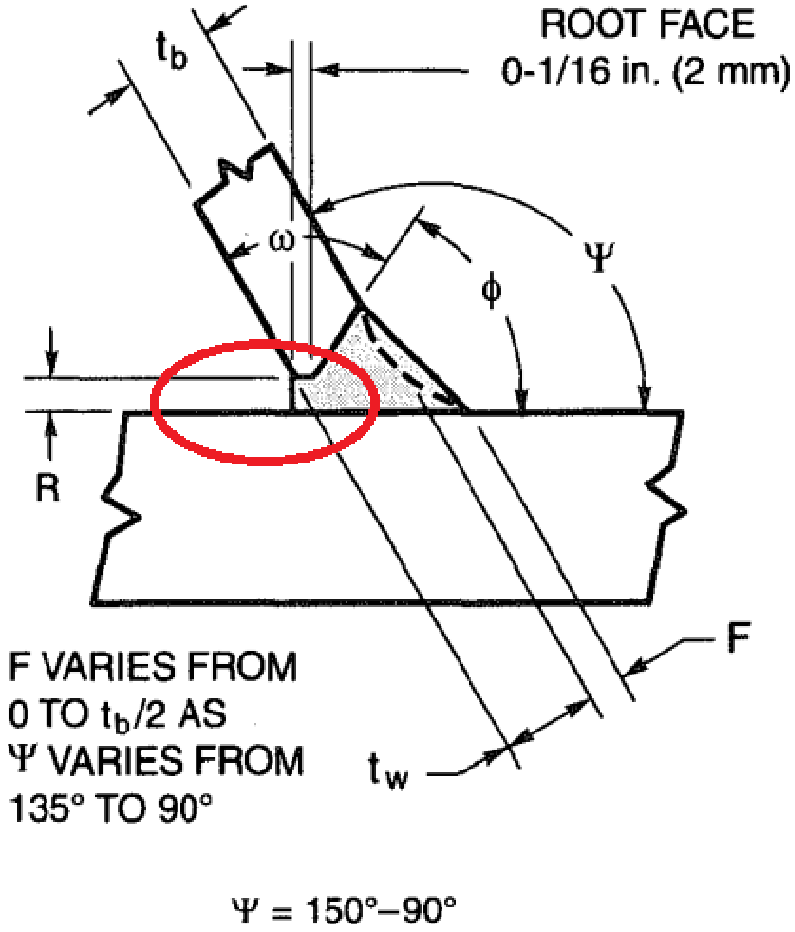


Figure 36 Root opening distance definition

Root face set to 2 mm provides the smallest section of weld (refer to Figure 36), thus it is modelled for LMC state. The 2 mm are measured in direction tangent to the chord surface what directly implies the manner of modelling this feature using extending along the curve called ‘Sweep’ in Inventor.

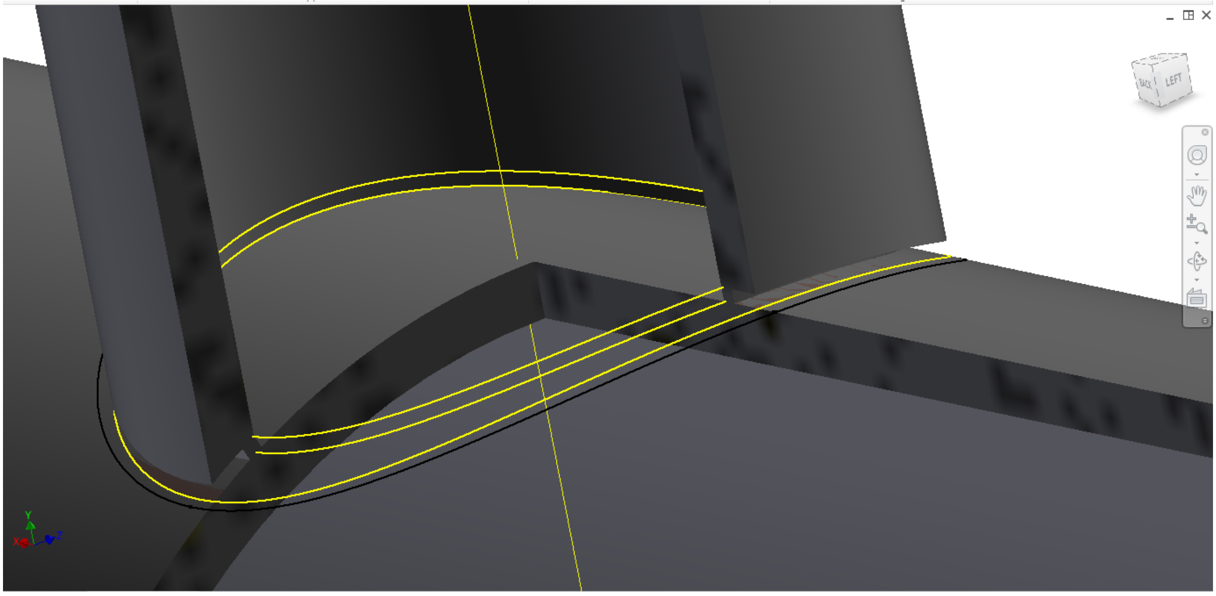


Figure 37 The root filling modelled to show the geometrical complexity of its shape. Main purpose of this operation was only to set a 3D curve distanced 2 mm from the inner edge of the brace.

The joint included angle φ, according to of Table 4 Joint and grove dimensions requirements AWSD1.1 2010 [I] Table 3.6, should not be less than 37.5° or half of Ψ, whatever is less. In our case half of Ψ is in range of from 45° to 60.6 °. Hence, for the model simplification we can assume φ=37.5° all around.

Note: The standard [I] does not precise how to measure the φ relative to a curved surface i.e. where is the set point of the plane tangent to outer ellipse (see the Figure 38 for clarification in 3D space).

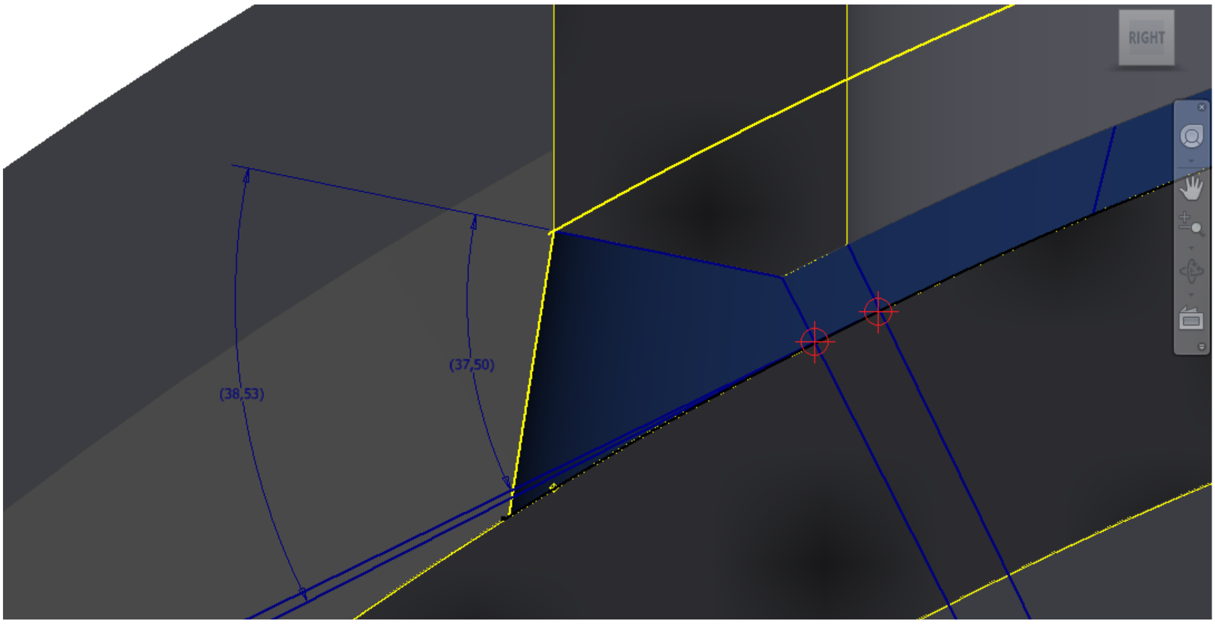


Figure 38 The tangency point ambiguity in saddle location – φ angle measure arbitrarily.

Note here, all the above is a theoretical approach. A constant angle of the end preparation all around the brace is a rational choice from the perspective of manufacturing. A smooth transition of end angle ω can be obtained in example using plasma cutting on a CNC machine

or a tilting milling head on also CNC lathe. In workshop reality, thin walled tubulars can be often shaped on a regular lathes or using hand grinders, what virtually enables smooth end angle transition however at questionable accuracy.
For this example choosing any ω such 45º ≤ ω ≤52.5º meets the Table 4 requirements.

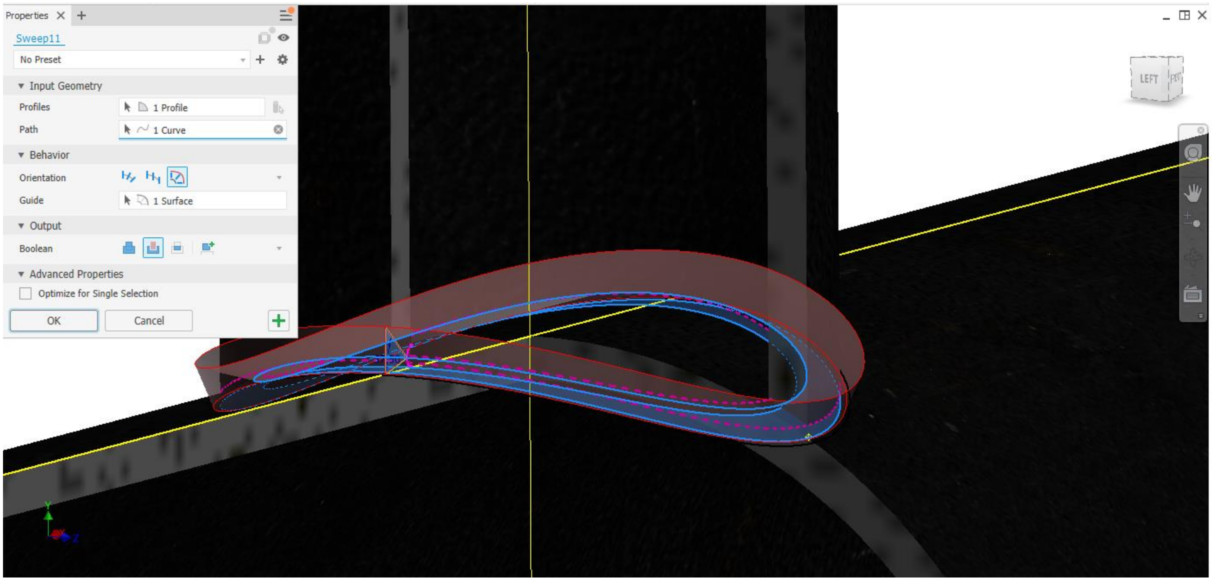


Figure 39 The brace end preparation profile was obtained using Sweep operation, alongside the inner edge. Keeping the minimum opening angle dependable of the chord curvature was achieved using controlled behaviour of Profiles. They are kept normal to the path and simultaneously follows the Guide of chord and bracket contact surface (a saddle shape)

Eventually the LMC model of weld is obtained:

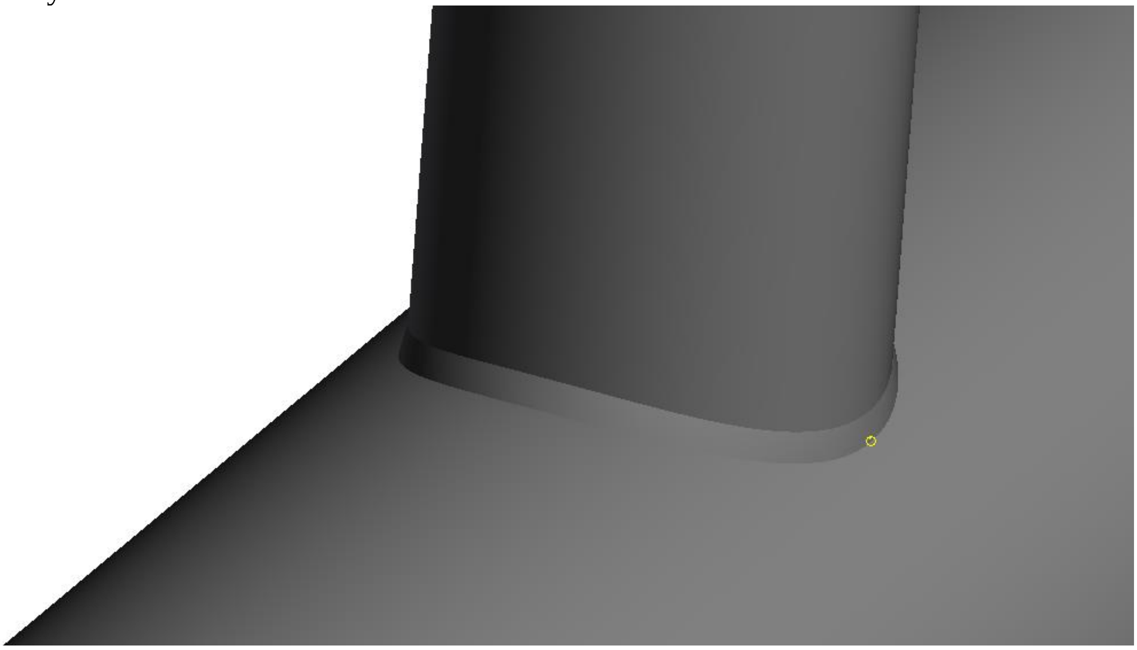


Figure 40 The weld geometry (no concave profile)

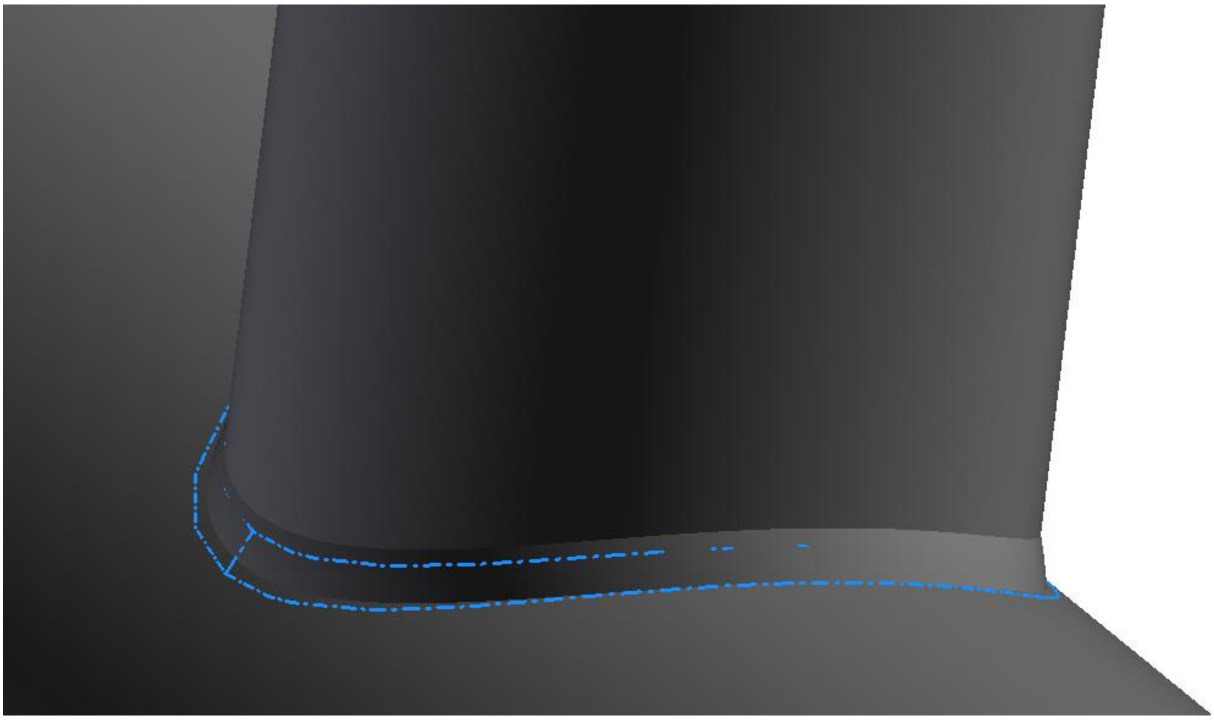


Figure 41 The LMC weld 3D visualisation compared with a regular chamfer 4 x4 mm.

8.5 The model of weld in MMC

Modelling the weld in its most material condition (MMC) upper limiting geometry is more challenging due to different requirements up to - and above Ψ=105º. See Table 4. The dihedral angle reaches value of 105º almost 44º from the crown point, i.e. for the mapping angle γ=44º. It can be read from Figure 27 or checked on the 3D model; Figure 42.

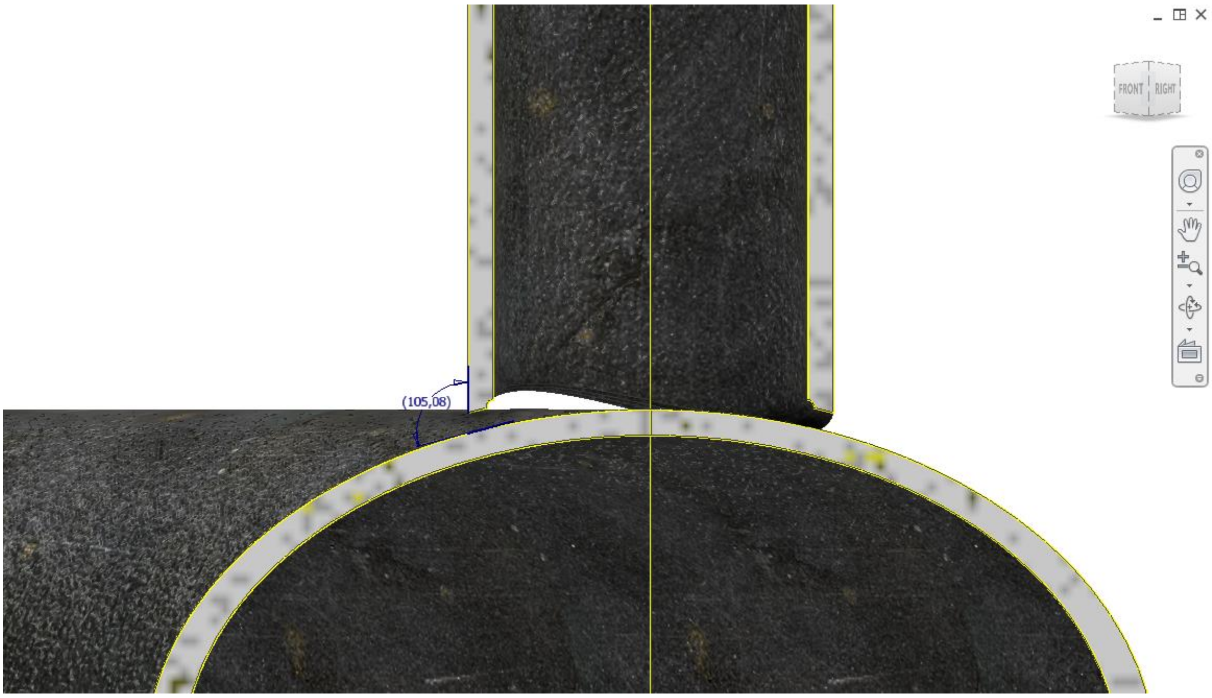


Figure 42 Dihedral angle reaches Ψ=105° for γ=44°, 136 °, 224 ° and 326 °.

My interpretation of AWSD1.1 table 3.6 (Table 4) is then as below:

Starting from the crown, 44º in each direction, the superior requirement is to keep the join included angle φ less or equal to 60º – because the dihedral angle in this zone is smaller than 105º. Closer to a saddle, the dihedral angle increases and the dominating requirement is to keep minimum preparation angle ω=45º.
Particularly in the saddle there is φ=76º, but in this case of dihedral angle the joint included angle is no more controlled.
In the crown itself: Ψ=90º and the included φ=60º what equals in end preparation angle ω=30º what is still more than minimum of 10º required.

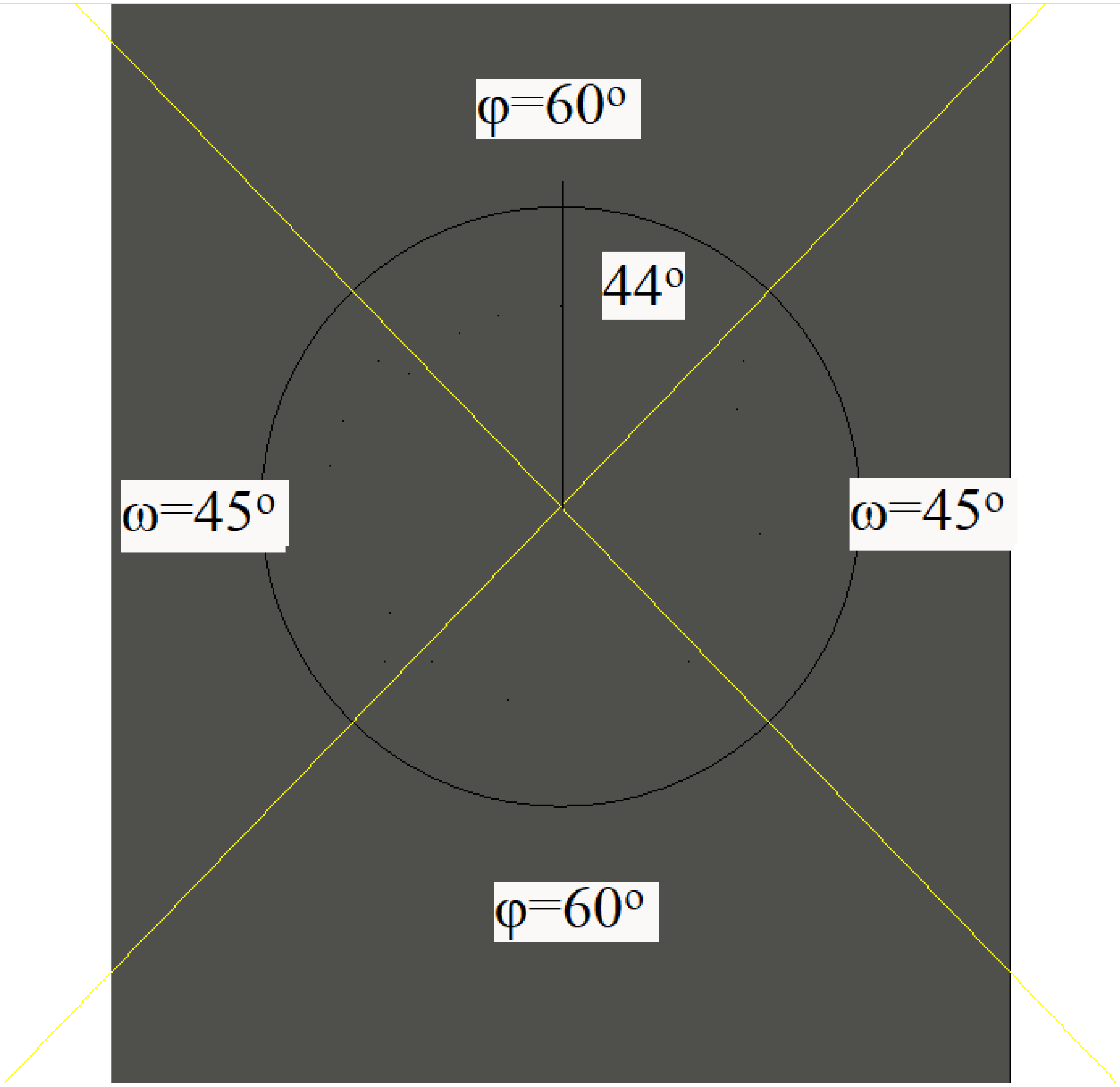


Figure 43 Joint included and end preparation angles control zones division - top view on the brace.

The transition between these sectors is smooth from definition, see below:

Equation 41

$$\Psi = \omega + \varphi$$

Equation 42

$$105^{\circ} = 45^{\circ} + 60^{\circ}$$

As shown in Figure 24 the dihedral angle values depends on the tubulars radii ratio (r/R) and for radii different enough (r/R = 1/5 and less, approximately) Ψ does not reach value 105º Conclusion here is, that the MMC model is unique regarding the tubulars diameters used and cannot be easily scaled – despite the LMC model.

For weld MMC state Root opening is set to 6 mm as per Table 4, detail B, SMAW welding method. This was an arbitrary choice as the standard [I] does not provide any special geometry for GTAW (Gas Tungsten Arc Welding).
The largest section of weld is achieved once root faces are in its lowest limit: 0 mm (refer to Figure 36) thus it is modelled like such.

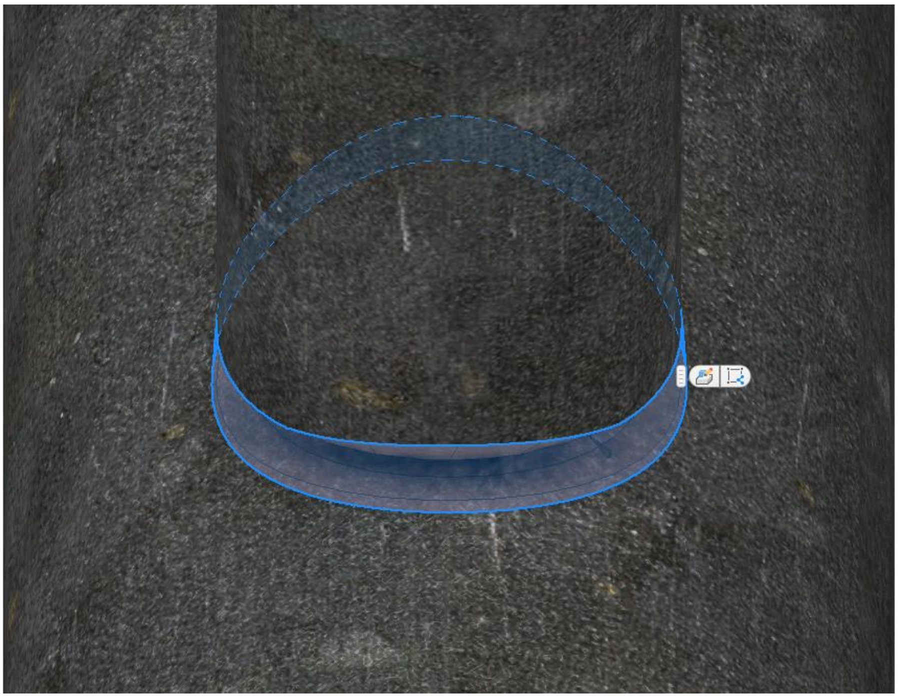


Figure 44 The weld surface eventually obtained in 3D model. The surface was then 'Stitched up' with surrounding surfaces and 'sculpted' into Inventor solid model.

Figure 45 3/4 cross section showing weld profile in crown and saddle. MMC model

9 Virtual inspection of scanned data.

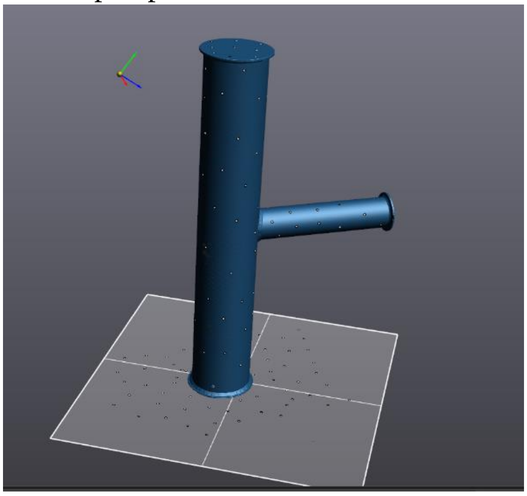
With scanning technologies, most of the manipulations of the information extraction and computations occur after inspecting the part [III].

The 3D CAD model prior the inspection was cleaned by removing unnecessary surfaces that will not be used for the inspection. This reduces the risk of measuring the wrong thing and facilitates the inspection process. This could be done directly with most metrology software during the inspection. It is however more efficient when performing this prior to the inspection, using CAD software with more CAD-handling tools.
After some test with Autodesk Meshmixer software I used eventually the dedicated Creaform VXelements™ CAD software.

9.1 Process workflow

The screenshots show step by step how the raw scanned data - a mesh was compared with a perfect model in aim to describe deviations. Screenshots presents the #1 specimen, serial number S31655-4000-T-03 (if not stated othervise) and all the steps were repeated for the remaining 6 ones.
Surface mesh used is of 0 mm thickness.

1. The background noise was clipped. During scanning a large part of floor was scanned. This needed to be removed in postprocess.



2. Reference points removed (black&white dots this can be done in VXscan without licence.)
3. The mesh was automatically upgraded using “Clean Mesh” function. To use it the original mesh was send to VXmodel module (licensed). This function, among others, removes isolated patches, self/intersections, surface spikes (noise), very narrow triangles (also noise rather than real surface) and fills smallest holes. The effects are not visible without a large zoom. This operation is the mesh noise reduction and shall not affect the overall measurement results.

4. This was decided to not utilize function “Fill Holes” in VXmodel as might influence the measurement. According to [VIII] mesh optimization may have modified the shape.

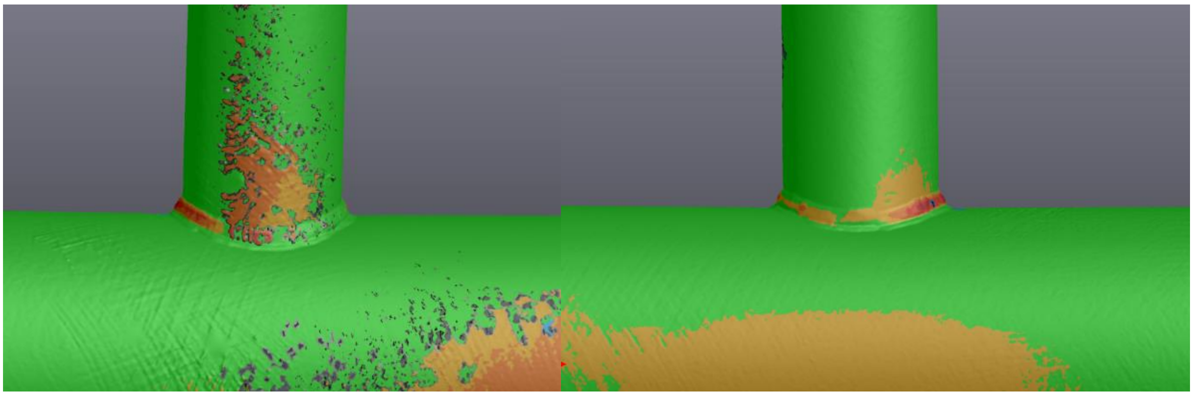


Figure 46 At left the specimen #2 mesh before noise filtration. A surface highlighted orange is overlapping the #real# surface beneath. This is a typical, but not common error during scanning, once the already scanned surface was not recognized and the acquired points create separated path. At right a view on the same side of specimen #2 after “Clean Mesh” function application and a manual correction of surface.

5. The reference LMC model (Least Material Condition of weld, nominal geometry of chord and brace) was imported from Inventor. It is represented by the steel grey object while the mesh representing the real measure surface is in blue on Figure 47.
   An *.iges format of model is required by VX. I.e.: the model is exported from Inventor as *.iges and then imported to VXmodel module. Model and mesh blue are not yet aligned their mutual orientation is random.

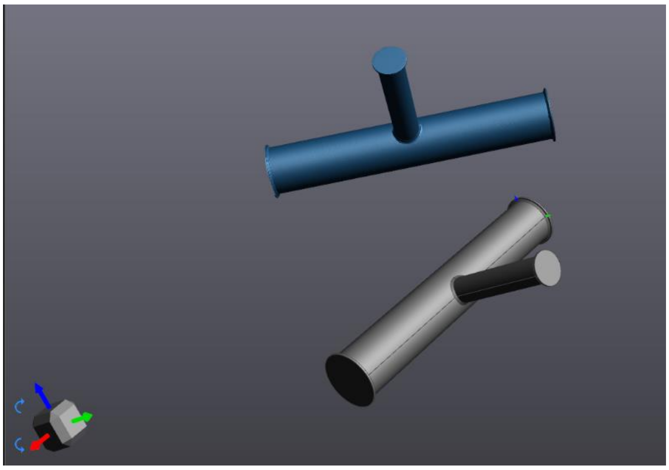


Figure 47 The mesh (blue) and reference CAD model (grey) imported together into VX environment – before alignment.

6. Two cylinders, one Φ=219.1 mm and the other Φ=114.3 mm were fit to the mesh surface. Two end surfaces approximating the chord and brace caps. There is no surface at bottom added. The grey reference model in background is not in use yet.
   The application algorithm fits a known (user assumed) surface of geometric solid using linear regression method to the data points – the mesh.

The user can set the maximum number of iterations for the algorithm computing the best fit possible. Maximum search distance and maximum search angle from the nominal target point to the triangles mesh data are recalculated at each iteration [III].

At this level it is visible where the scanned surface -blue- is exceeding the nominal, mathematically perfect, shape of cylinders – green surfaces. The operation described above is a part of reverse engineering process, that is in general retrieving the shapes and dimensions from the manufactured component, based on a measurement,: conventional or like in this case a touchless scanning. Knowing position of the best fitted cylinders enables a 'virtual measurement' of angle between chord and brace of the specimen, see step 7.

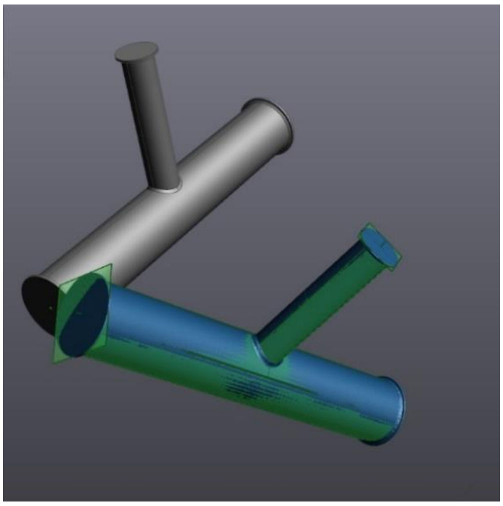


Figure 48 Approximating the mesh surface (blue) with geometric primitives (green)

The below steps are done after sending the model & scanned mesh into VXInspect - VXelements™ module intended for reverse engineering and measurement reporting.

7. Manual alignment of reference model (grey) with the scanned mesh (blue) – now they are both in the same orientation. Chord and brace approximated entities were easily recognized by "Best fit surfaces" algorithm.

8. Angle measurement between axes of the approximated cylinders – see step 6. The angle is 89.376º resulting in almost 5 mm deviation of the brace end cap ("the nose"). The green entities are statistically best approximation of real surface with virtual cylinders.

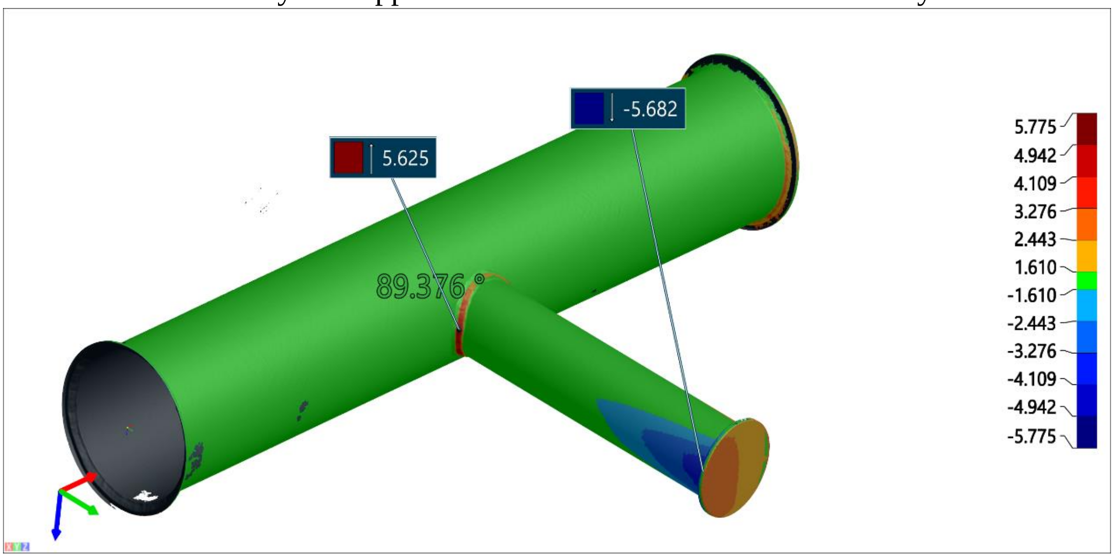


Figure 49 Figure 44 Virtual measurement of brace to chord angle on a scanned geometry mesh (specimen #1 data).

9. Function Colormap applied from VXinspect module.
   The Colormap shows error distribution between the selection done and the entity created. Tolerance zone was set to range from -1.61 mm to 1.61 mm what is relevant for the brace size as per API 5L. Surface in this tolerance is coloured green. All surfaces beyond tolerance are coloured as follows:
   - Red (warm hue) indicates excess of material areas/ where the scanned surface is above the upper limit deviation(es).
   - Blue (cold hue) for material shortage areas where the scanned surface is below the lower limit deviation (ei).

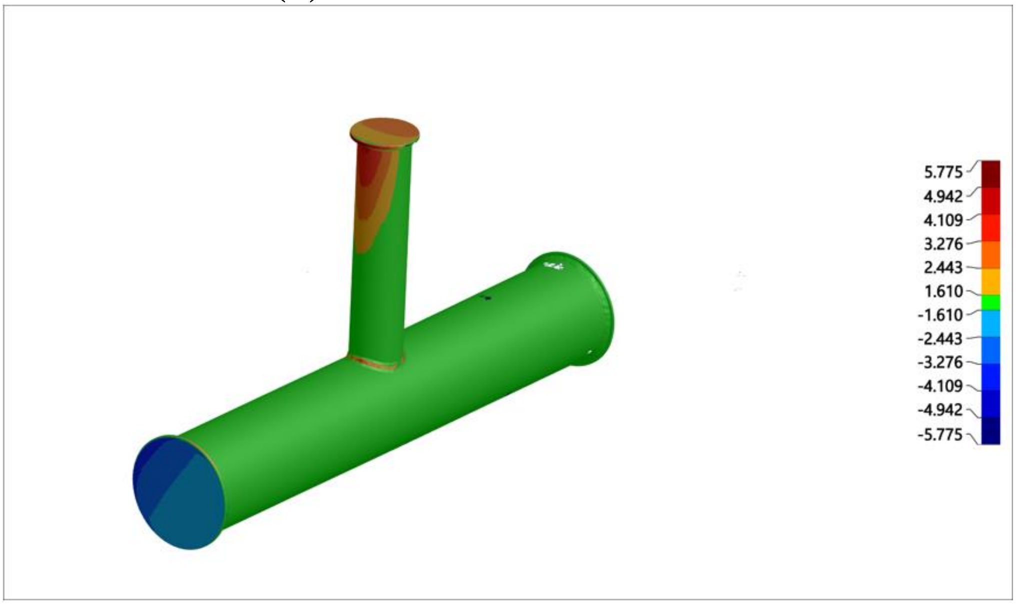


Figure 50 A colour map illustrating deviation range of the measured specimen 1 / a render picture.

10. Multiple cross section applied in radial pattern around the brace axis. The 3D view below shows the cross section planes location (green lines). A bunch of section planes each spaced by 10º is used for the Inspection Reports – see Appendix B.

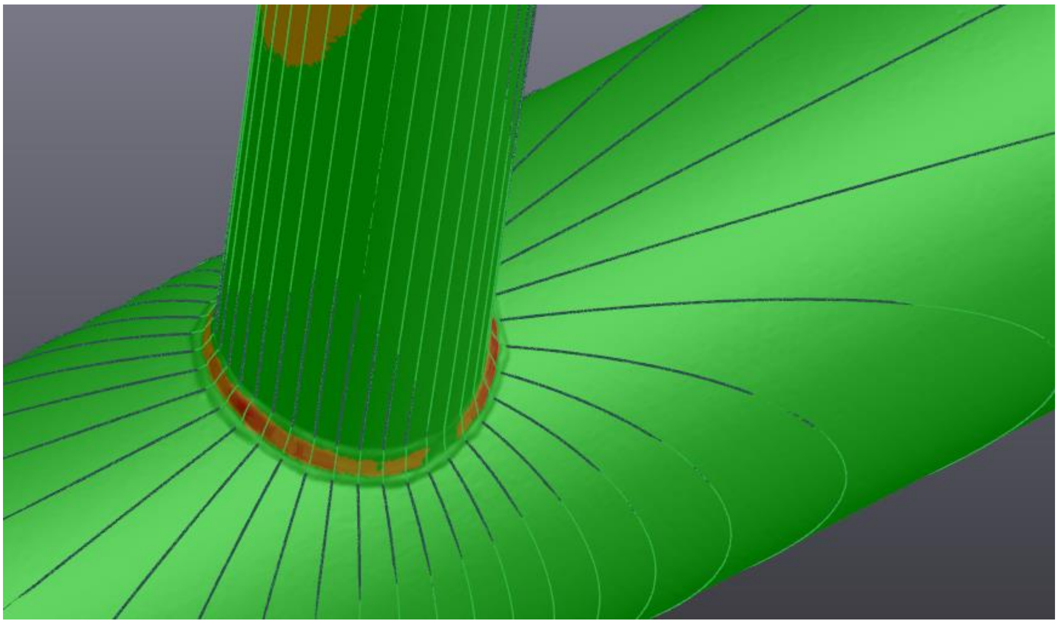


Figure 51 Outline drawing of cross section planes location in the measured specimen.

11. The below is cross section through the saddle points. Here, in saddle, the amount of deposited weld is smallest in entire joint. Nevertheless, there is still surplus of more than 0.15 mm over the minimum required weld size - LMC model according to AWSD1.1. (there is over 2mm surplus at opposite side, the weld reveals to be very asymmetric after inspection. It can be also due a slight eccentric positioning of the brace before welding regarding chord axis.
    Please notice all the brace cylinder is inside the tolerance zone (green) and no trace of skewing is visible.

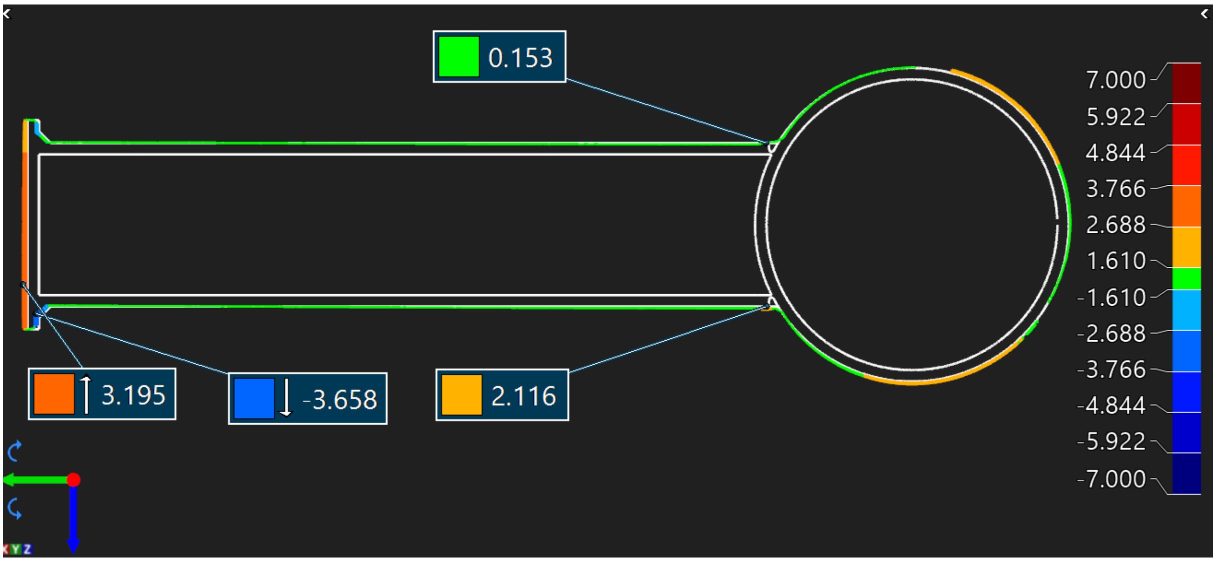


Figure 52 Cross section thru saddles of specimen #1 – colormap profile

12. Detail below showing the weld cross section (in the plane of brace cylinder axes). Visible extra material on the weld seam despite tendentious material deficit on surrounding of chord. White lines present the ideal model with perfectly symmetric position of brace axis. Extra material on upper part and missing material on the below is a clear message of the brace being skewed referring to the chord – real angle is not 90º.

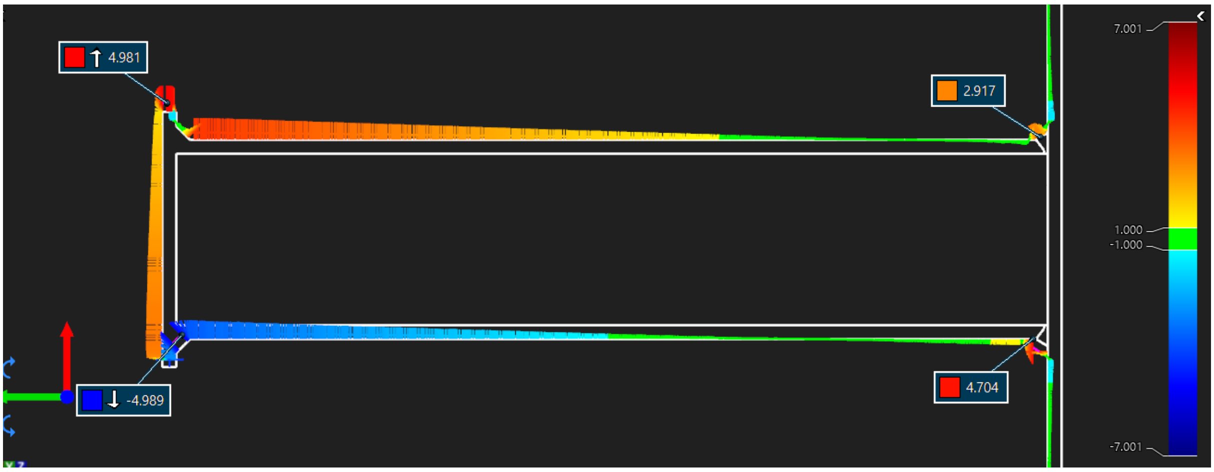


Figure 53 Cross section thru crowns γ=0º,.Drawing visualises clearly the skewness of a brace.

9.2 Geometry comparison with MMC model.

On every cross section, as well as on the general colour map 3D view it is seen that the real (scanned) mesh exceeds the outer weld limiting geometry. It is well seen at weld toe area, close to the chord, where the extra material over required maximum is deposited.
In some sections of upper weld section the real surface is slightly below the maxim one, however this is still in "green zone" inside tolerance range.

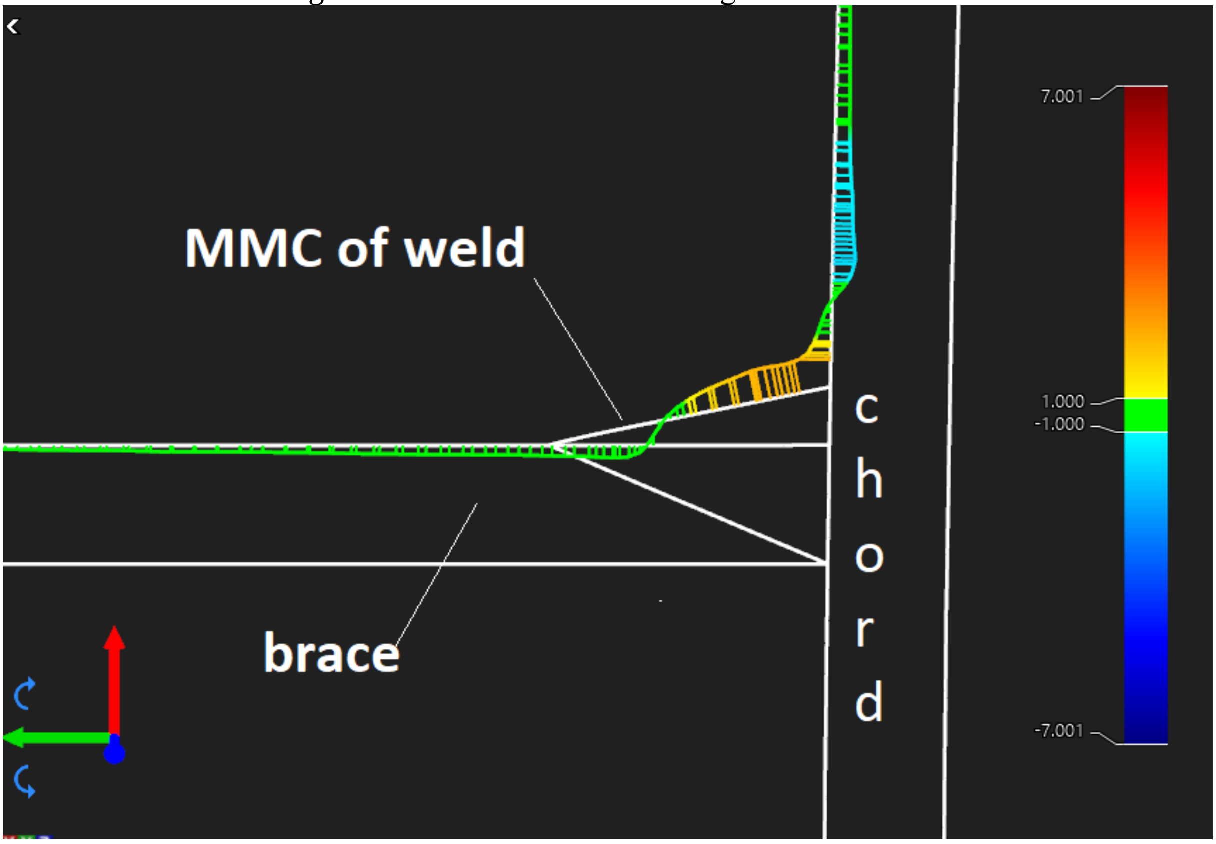


Figure 54 Cross section 10° from upper crown of weld. The colour line is the scanned geometry

9.3 Tolerances

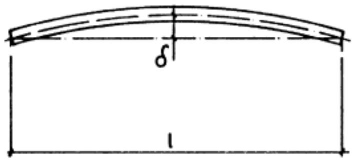
The code [I] was specifically developed for welded steel structure that utilize carbon or low alloy steels that are 1/8 inch [3 mm] or thicker with a minimum specific yield strength of 100 ksi [690 MPa] or less.
Metric (SI, Système international d'unités) version of standard is indicated ‘M’ [I].

The unsupported length of chord can be estimated as 1300 mm, what gives out of straightness acceptable deviation max 1.95 mm.
The unsupported length of brace can be estimated as 500 mm, what gives out of straightness acceptable deviation max 0.75 mm.

Table 6 Tolerances of straightness for tubulars [II].

11.1.5 Straightness of members which are based on buckling calculations according to DNV-RP-C201 and DNV-RP-C202 shall be within the tolerances given in Table 1.

Table 1 Tolerances for straightness

Detail	*Tolerance*	*Fig.*	*Comments*
Bars and frames	Max. out of straightness $\delta = 0.0015\,l$		l = unsupported length.

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The tubulars diameter tolerances are restricted by standard API 5L.

Table 7 The tubulars diameter tolerances according to standard API 5L

Table 1 --- Tolerances for diameter and out-of-roundness

<table>
<tr><th rowspan="3">Specified outside diameter D mm (in)</th><th colspan="4">Diameter tolerances mm (in)</th><th>Out-of-roundness tolerances mm (in)</th><th></th></tr>
<tr><th colspan="2">Pipe except the end a</th><th colspan="2">Pipe end a, b, c</th><th rowspan="2">Pipe except the end a</th><th rowspan="2">Pipe end a, b, c</th></tr>
<tr><th>SMLS pipe</th><th>Welded pipe</th><th>SMLS pipe</th><th>Welded pipe</th></tr>
<tr><td>< 60,3 (2.375)</td><td colspan="2">- 0,8 (0.031) to + 0,4 (0.016)</td><td colspan="2"></td><td colspan="2">d</td></tr>
<tr><td>≥ 60,3 (2.375) to ≤ 168,3 (6.625)</td><td colspan="2">± 0,007 5 D</td><td colspan="2">- 0,4 (o.o16) to + 1,6 (0.063)</td><td rowspan="2">0,020 D</td><td rowspan="2">0,015 D</td></tr>
<tr><td>>168,3 (6.625) to ≤ 610 (24.000)</td><td>± 0,007 5 D</td><td>± 0,007 5 D but.maximum of + 3,2 (0.125)</td><td colspan="2">± 0,005 D, but maximum of ± 1,6 (0.063)</td></tr>
<tr><td rowspan="2">> 610 (24.000) to ≤ 1 422 (56.000)</td><td rowspan="2">± 0,01 D</td><td rowspan="2">± 0,005 D, but.maximum of + 4,0 (0.160)</td><td rowspan="2">± 2,0 (0.079)</td><td rowspan="2">±1,6 (0.063)</td><td>0,015 D but maximum of 15 (0.6), for d / t ≤ 75</td><td>0,01 D, but maximum of 13 (0.5). for d / t ≤ 75</td></tr>
<tr><td>by agreement for d / t > 75</td><td>by agreement for d / t > 75</td></tr>
<tr><td>> 1 422 (56 000)</td><td colspan="6">as agreed</td></tr>
</table>

a The pipe end includes a length of 100 mm (4.0 in) at each of the pipe extremities.

The brace diameter 114.3 +/- 0.86 mm
The chord diameter 219.1 +/- 1.64 mm

Including DVN-OS-401C straightness errors:

114.3 +/- 1.61 mm
219.1 +/- 3.54 mm

Out of roundness tolerance is less or equal to 0.02 of the outer diameter.
The brace roundness 2.29 mm
The chord roundness 4.38 mm

The angular dimension tolerances are not directly provided in DNV-OS-403 standard. They are not mentioned at manufacturing drawing either (Figure 4).Therefore I will refer to another well recognized international standard ISO 2768 T1. According to Table 8 the value for approximately 500 mm feature shall be +/- 20’ [minutes] what expressed in decimal fraction of a degree means 1/3° or 0.(3)°. I assumed very coarse class “v” allowing the greatest deviations. A welded structure is expected to fall into coarse or very coarse class.

Table 8 Angular dimension tolerances per ISO 2768 T1 [XXI]

General Tolerance Chart 3 - Angular Dimensions

Permissible deviations in degrees and minutes for ranges in nominal lengths	f (fine)	Tolerance class designation (description)		v (very coarse)
		m (medium)	c (coarse)	
up to 10	±1°	±1°	±1°30′	±3°
over 10 up to 50	±0°30′	±0°30′	±1°	±2°
over 50 up to 120	±0°20′	±0°20′	±0°30′	±1°
over 120 up to 400	±0°10′	±0°10′	±0°15′	±0°30′
over 400	±0°5′	±0°5′	±0°10′	±0°20′

10 Discussion on the inspection results

Setting a serial inspection of multiple meshes with a report generation requires a little of patience, mostly for all the visual settings. Each specimen mesh needs to be imported to VXmodel module and then a separate part needs to be created. The entities (cylinders) of a new mesh needs to be confirmed manually.

I have chosen that each part *representing a separate specimen is measured in an individual alignment to the reference CAD. It is because I have not assigned any datum for the element end plate (bottom plate for example). Instead, the inspection answers how well the brace was welded to the chord.

Specimen 4 is the one with the most correct perpendicularity *lowest angle tolerance. A side effect of it is concentration of extreme deviation from the reference o the weld profile. In this specific copy of T/connection the weld exceeds minimum profile up to 6 mm.

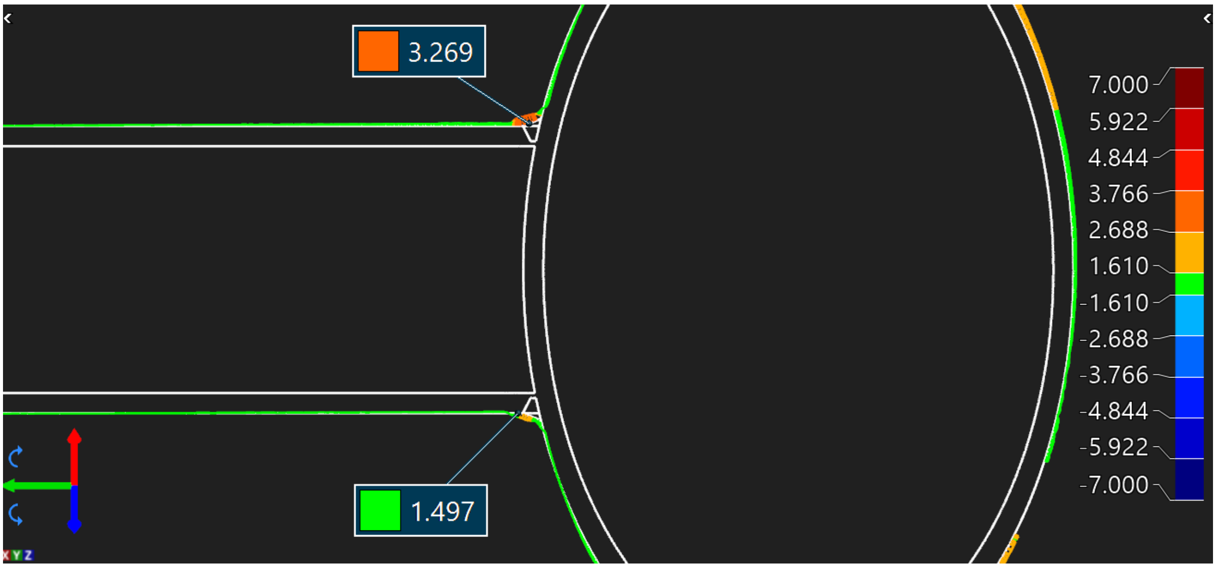


Figure 55 Specimen #4 cross section γ=30°

All the specimens welds shows to exceed not only LMC but also MMC reference profile, Figure 56. Sometimes extra portion of material in welding seam is a few millimetres thick. An average shape of weld is more similar to a fillet weld, or at least the toe is much longer (in the direction of chord axis) and visibly concave making a smooth transition between brace and chord wall at a more gentle angle. From other perspective, the standard [I] allows for much higher profiles (in direction of brace) where the inspected welds usually do not follow the MMC in that region.

It was noticed at some specimens a negative deviation appears in the area surrounding weld toe, on a chord surface as shown for example in Figure 54. That might be a trace of heat distortions.

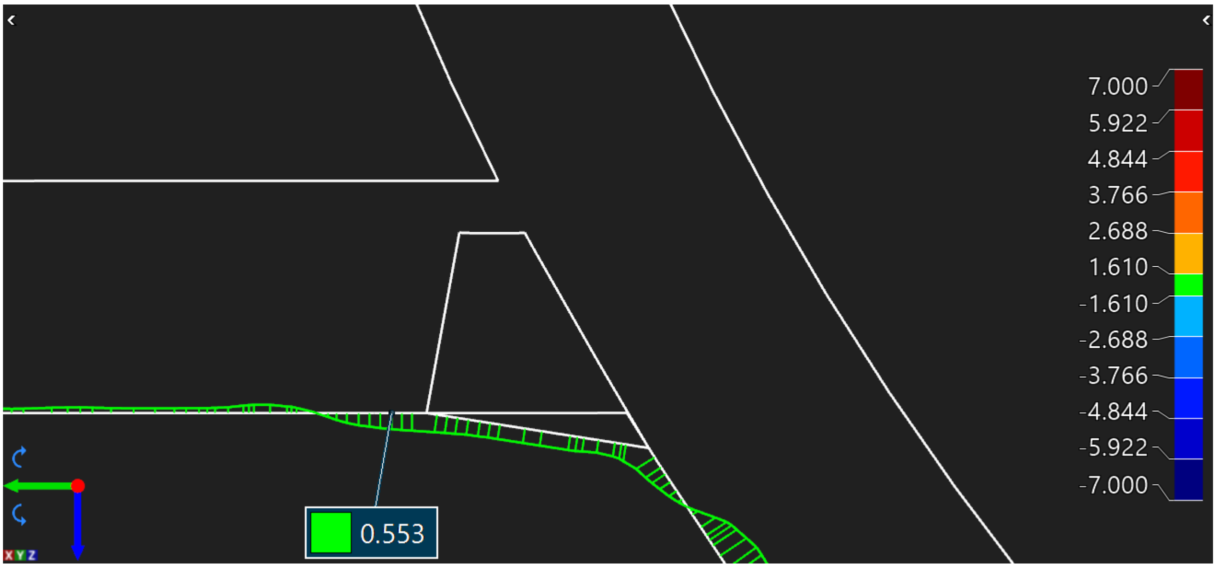


Figure 56 Specimen3, detail of weld profile in the saddle. This specimen is one of the closest to the LMC standard profile geometry.

A Table 9 below is a short statistic summary of mesh inspection. Please see the reports (for details in Appendix B.

Table 9 Basic comparison of tolerances between specimens

Specimen no	**Report number**	**Brace Angle [º]**
#1	S31655-4000-T-03	89.374
#2	S21655-4000-T-04	89.557
#3	S31655-4000-T-05	89.499
#4	S31655-4000-T-01	89.952
#5	S31655-4000-T-06	89.350
#6	S31655-4000-T-02	89.329
#7	S31655-4000-T-07	89.692
Mean		89,536
Standard Deviation		0,225

Standard deviation was calculated considering a small sample correction (N=7) according to the below equation.

Equation 43

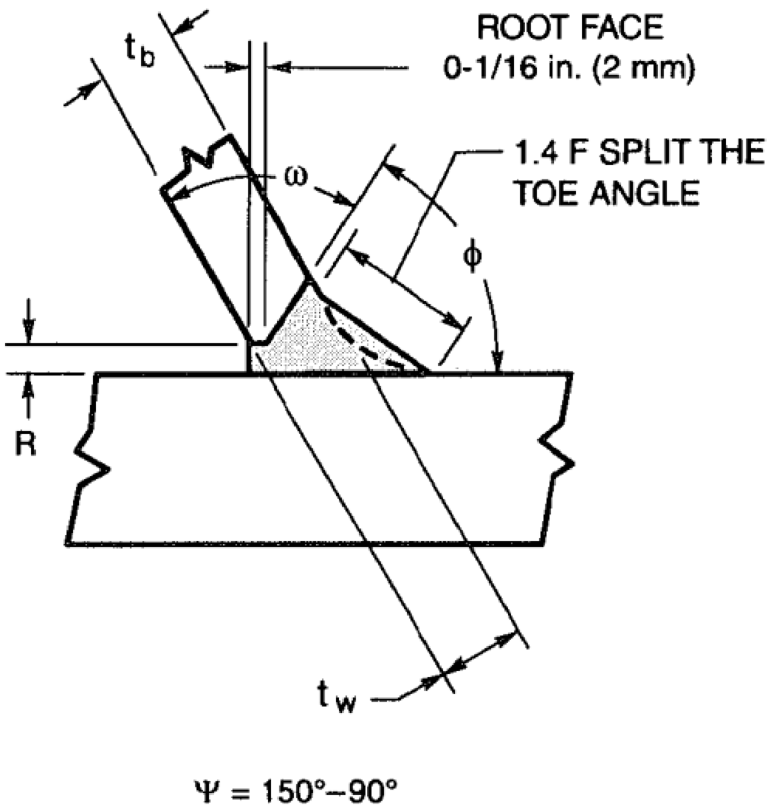
$$SD = \sqrt{\frac{1}{7-1}\sum_{i=1}^{7}(x_i - \mu)^2}$$

The angle measured is always less than the desired 90º +/- 0.333º and this is due to symmetry of specimens – top and bottom was not indicated in inspection. Worth to highlight that the mean angle 89.536 º does not fall under the tolerance zone, what reflects the fact that only one specimen (#4) passes the very coarse class of angular tolerance. The statistic sample N=7 is rather low what makes the standard deviation heavily biased.

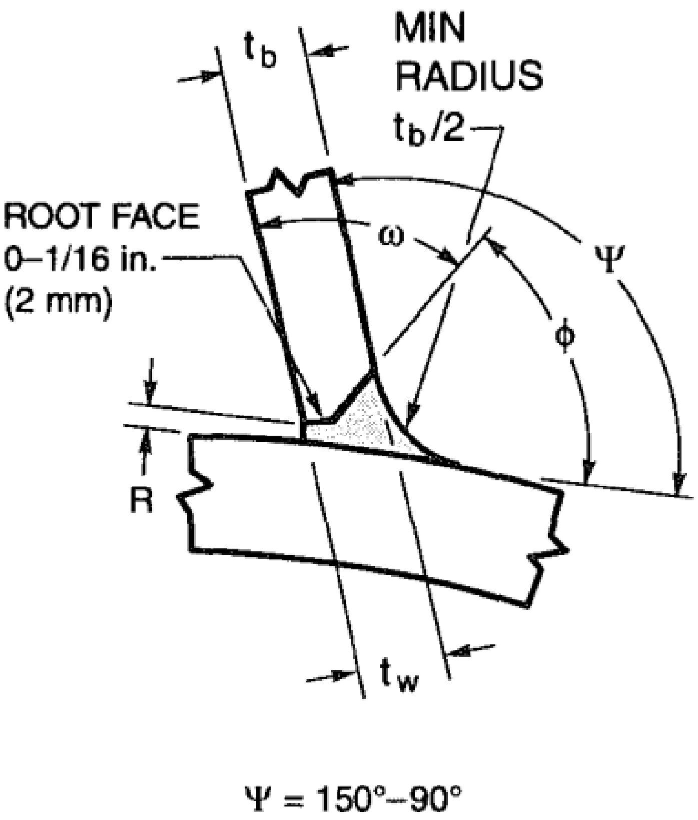
11 Improved weld Profiles for increased fatigue resistance per AWSD1.1

For the purpose of enhanced fatigue behaviour, the following profile improvements may be undertaken for welds in tubular T-connections (Y-, or K- too) as guided by Fatigue Behaviour Improvement section of [I] as illustrated on Figure 58:

- A capping layer of weld may be applied to achieve the welded surface merges smoothly with the adjoining base metal, and approximates the profile shown in Figure 58. The profile can be then checked with a disc an wire to proof smoothness and lack of notches greater than1mm. The method is described slightly wider below and illustrated in Figure 59
- The weld surface may be ground to achieve the profile shown in Figure 58. Final grinding marks shall be only transverse to the axis of weld.
- The toe of the weld may be peened with a blunt instrument [I]. Where 'peening' is a coarse manufacturing method of strike the surface with a hammer or the peen of a hammer. Its aim is to lead to local plastic deformation what smooths the transition between weld and base metal. It also inducing a compressive residual stress in the volume of weld. The standard [I] advising peening after visual inspection, and followed by magnetic-particle inspection (surface NDT method). A shortcoming of weld peening can be possibility of locally degraded notch toughness.



- *Figure 57 AWSD1-1 2000 (2010) [I] figure 3.9 Detail B adequate for the dihedral angle range on T-joint - Standard Flat Profiles for Intermediate Thickness*



- *Figure 58 AWSD1-1 2000 Figure 3.10--Prequalified Joint Details for Complete Joint Penetration Groove Welds in Tubular T-, Y -, and K-Connections--Concave Improved Profile for Heavy Sections or Fatigue (see 3.13.4)*

According to the Table 10 the specimen fabricated of 8 mm thick tubulars does not fall under any requirement of 'reinforced' weld profile for increasing fatigue resistance. Based on that the required by standard [I] geometry of finished weld is sufficient as shown in Figure 57. However, a scenario says that the specimen present 'a scaled member' of real structure and on this basis a Concave smooth profile will be parallelly considered for unlimited fatigue category – see Figure 58 and Figure 59 for more detailed weld geometry. (the source figure number is always stated in a figure caption)

Table 10 Fatigue Category Limitations on weld size [I]

Table 2.7
Fatigue Category Limitations on Weld Size or Thickness and Weld Profile (Tubular Connections) (see 2.36.6.7)

	Level I	Level II
Weld Profile	Limiting Branch Member Thickness for Categories X_1, K_1, DT in. (mm)	Limiting Branch Member Thickness for Categories X_2, K_2 in. (mm)
Standard flat weld profile Figure 3.8	0.375 (10)	0.625 (16)
Profile with toe fillet Figure 3.9	0.625 (16)	1.50 (38) qualified for unlimited thickness for static compression loading
Concave profile, as welded, Figure 3.10 with disk test per 2.36.6.6(1)	1.00 (25)	unlimited
Concave smooth profile Figure 3.10 fully ground per 2.36.6.6(2)	unlimited	—

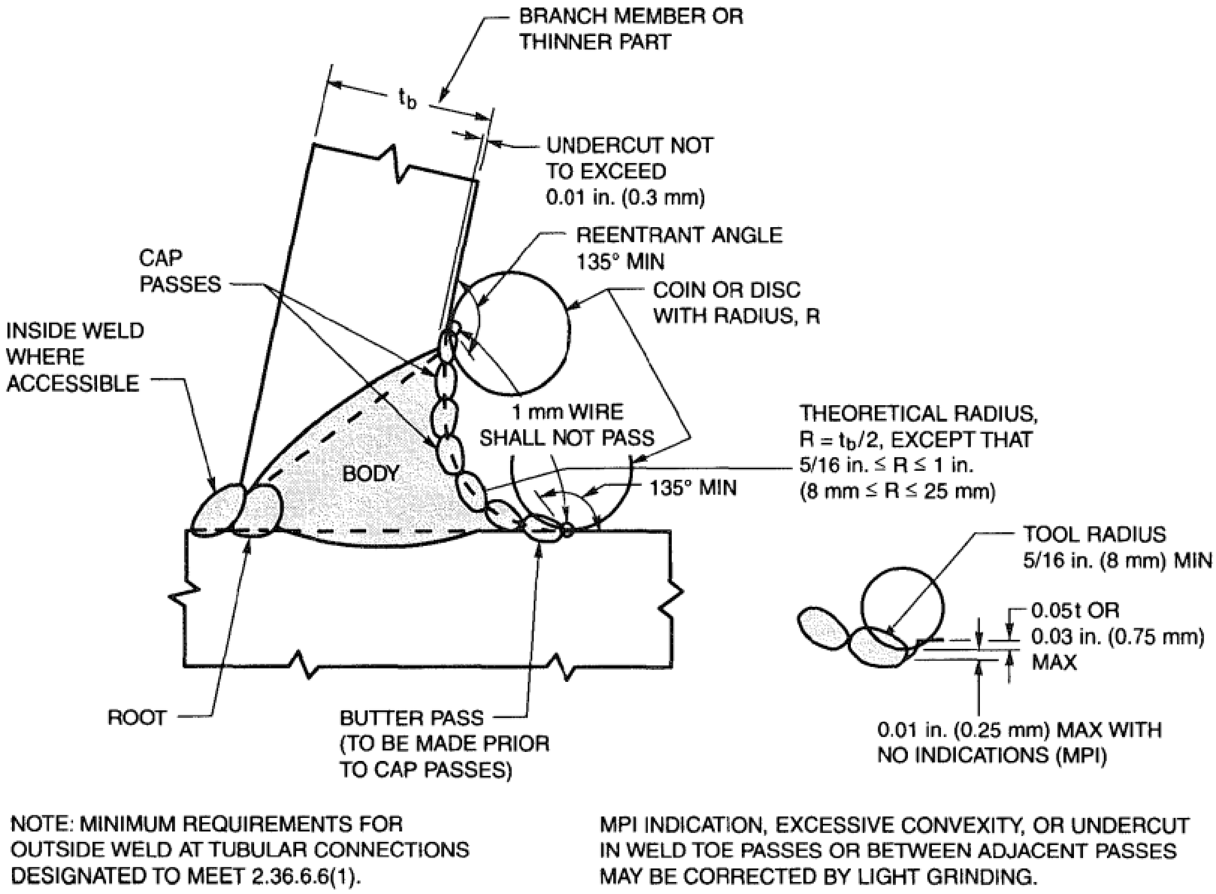


Figure 59 Figure C3.10 (C2.9 in 2010 edition)-Improved Weld Profile Requirements [I]

Figure 59 shows an offshore industry practice for improved weld profile. The desired profile is concave, with a minimum radius of one-half the branch member thickness, and merges smoothly with the adjoining base metal [I]. It is long established despite being not universally used.
Achieving the desired profile as-welded – to avoid expensive machining - generally requires the thorough selection of the two below factors:

- good wetting and profile characteristics welding materials,
- welding specialist experienced in the 'stringer bead wash pass technique' for various positions and geometries,

Usually high deposition rate processes in the overhead and vertical positions have difficulties in achieving the improved weld profile [I].

The standard [I] describes interesting and very approximated inspection method of the finished weld profile. This mostly visual method involves a disk of the specified radius test being applied to resolve borderline cases. Notches in the desired weld profile are unacceptable if a 0.04 in. (1 mm) diameter wire can be inserted between the disk and the weld, either at the toe of the weld or between passes, ref Figure 59.

Once grinding starts, note that the permissible notch depth is reduced to 0.01 in. (0.25 mm); merely flattening the tops of the individual weld passes, while leaving sharp canyons in between, does little to improve the fatigue performance [I].

Shot peening is less radical in its deformation effects, but also less effective in improving geometry.

12 Conclusions

According to chapter, all the inspected specimens weld profile passes the least material condition (LMC) required by the standard [I]. However, all of them exceeds at the same time the most material condition weld profile (MMC) in a vast number of analysed cross sections. Usually the surplus of deposited material is significant comparing to the weld thickness. Generally the welds fabricated, although conservative and of good visual quality, do not meet the standard [I] geometrical requirements.

The explicit geometry following AWSD1.1 requirements (Table 4 Joint and grove dimensions requirements AWSD1.1 2010 [I] Table 3.6 and weld profiles as shown in Figure 19, Figure 57, Figure 58) is complex in 3D. It has also a theoretical nature and could be considered as limiting boundaries only for a real manufactured shape. Particularly the end preparation, as mentioned, would be not cost effective, and it is usually only estimated with available technology (machines) not seldom by hand grinding with very limited end angle control.

The tubular end preparation geometry is crucial for correct (reliable) weld joint and the standard [I] devotes a lot of attention to this aspect. General industrial approach is about to manufacture a preliminary (or a test weld) for validation. This validation process includes destructive examination of weld. Typically a cut-offs are performed to check the geometry correctness according standard, such AWSD1.1. The pieces of the welded joints are then also subject for hardness check, microscopic visual examination, and even a tensile test on samples cut out from the weld. 3D scanning, or any other measurement method cannot replace these destructive tests. However knowing the outside geometry of weld can be useful for quality control of the repeated process. And has a great advantage of being non-destructive. It is possible to establish a process of semi-automated virtual inspection even using the VXelements™ software what is much more powerful manner of inspection than only visual check of weld quality, or the disc and wire method suggested in [I].

The angle φ definition is ambiguous, as the Figure 20 and Figure 57 does not take into account chord curvature, they perhaps presents only section through a crown, where it would be much more difficult to interpret in saddle.

The LMC weld joint model is able to be easily scaled. Its main assumption is a constant joint included angle all around the brace. Because this is dependent on very nonlinear function of dihedral angle, the resulting end preparation geometry has complex curvature. As mentioned in 8.4 it is rather not likely such geometry is manufactured and instead a constant end preparation angle will be chosen in the accepted by standard range. This will result in kind of conical - saddle surface that still can be challenging for a regular workshop capabilities.

The specimens were manufactured in intent to study a weld performance on a compact size model with vision of scaling the results for greater constructions. It is a common approach , frequently used in aerospace industry for issues of aerodynamics. It is important to notice that scaling has got its limitations on multiple planes. It is possible to scale the dimensions and keep desired shape on the model, assuming tolerances are also scaled. Nevertheless, the property of materials depend on its thickness, precisely for alloy steel the yield varies on thickness, being considerably lower in the middle of thick sections- refer to section 4.3. We cannot assume full uniformity of heat transfer on components with much different sizes. It is expected the ratio of energy introduced in weld process for considerably small thermal

capacity of welded components will be considerably larger than for those thick-walled. Thin and light component will cool down faster, hence the crystal microstructure will differ (it is common to overheat thin welded sections, making them brittle). Thicker walls are welded with multiple passes, as the energy source for welding is limited. Number of passes used slightly change also the geometry of welded section.
Not only the above needs to be considered when interpreting the scaled experiment results. As briefed in the chapter 0, the standard recognizes four weld profiles depending on the wall thickness - Table 10. This can be considered as effect of scale in reference to manufacturing costs: While a smooth weld profile transition can be implemented by multiple weld passes for considerably big joint, similar profile can be only obtained by machining on a small one. Because there is few passes or a single pass.

The MMC model, in definition being the upper tolerance limit for the weld volume is consequently exceeded at every measured specimen – as shown in the reports. From one perspective it means there is more material deposited, particularly in the weld toe area what virtually makes the joint stronger. This is true however mostly for static loads. In matter of fatigue resistance, the weld shape is not optimal according to [I]. Cyclic load mode emphasizes the importance of ‘hot spots’ and stress concentration points. They might be created due to not-smooth weld profile or increased transition angle between fillet and chord – the ‘as welded’ profile of weld toe.

Creaform application VXscan, paired with the scanner ‘HandySCAN 3D’ is really plug and play solution. Having no previous experience nor with this hardware neither the software I became an efficient operator in short time. The interface is clear and functions are intuitive. Comparing to a few 3D application I had previous experience I dare to name VXelements™ an user friendly environment. I can especially recommend the built in tutorials that enabled me to understand the application basic capacities quickly. A bit more demanding were options for automatic metrology report generation and settings for serial virtual inspection (of multiple specimens scanned meshes).

A drawback of the ‘HandySCAN 3D’ technique are the two demands for the measured surface preparation:

1. Need for reflective coat on the surface. It is possible to scan a bare surface, however as tested, the mesh quality obtained is compromising. Painting of a huge element is time taking and shall be done in portions, as the paint vanishing after time. The spray paint used is recommended for scanning and 3D printing industry
2. Application of the targets on painted surface is also time consuming. Each sticker needs to be placed manually in quite dense pattern what for the specimen of this size resulted in hundreds of targets. Please remember the time is running and the paint will not last long, and this operation needs to be done quickly.

Summarizing, the acquisition of geometry by hand laser is only a fraction of time used for surface preparation. Need of paint and targets application results in limited usage for huge structures and completely excludes this method from subsea sector (underwater operations). In my opinion, however it was not a scope of the study, use the scanner outside premises is also limited, mostly by atmospheric conditions. Nevertheless the scanner surprised me with efficiency and ease of use in laboratory and industrial (meaning the painting booth) environment. An advantage is undoubtedly that the system is completely portable – all fits in a purposed hard plastic suitcase.

There is an alternative solution to HandyScan3D relaying on the targets stuck to the surface. The MetraSCAN 3D projects a laser cross on the surfaces of the part that is observed by two dual sensors, which are mounted on the scanner to record the data. It means the principle of triangulation is used to locate the scanner and part as well as to take measurements. The accuracy of this scanner is not affected by environmental conditions, like vibrations. Moreover, this solution offers a very high volumetric accuracy [III].

Although angle between the axes is kept around 90º only single specimen passes the inspection, see chapter 10. The measurement shows that the effecting displacement of the brace end cap is huge (up to 5mm) and generally not acceptable by tolerances on so short length of tubular. This serious displacement can cause problems at future fatigue test on a machine. An upgrade to dimensioning method on the manufacturing drawing could solve this problem. It is worth to notice when talking on tolerances that they were not called out in the manufacturing drawing. Instead a standard [II] was referenced but it does not provide the perpendicularity tolerance. Proposed solution is to dimension the end cap centre (the nose) of brace referring to one end of the specimen chord or/and require a tolerance of position on the brace axis with required value. Suggested tolerance field is of ø3.2 mm, as mentioned in chapter 8.3.

13 Appendices list

Table 11 List of appendices

No:	Appendix topic
A	SJA – Safe Job Analysis
B	Virtual Inspection Reports – series of 7 metrological reports for specimens, generated in VXinspect application, named after serial numbers of inspected specimens.

14 List of tables

15 Bibliography

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Appendix A Safe Job Analysis SJA

SAFE JOB ANALYSIS (SJA)

Department/Unit: Institutt for maskin, bygg og materialteknologi
Participants: Krzysztof Jan Kołos
Task: Welded specimen scanning
Date: 06.02.2022
Signature:

Subtasks	**What can cause an undesirable incident(s)**	**Possible preventive measures** (including training and protective equipment)
Lifting specimen	Handling the test specimen, as it is heavy and there is a potential danger of crushing fingers or toes.	Use proper lift techniques. Use PPE (hard nose shoes and gloves)
Transporting specimen on a trolley	Specimen can fall during transport from storage to laboratory and there is a potential danger of crushing fingers or toes. Training on usage of trolley.	Placing the weight centrally on the trolley. Use PPE (hard nose shoes and gloves) Fastening the specimen during carriage.
Overspray	The spray paint used for contrast on the scanned surface is not harmful for human being however in higher concentrations it can be irritating.	Make sure that ventilation in the room is accommodated for use.
	The aerosol is highly flammable	Keep the can away from open fire and heat sources. Do not spray next to a flame or any incandescent object. Do not smoke neither use an open fire during and shortly after the application of paint.
Specimen stability during scanning	Specimen during scanning is positioned vertically in its semi-stable state. It is possible it will fall once knocked off with a considerable force.	Secure specimen and area around it during scanning Make sure that the specimen is stable and in case of fall, it does not hit equipment or any human being.

Subtasks	**What can cause an undesirable incident(s)**	**Possible preventive measures** (including training and protective equipment)
Eye injury hazard - direct and reflected beam	The scanner users class 2 laser. Class 2 visible-light lasers are considered safe for unintentional eye exposure, because a person will normally turn away or blink to avoid the bright light.	Make sure you do not face the scanner to your eyes or somebody else. Do NOT deliberately stare into the beam this can cause injury to the retina in the back of the eye. Protective glasses are not necessary for class 2 laser operation.

Appendix B Virtual Inspection Reports

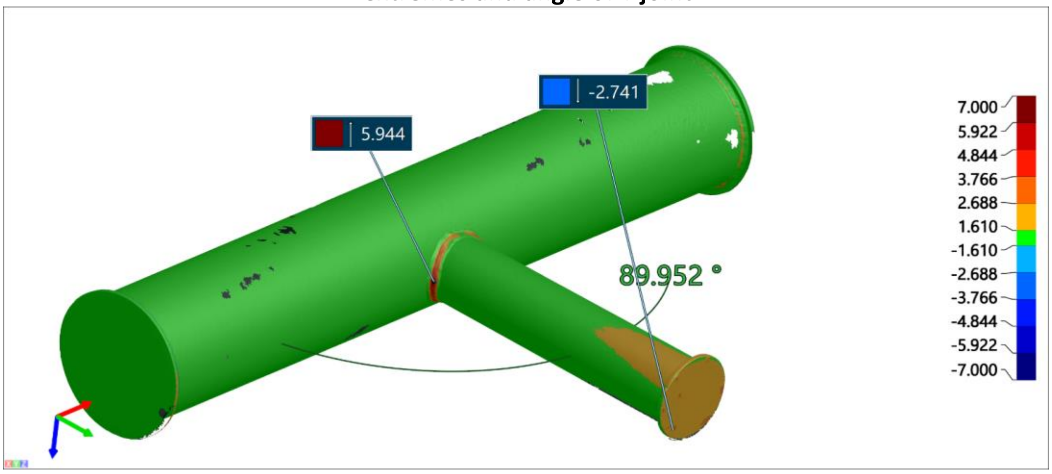
Project information

Organization	UIS
Units	mm

Part information

Part name	S31655-4000-T-01
Operator name	Kris Kolos

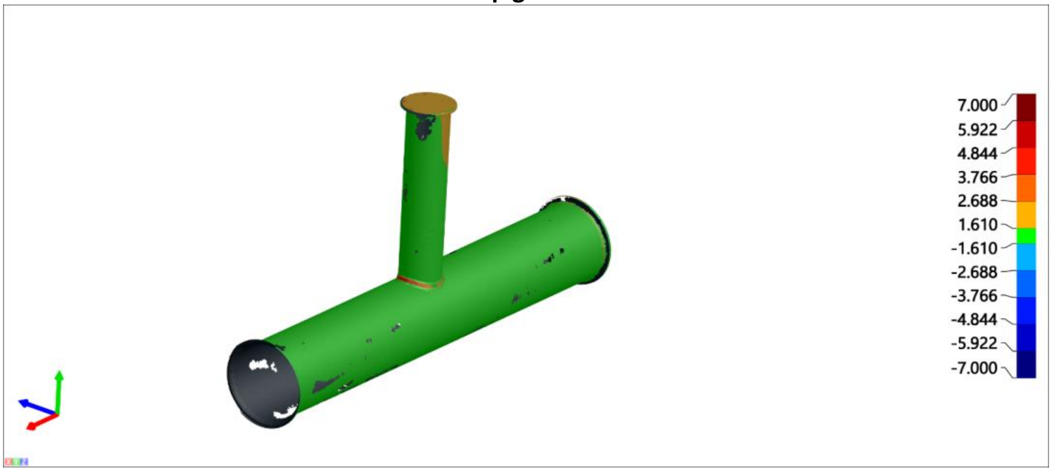
extremes and angle of T joint



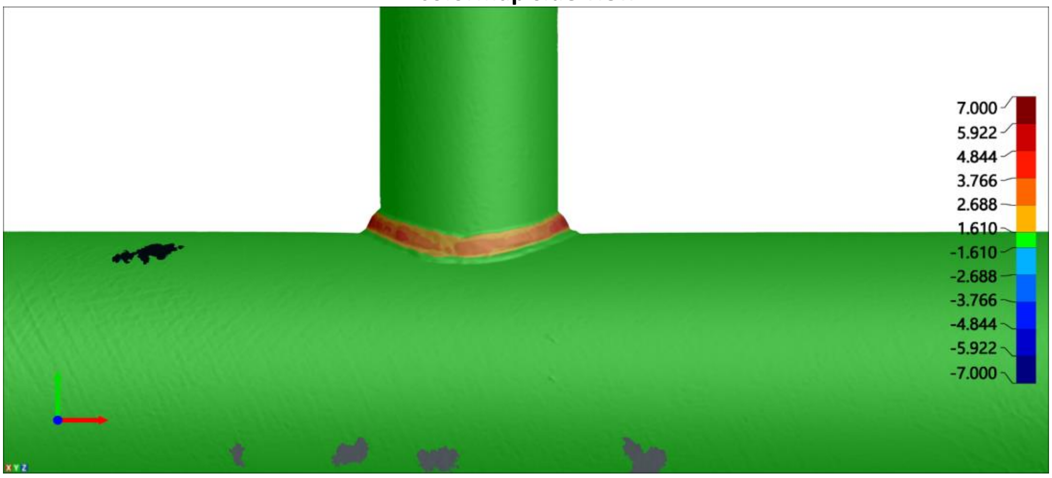
Color map 1 - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-2,741	-2,741	**-1,131**
Max.	1,610	0,000	5,944	5,944	**4,334**
±	3,220	0,000	8,685	8,685	**5,465**
SD	1,000	0,000	0,578	0,578	

colormap general view



colormap side view



Cylinder 1 - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,510	0,410	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		8,276		**3,896**

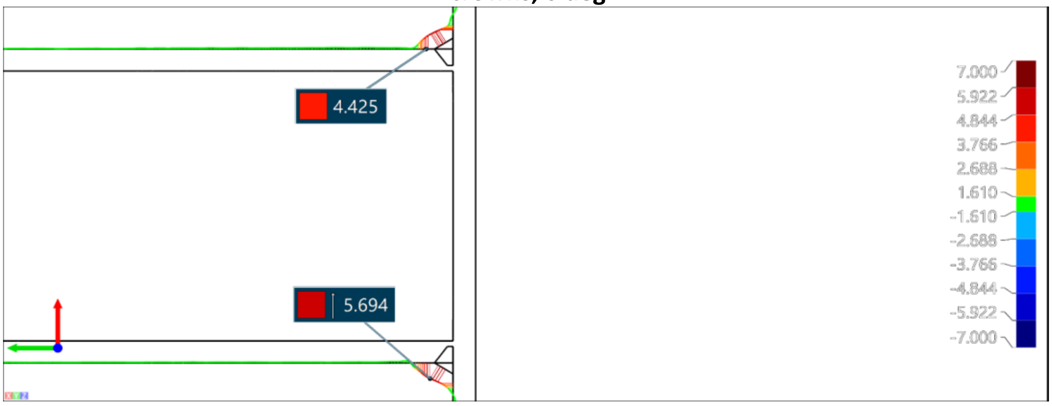
Cylinder 2 - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	115,650	1,350	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		4,017		**1,727**

Angle [°] - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,952	-0,048	
∠XZ	+0.333 -0.333	0,000	72,778	72,778	**72,445**
∠YZ	+0.333 -0.333	0,000	47,754	47,754	**47,421**

crowns, 0 deg



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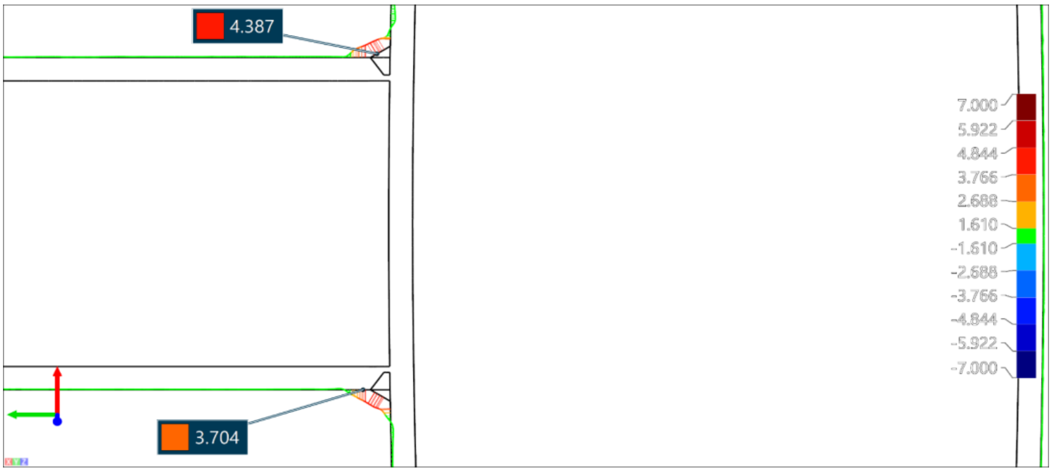

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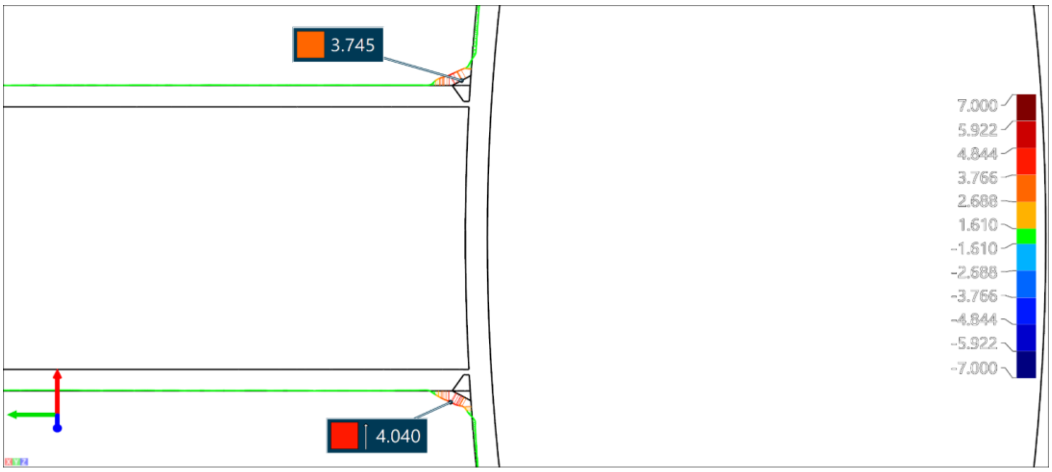

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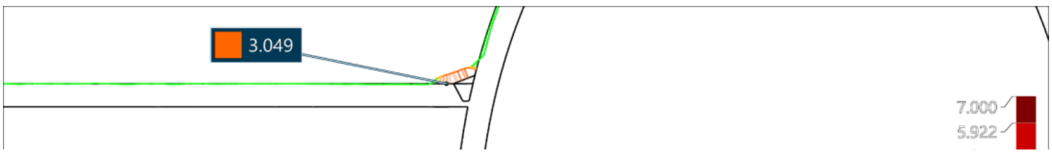

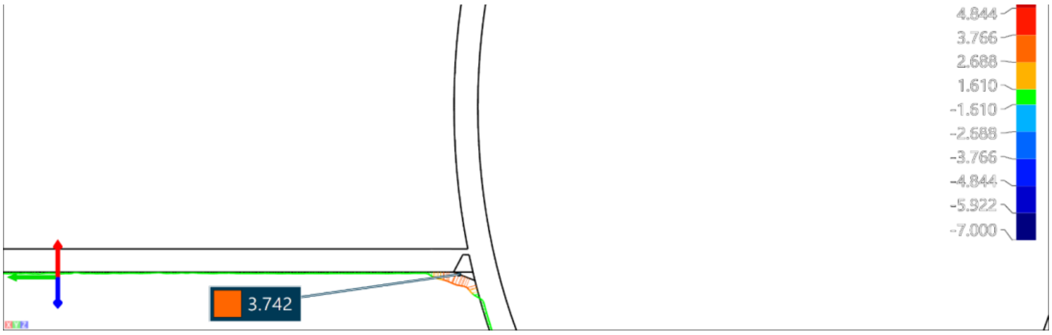
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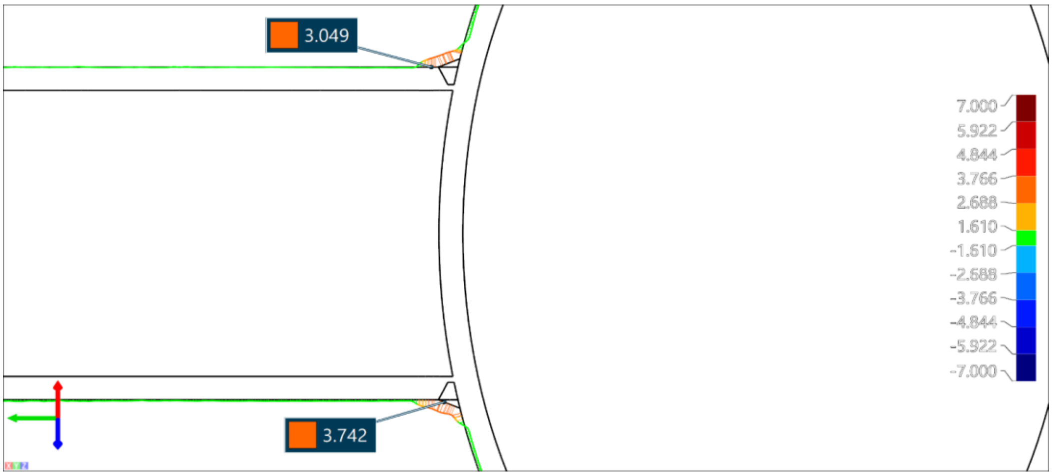
3.742

40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-7.000
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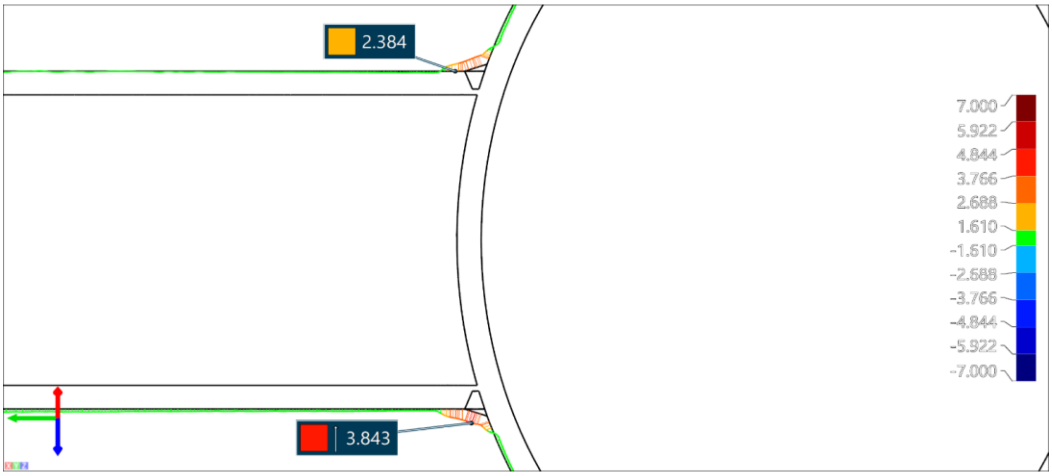
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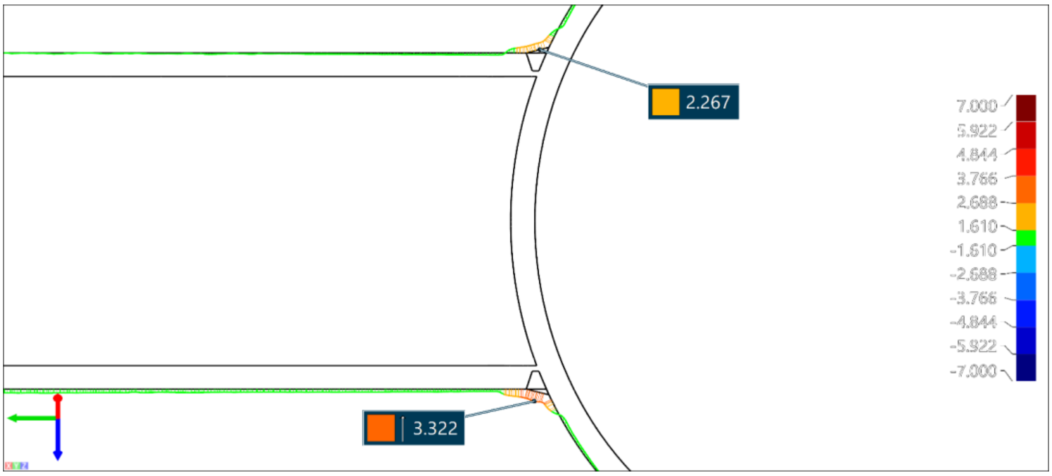
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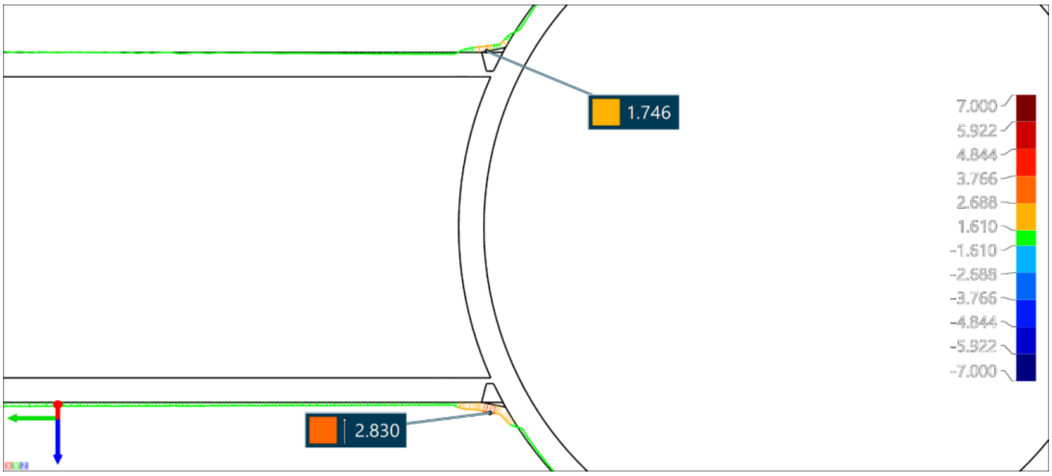
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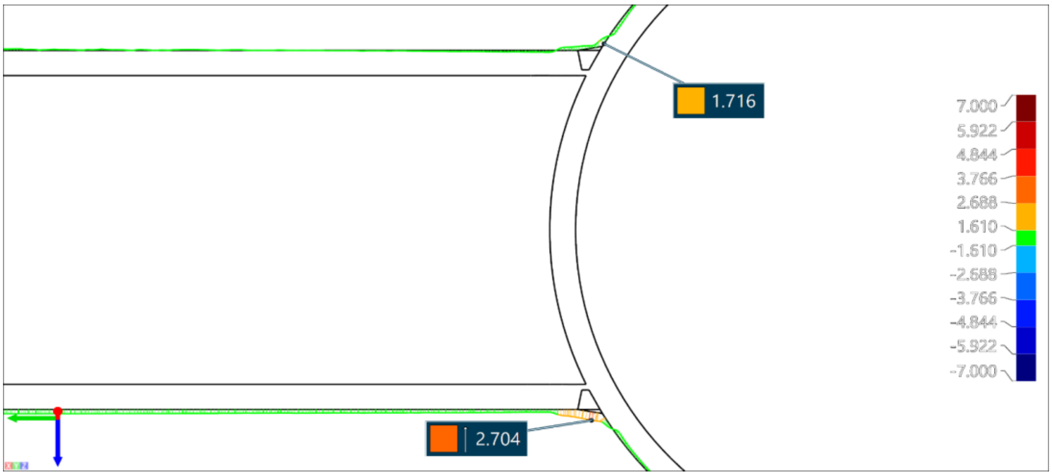
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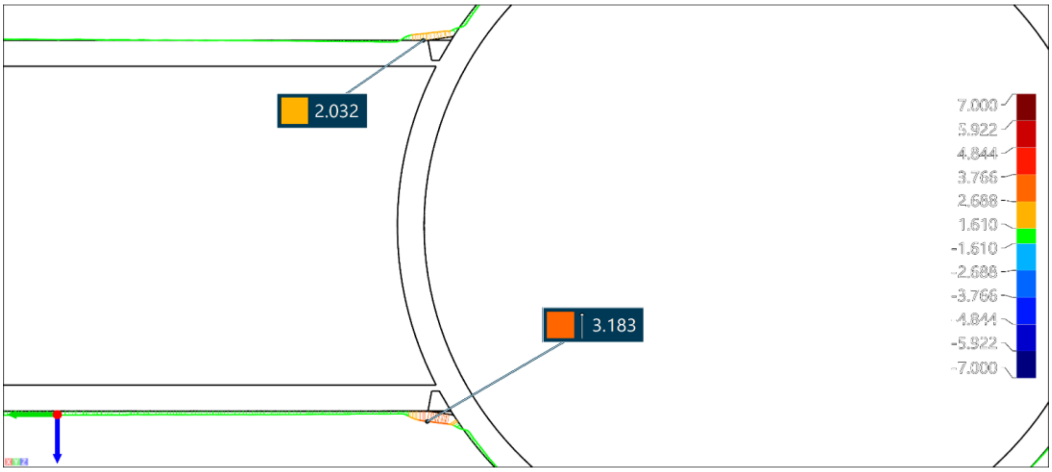
-7.000

saddle



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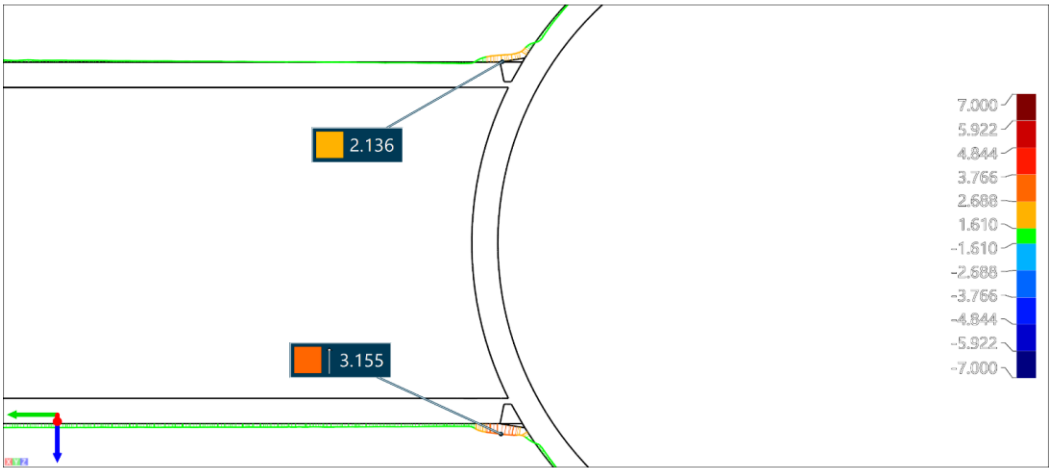

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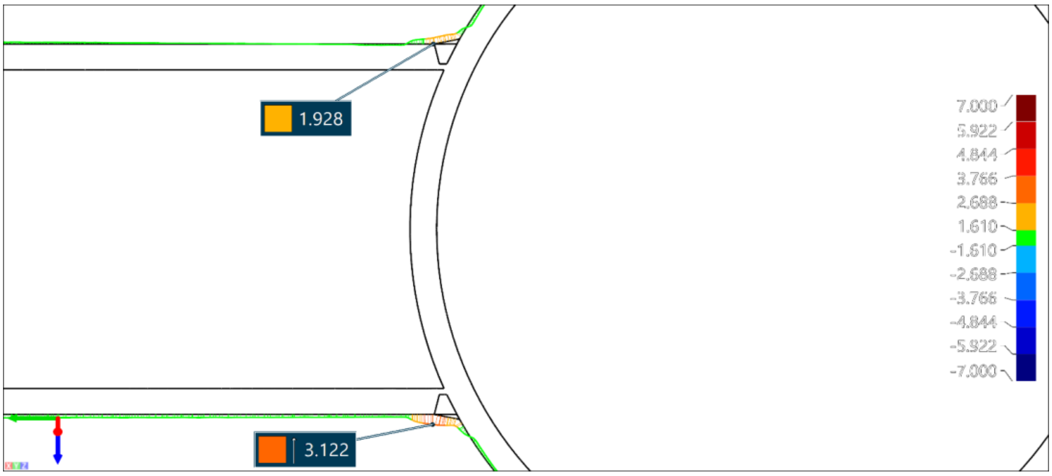

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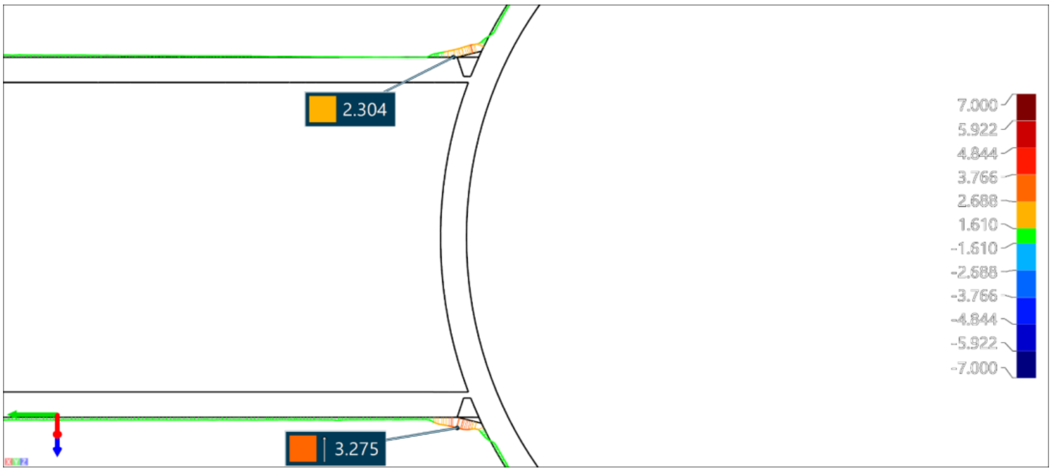

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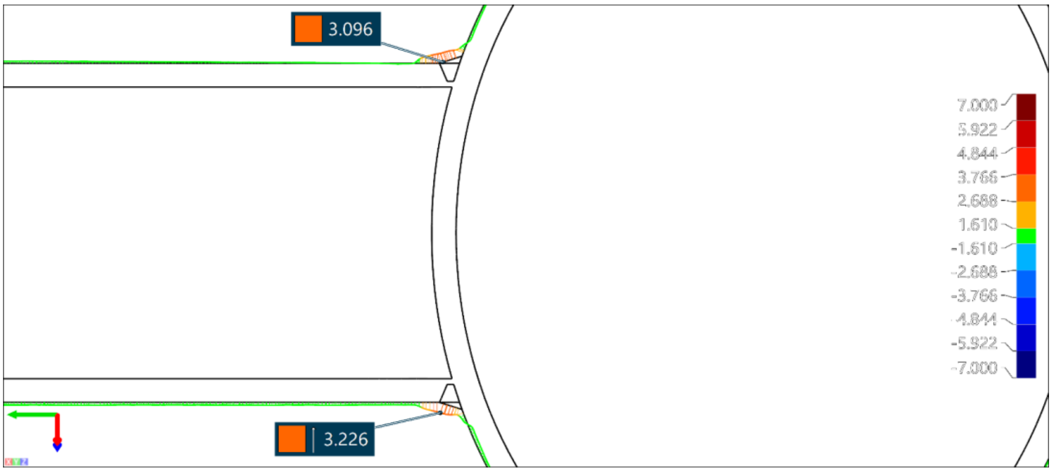
3.275
7.000
5.922
4.844
3.766
2.688
1.610
-1.610
-2.688
-3.766
-4.844
-5.922
-7.000

130



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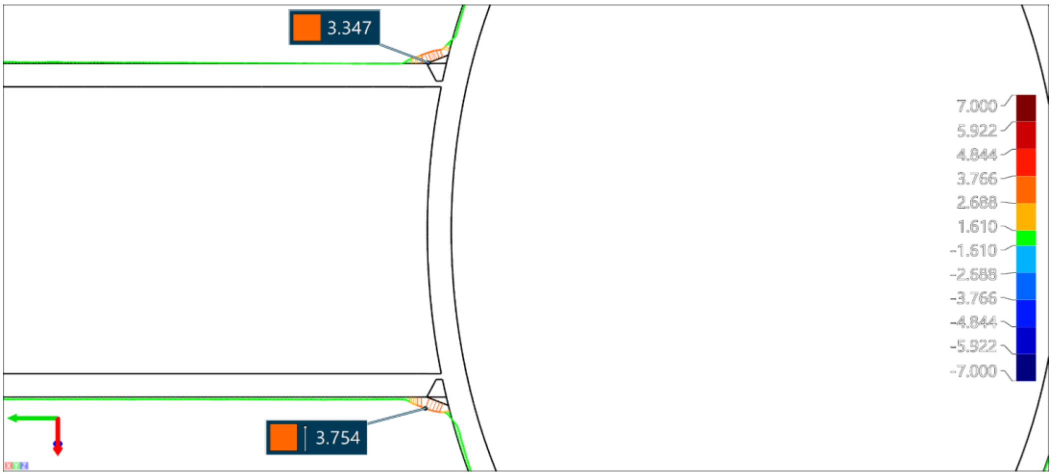
140



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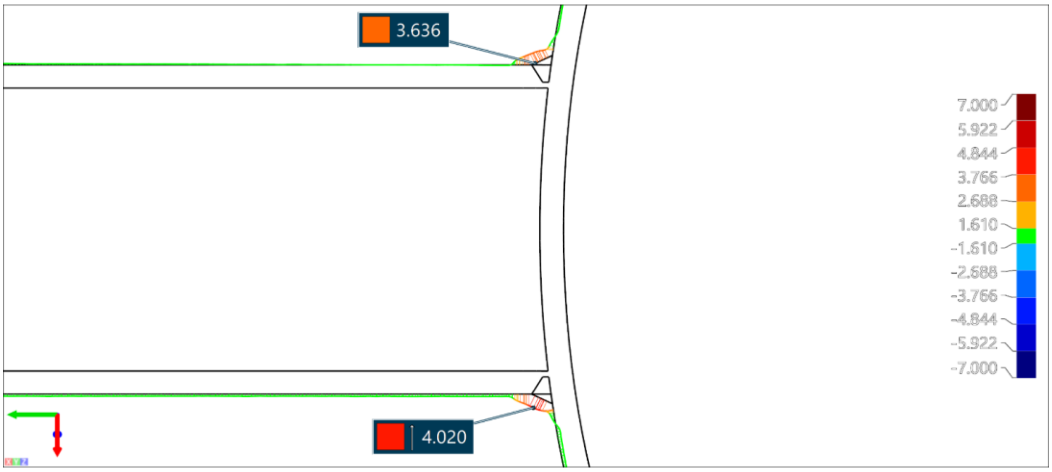
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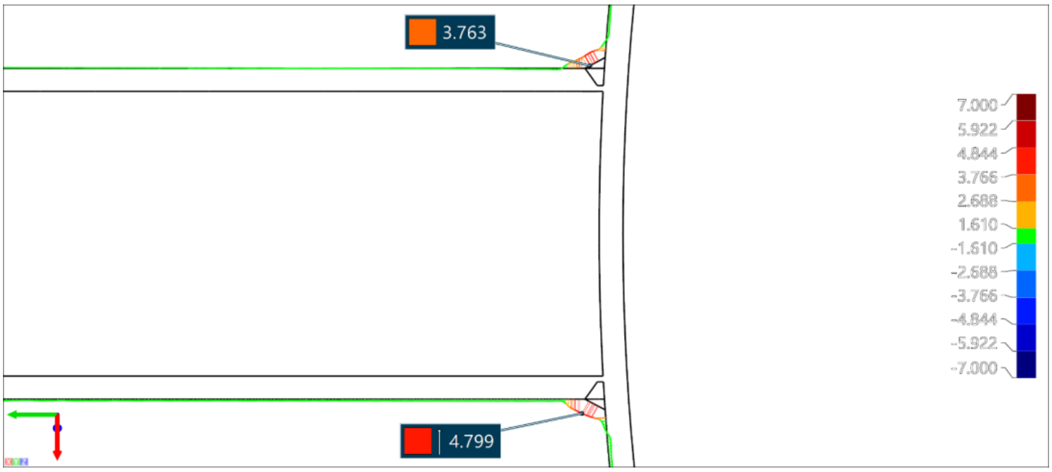
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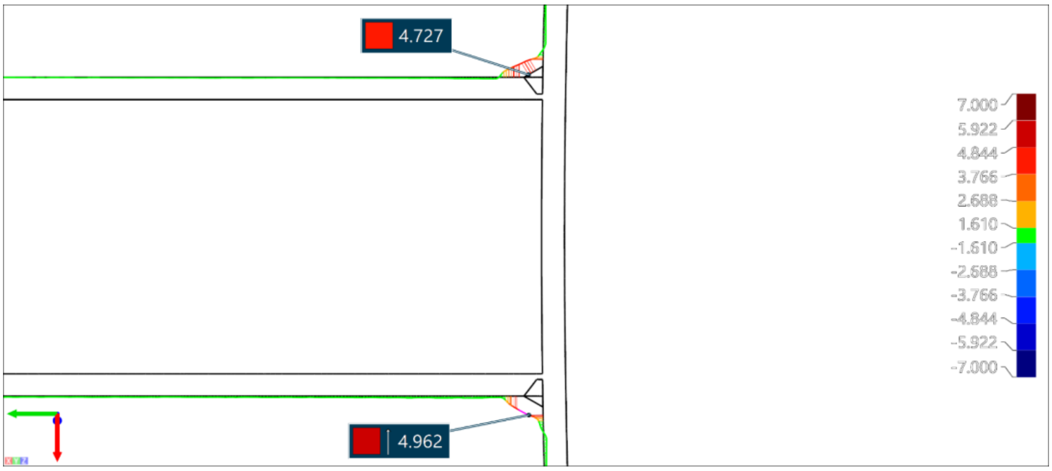
170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-4.844
-5.922
-7.000

MMC

Project information

Organization	UIS
Units	mm

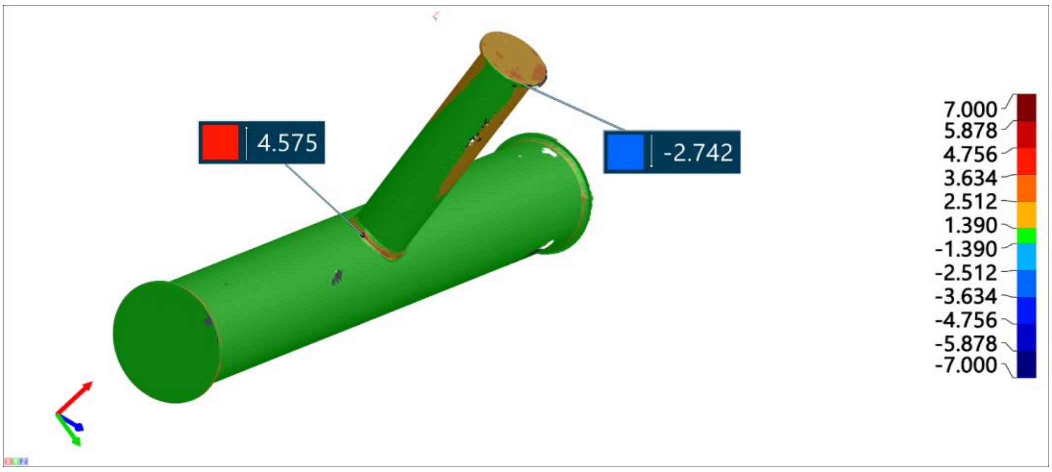
Part information

Part name	S31655-4000-T-01
Operator name	Kris Kolos

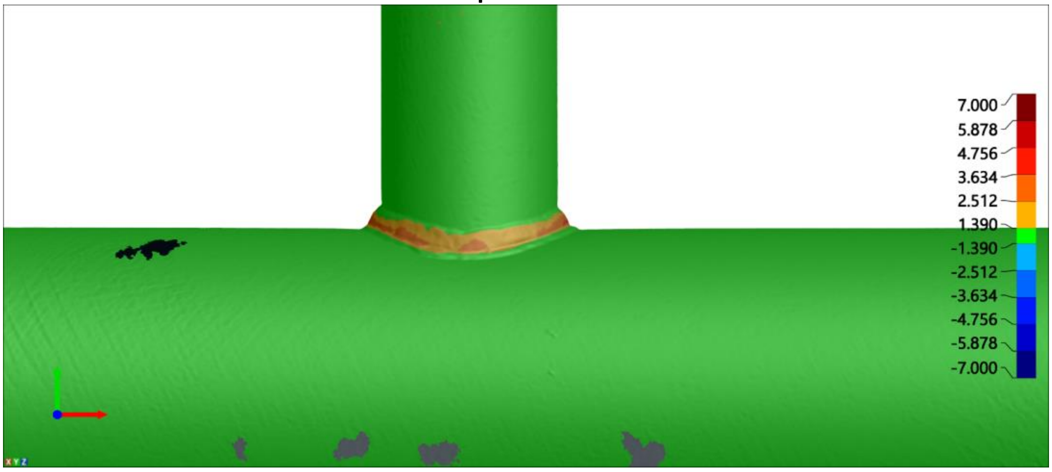
Color map 1 - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-2,742	-2,742	**-1,132**
Max.	1,610	0,000	4,575	4,575	**2,965**
±	3,220	0,000	7,317	7,317	**4,097**
SD	1,000	0,000	0,561	0,561	

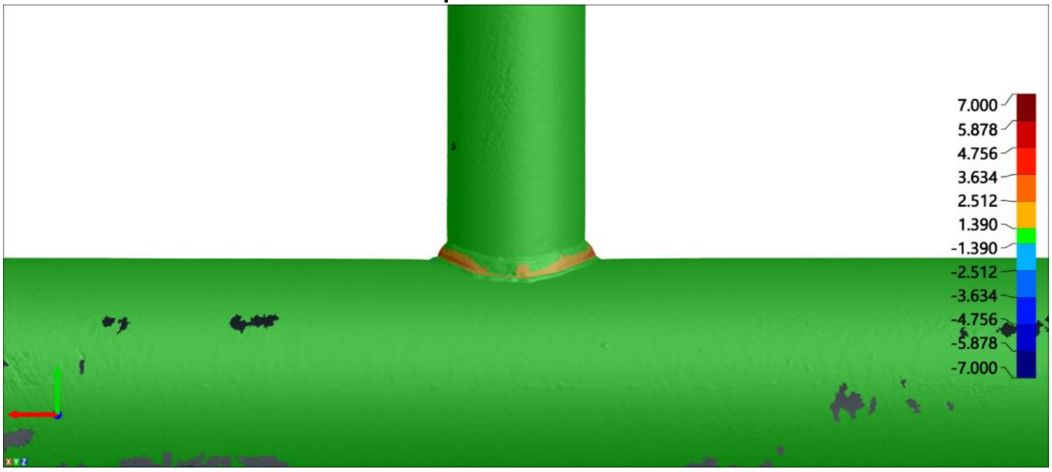
extremes at MMC



colormap side view MMC



colormap other side view MMC



Cylinder 1 - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,510	0,410	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4,380	4,380		8,276		**3,896**

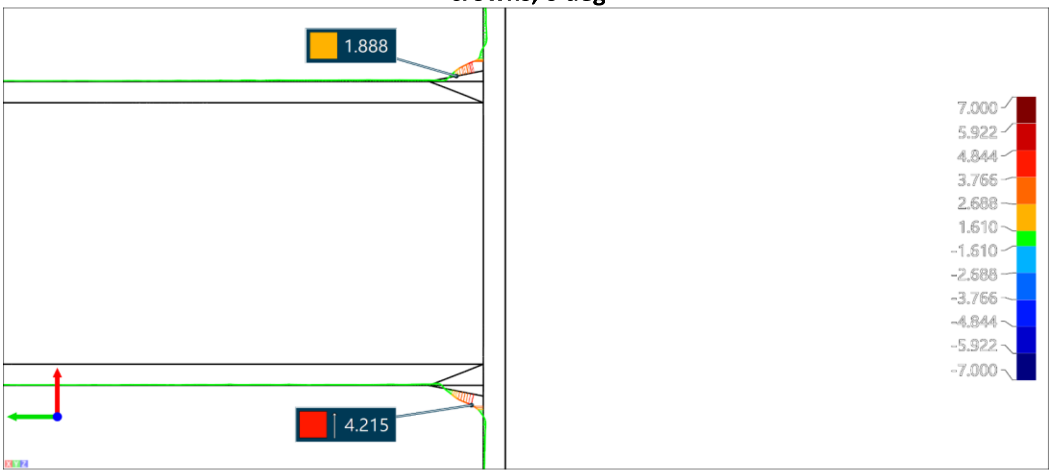
Cylinder 2 - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	115,650	1,350	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		4,017		**1,727**

Angle [°] - Scan4

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,952	-0,048	
∠XZ	+0.333 -0.333	0,000	72,788	72,788	**72,455**
∠YZ	+0.333 -0.333	0,000	47,261	47,261	**46,928**

crowns, 0 deg



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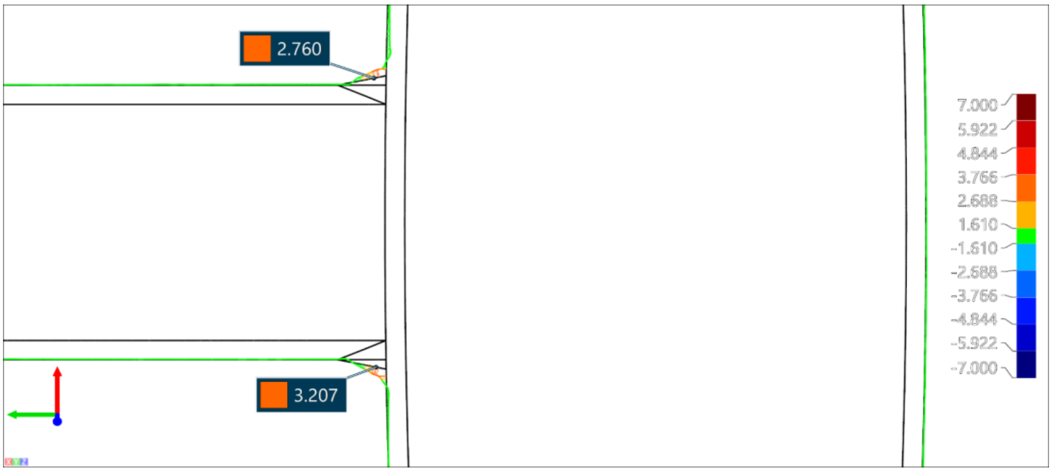
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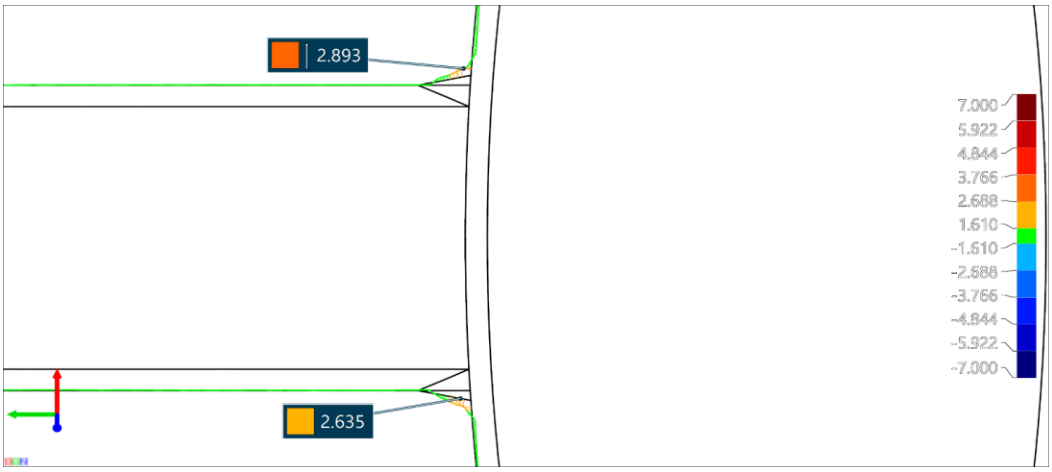
20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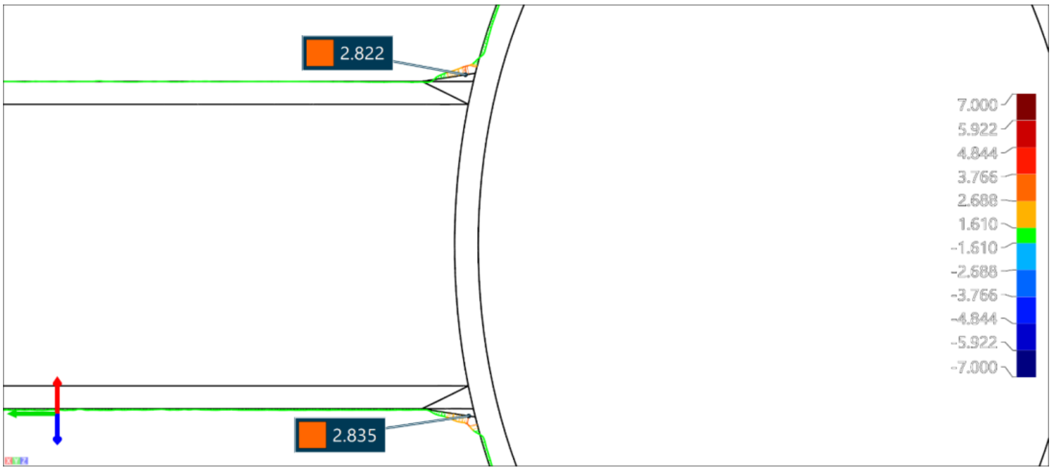
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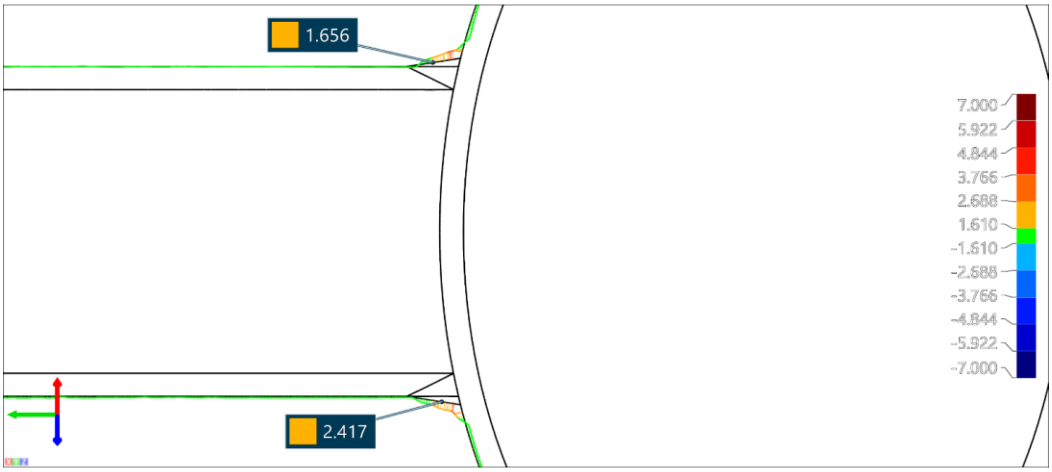
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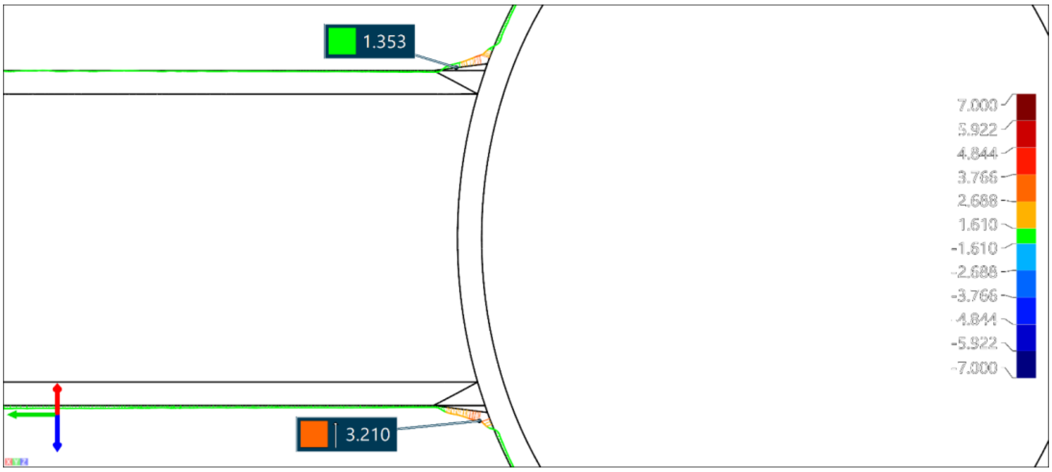
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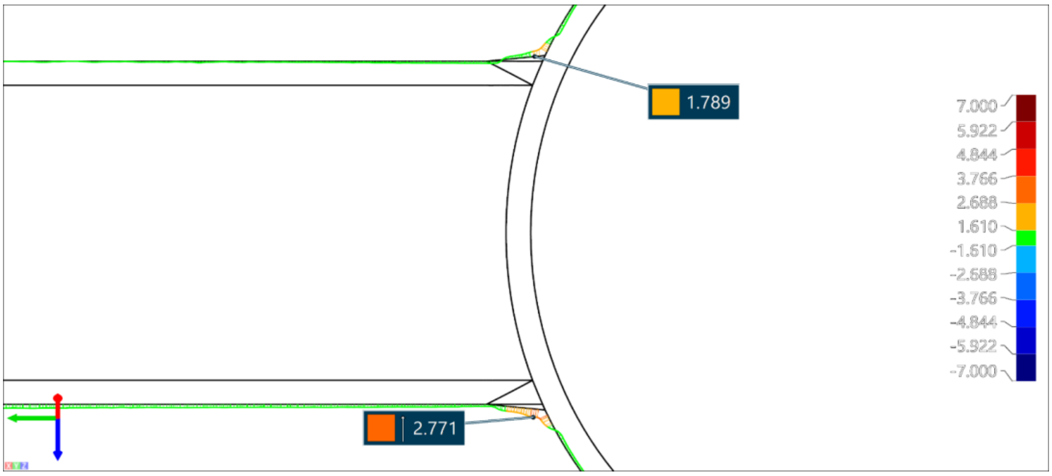
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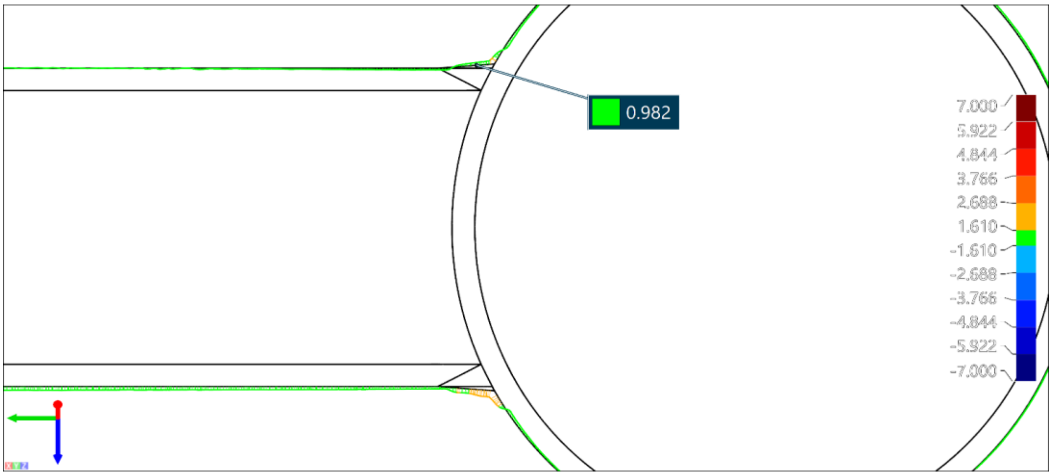
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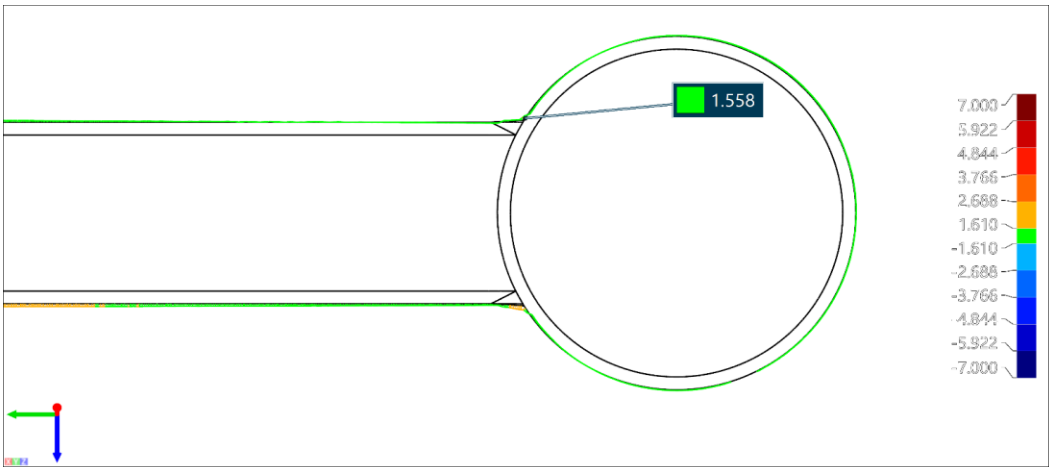
80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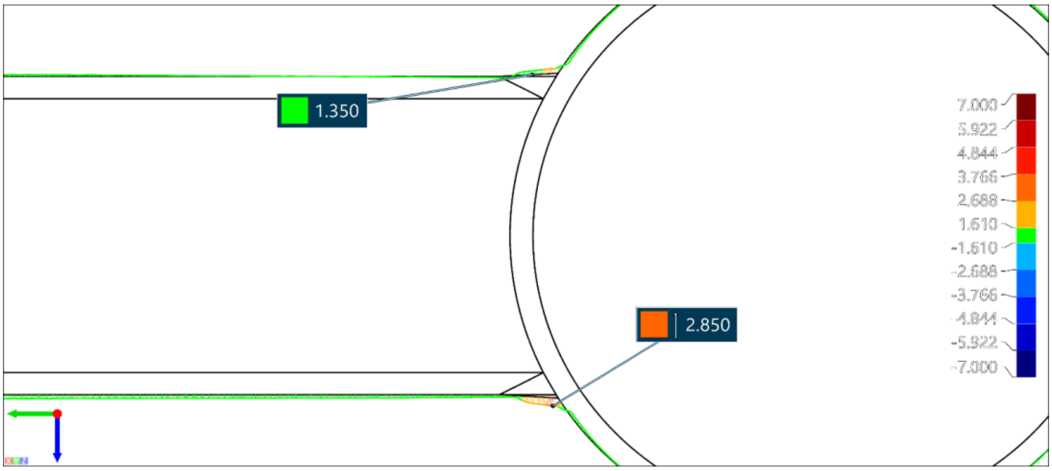
saddle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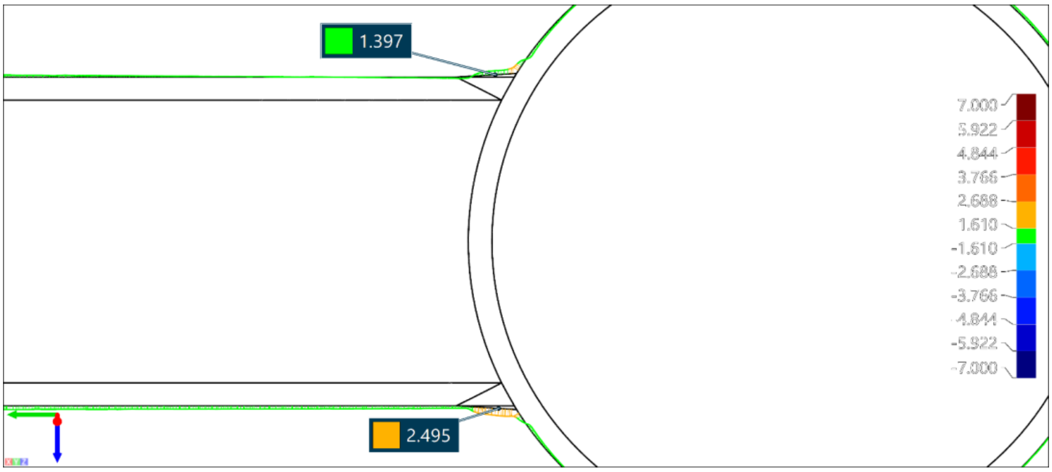
100



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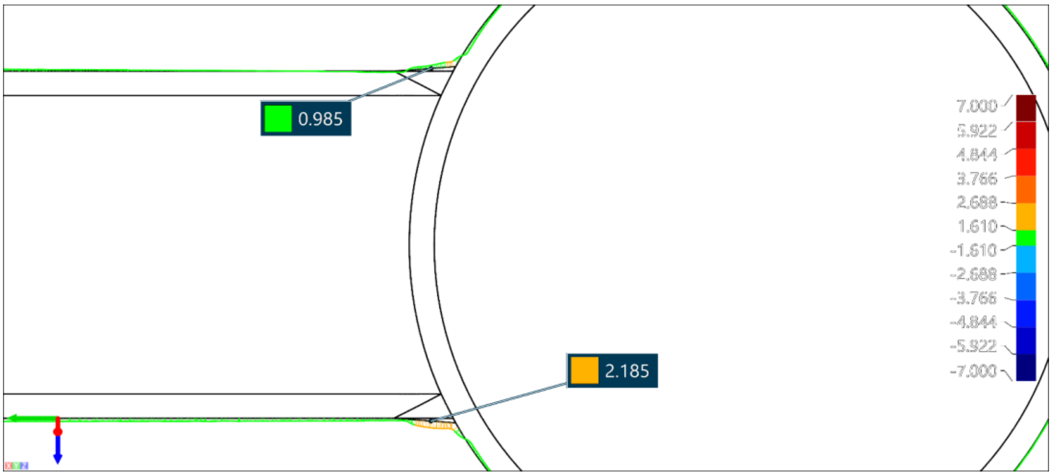

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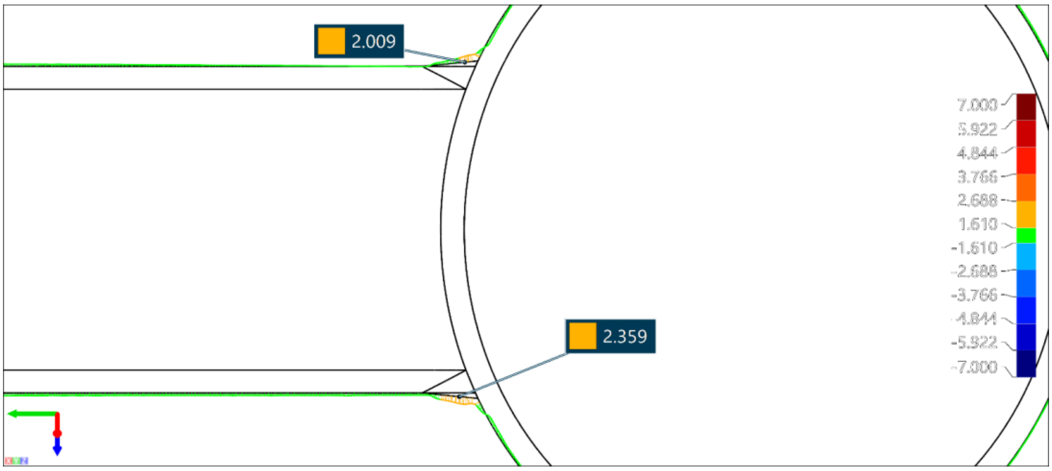

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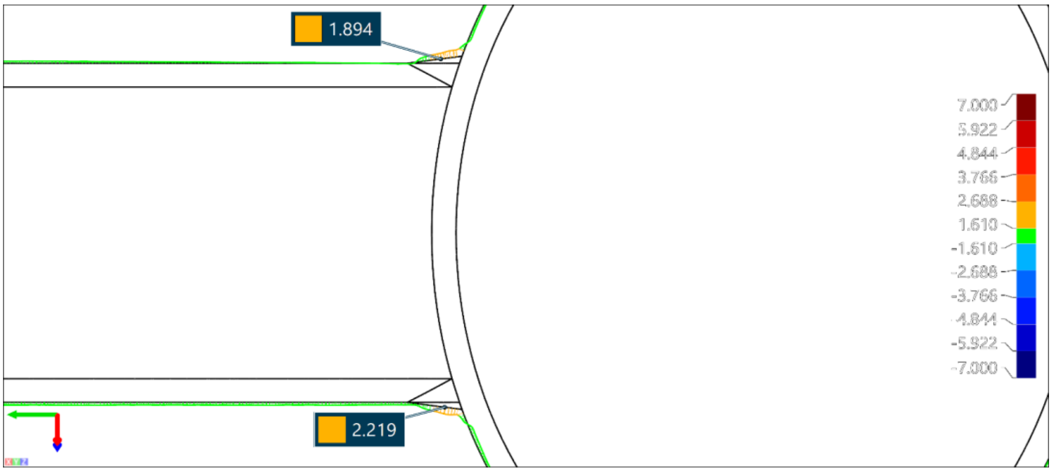
130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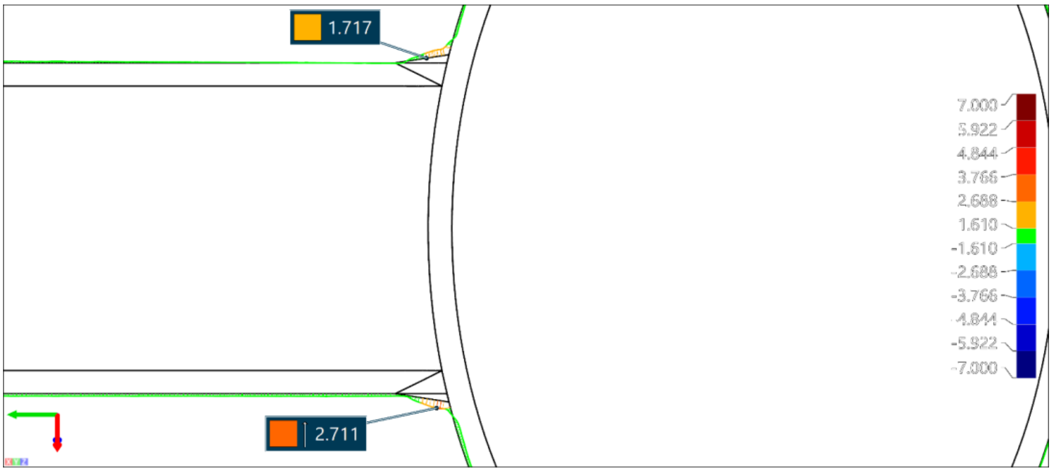
140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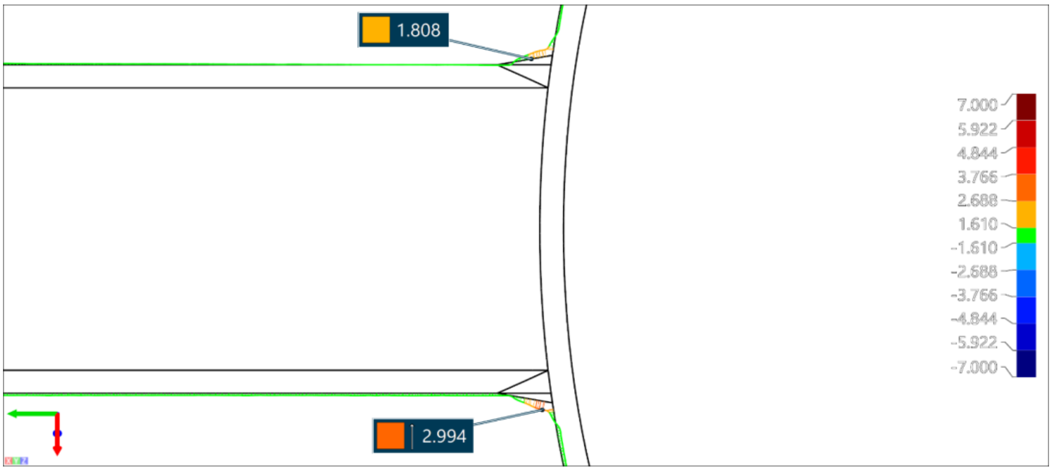
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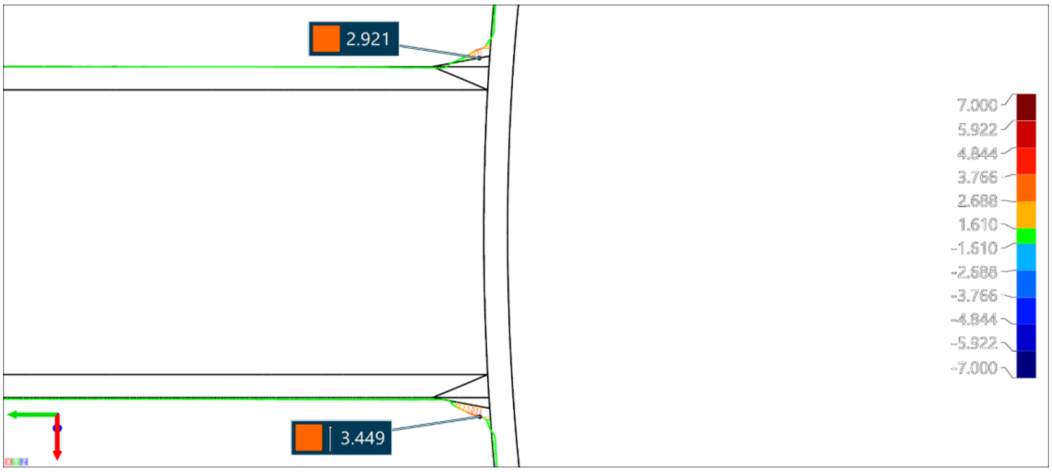
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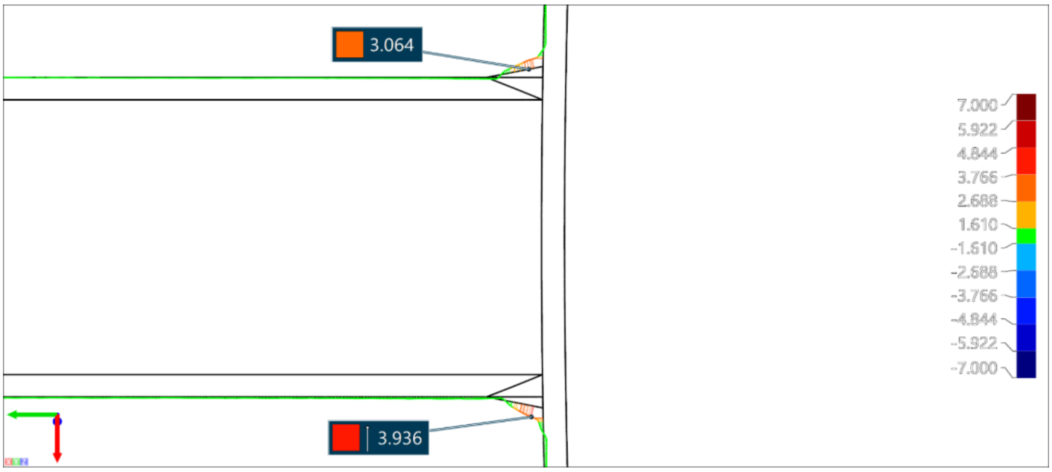
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-5.922
-7.000

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Report prepared by

Name ____

Date ____

Signature ____

Report reviewed by

Name ____

Date ____

Signature ____

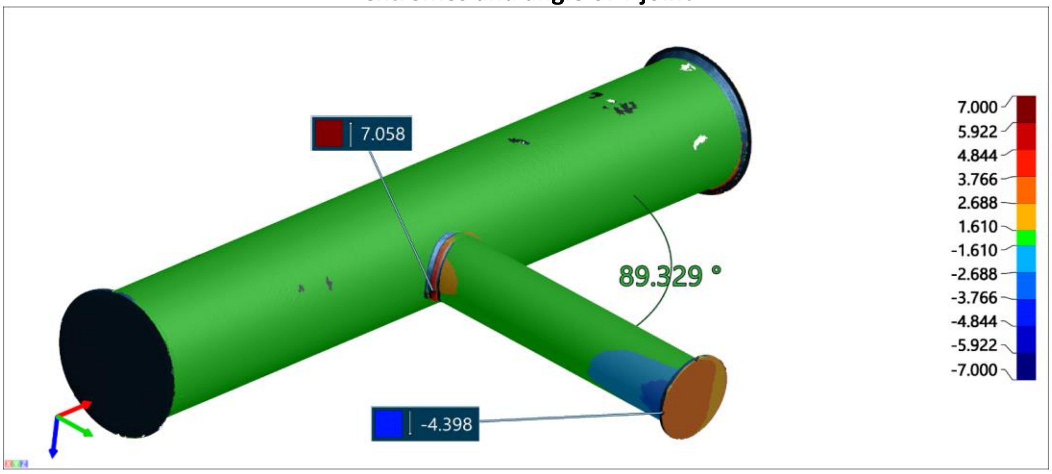
Project information

Organization	UIS
Units	mm

Part information

Part name	S31655-4000-T-02
Operator name	Kris Kolos

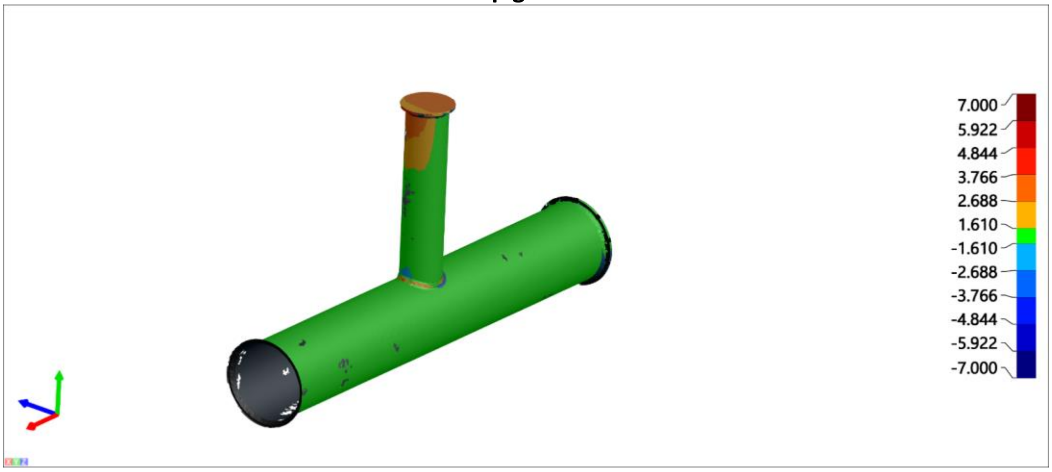
extremes and angle of T joint



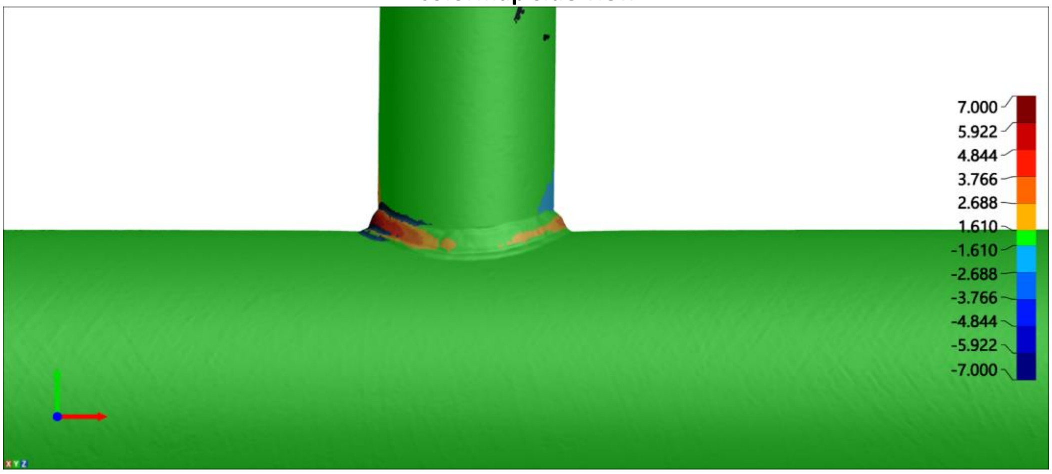
Color map 1 - Scan6

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-4,398	-4,398	**-2,788**
Max.	1,610	0,000	7,058	7,058	**5,448**
±	3,220	0,000	11,456	11,456	**8,236**
SD	1,000	0,000	0,770	0,770	

colormap general view



colormap side view



Cylinder 1 - Scan6

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∅	+3.540 -3.540	219,100	219,443	0,343	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		2,146		

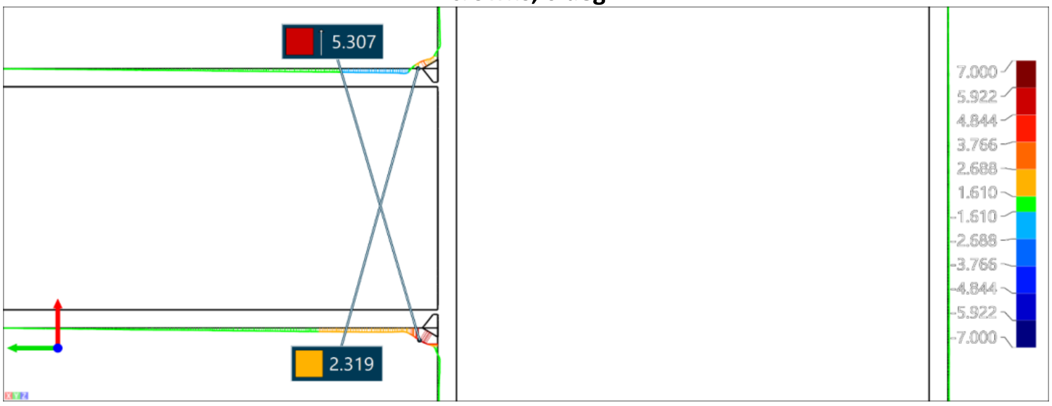
Cylinder 2 - Scan6

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∅	+1.610 -1.610	114,300	114,608	0,308	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		11,325		**9,035**

Angle [°] - Scan6

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,329	-0,671	**-0,338**
∠XZ	+0.333 -0.333	0,000	8,988	8,988	**8,655**
∠YZ	+0.333 -0.333	0,000	5,715	5,715	**5,382**

crowns, 0 deg



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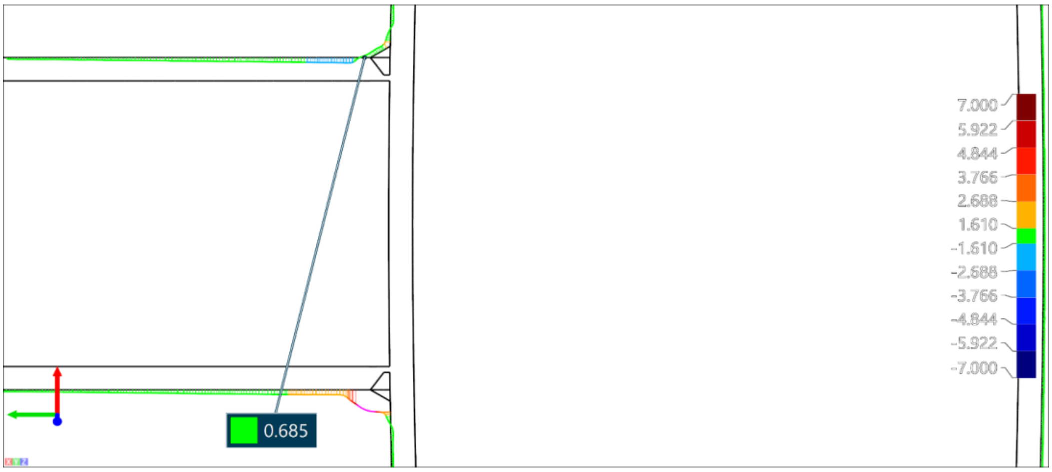

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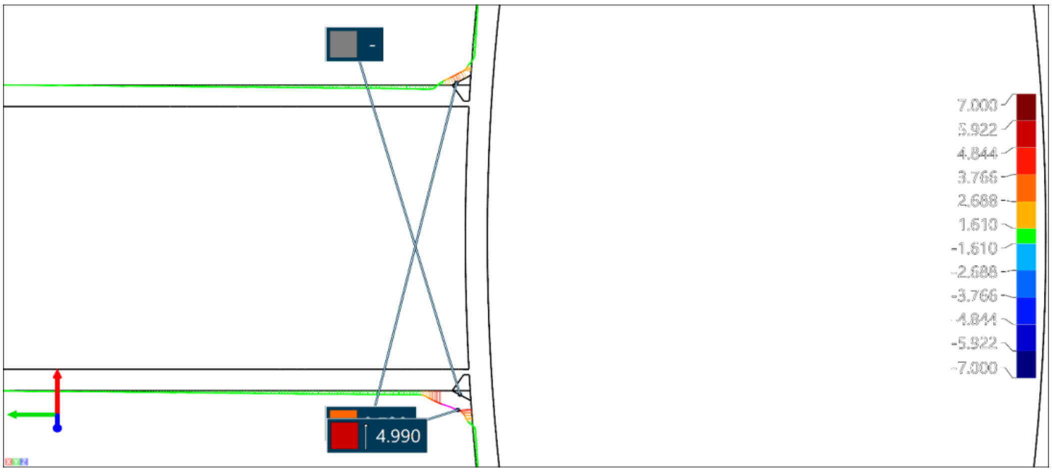

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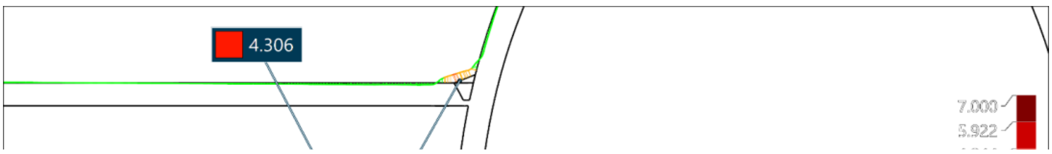

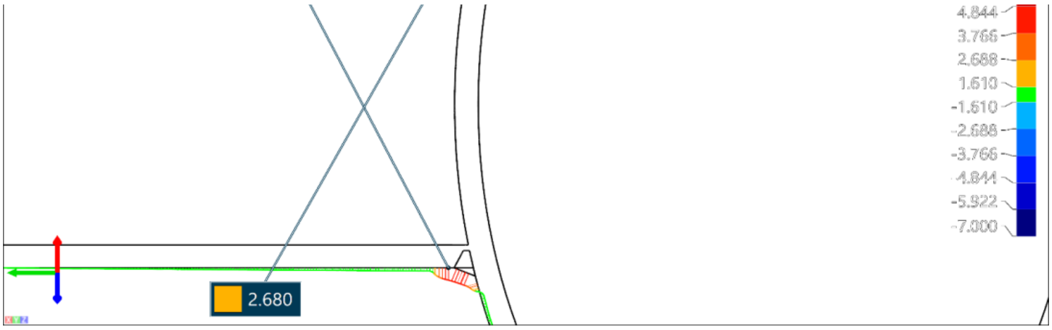

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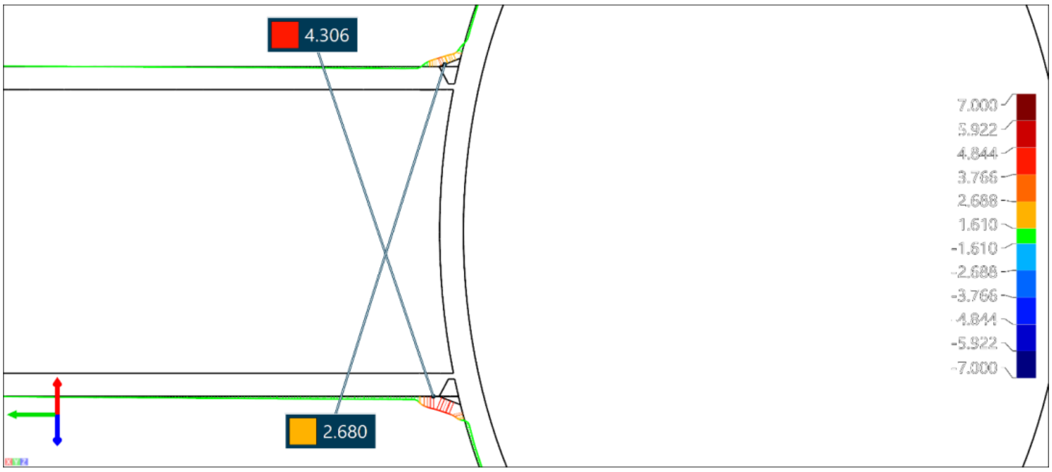

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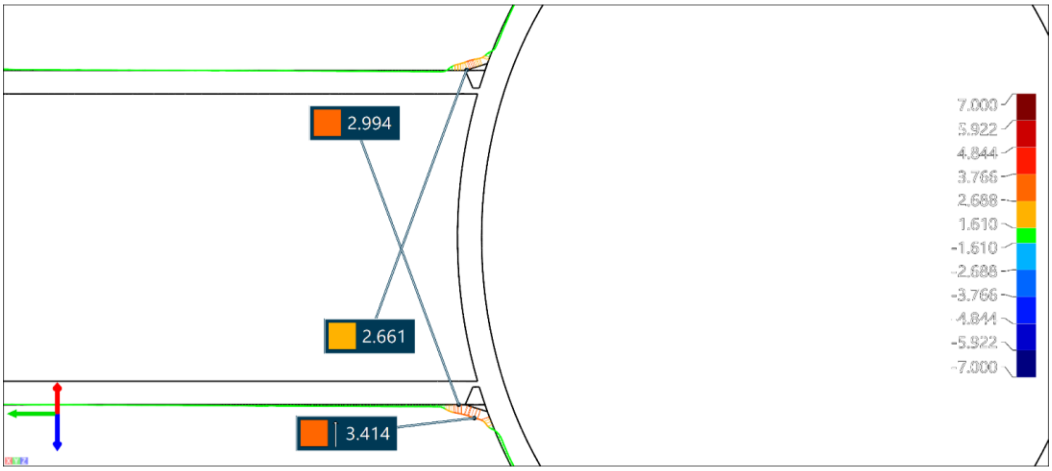

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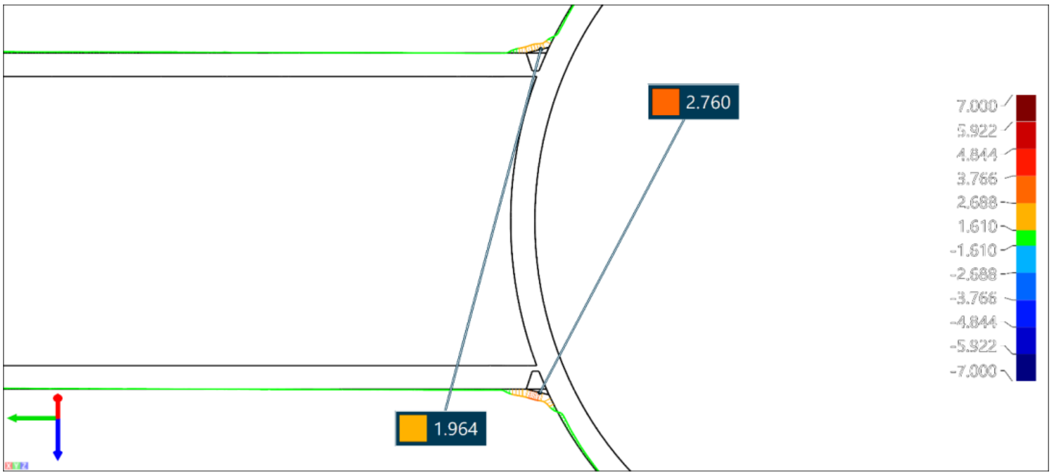

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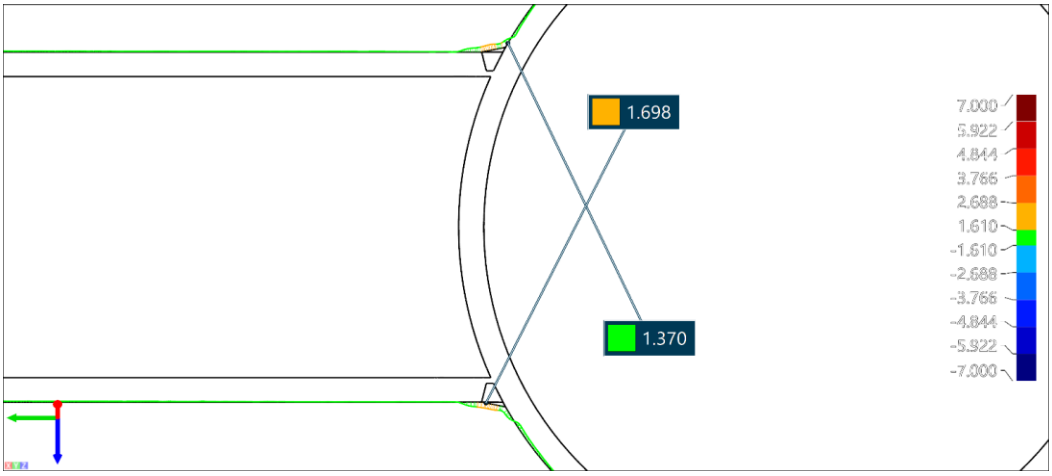

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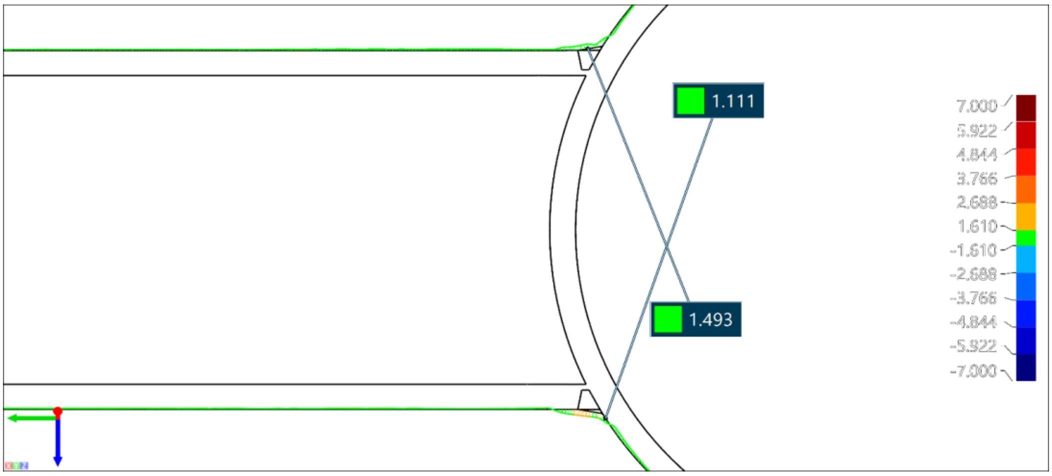
80



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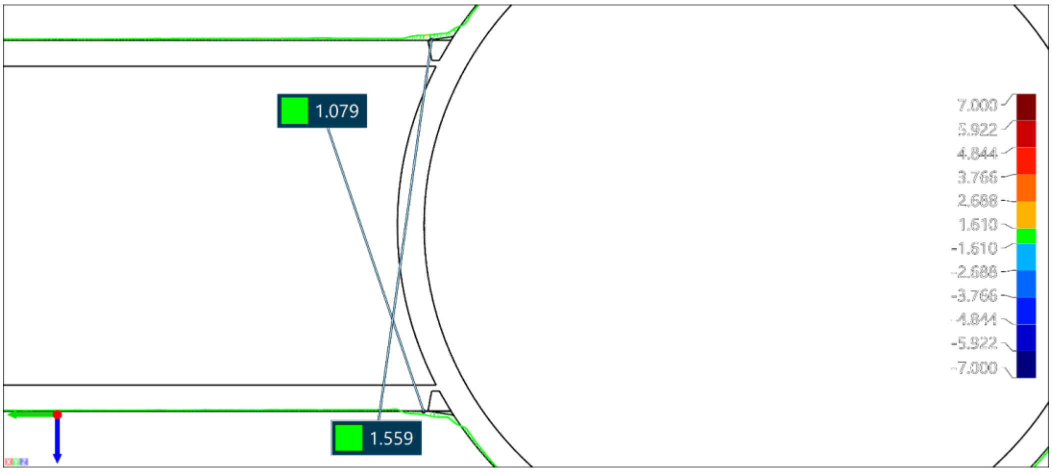
saddle



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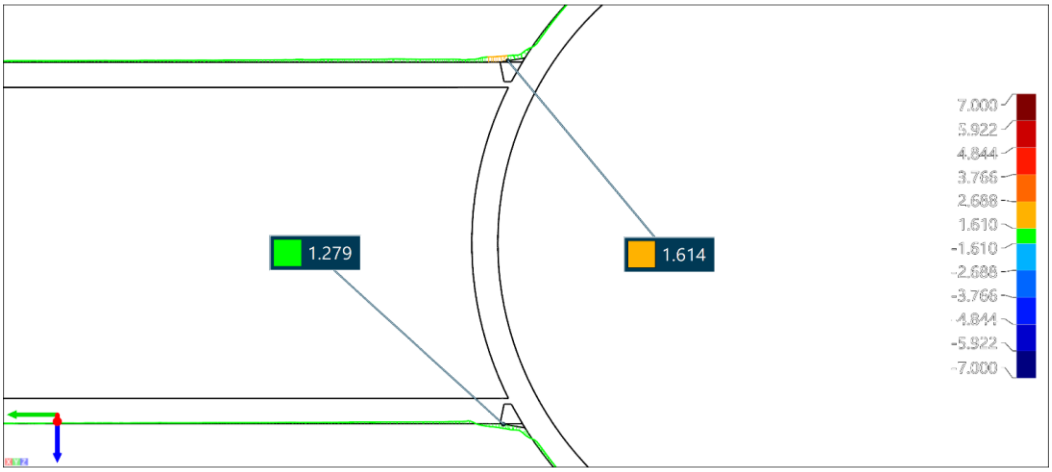

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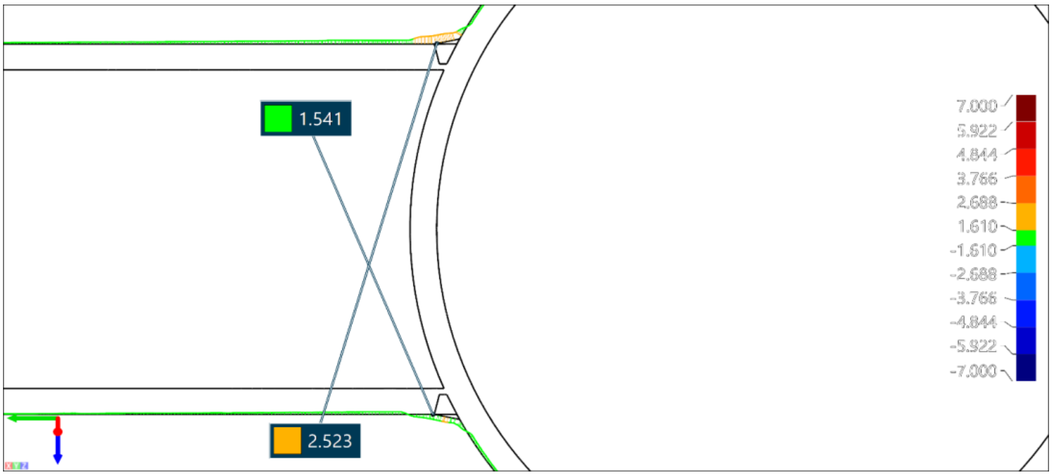

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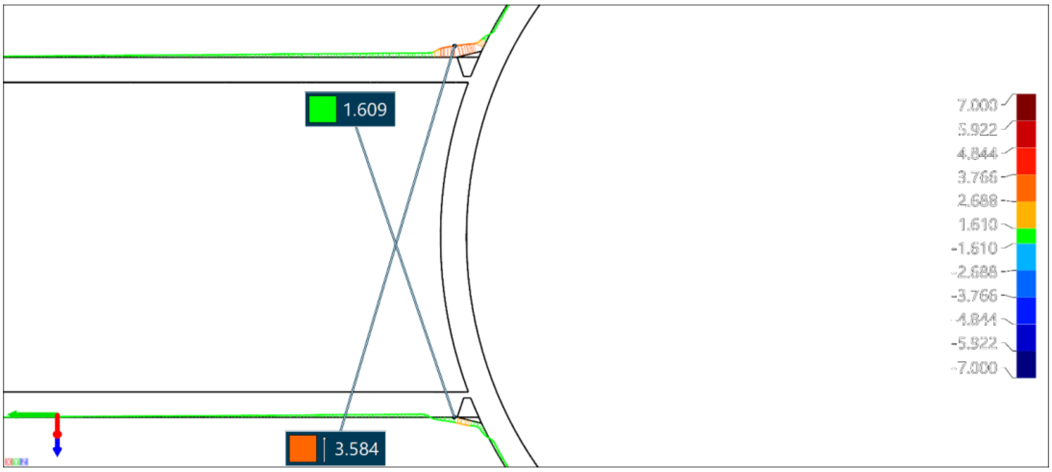
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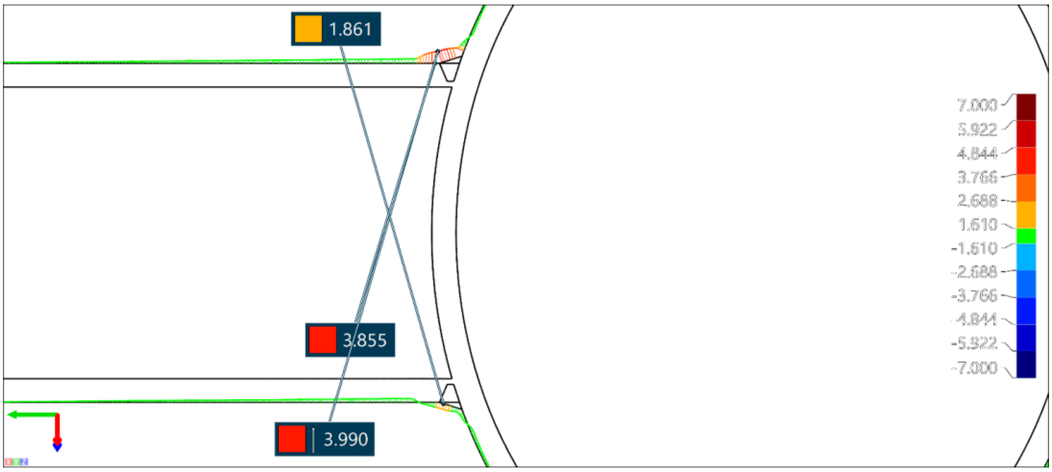
-3.766
-4.844
-5.922
-7.000

130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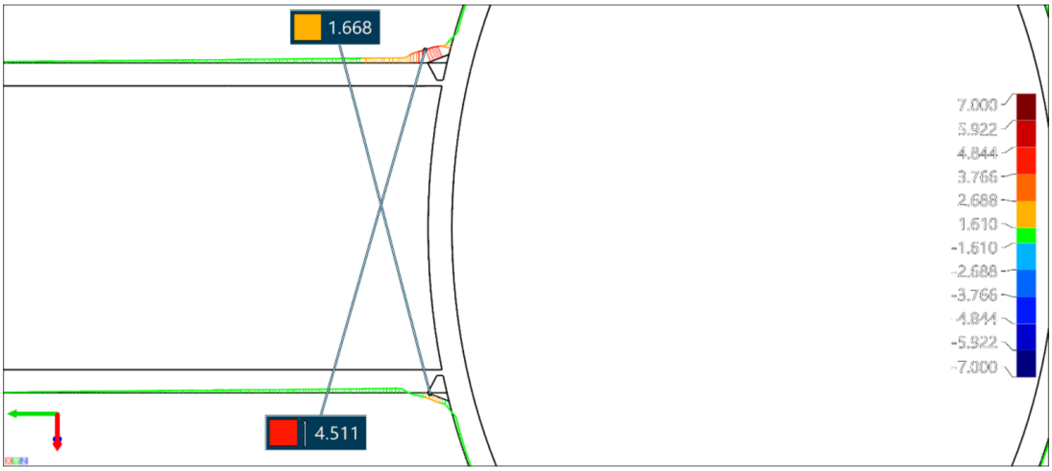
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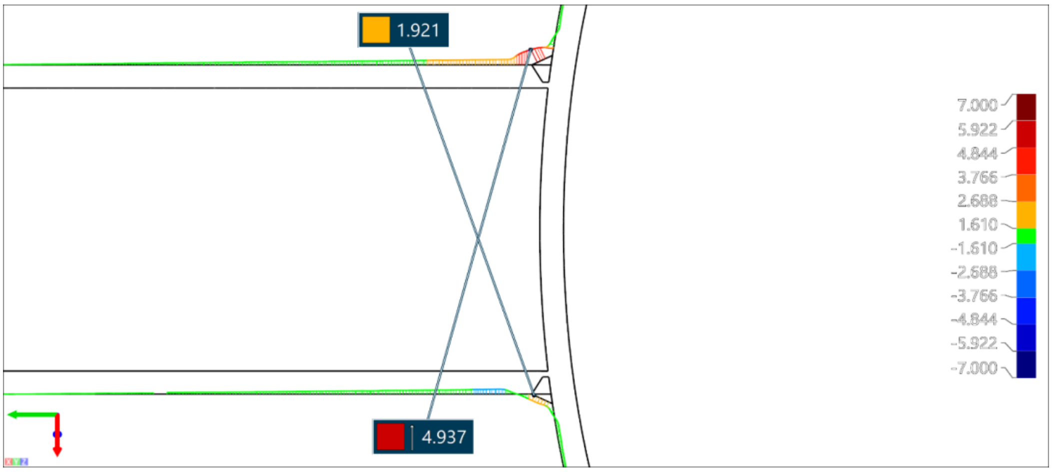
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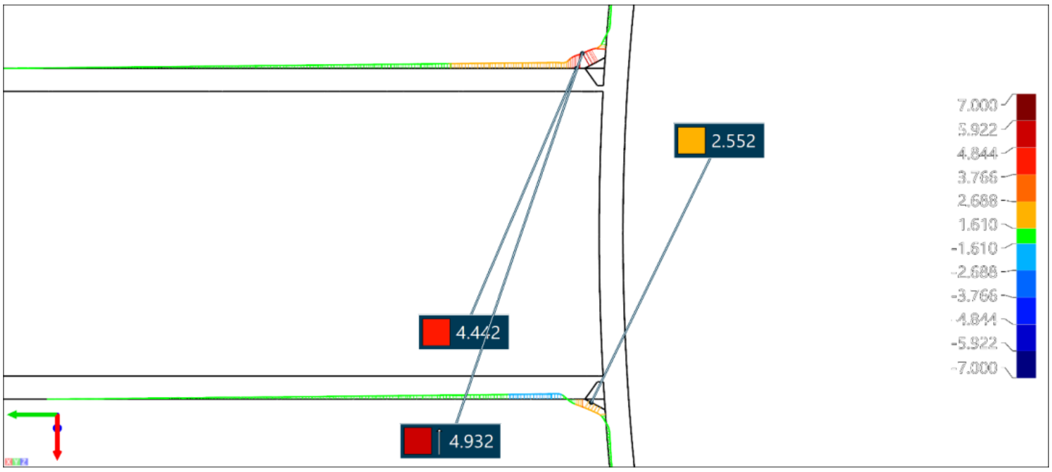
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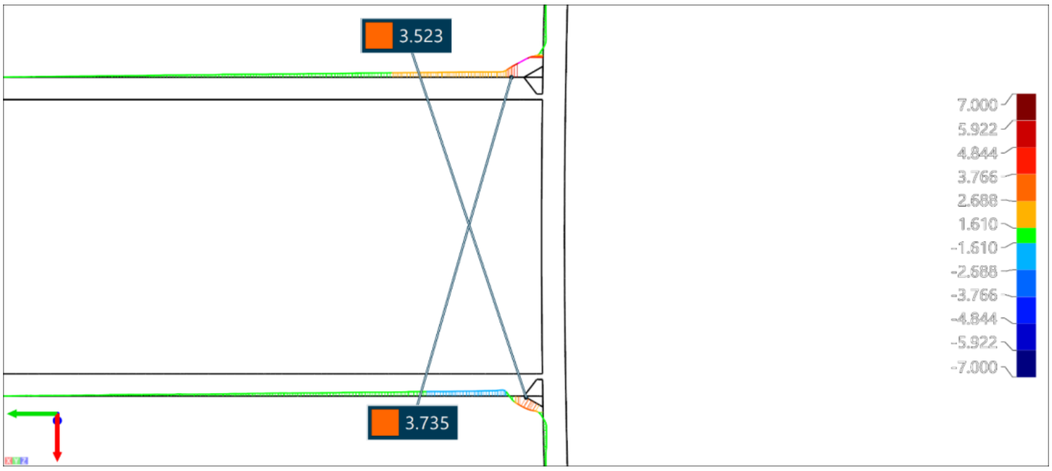
170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1.610
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-2.688
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-4.844
-5.922
-7.000

CREAFORM AMETEK ULTRA PRECISION TECHNOLOGIES

MMC

Project information

Organization	UIS
Units	mm

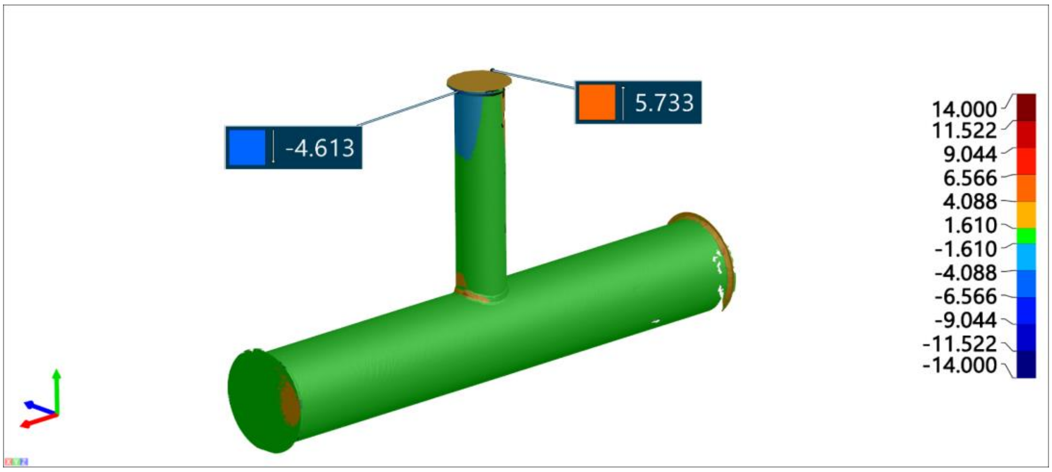
Part information

Part name	S31655-4000-T-02
Operator name	Kris Kolos

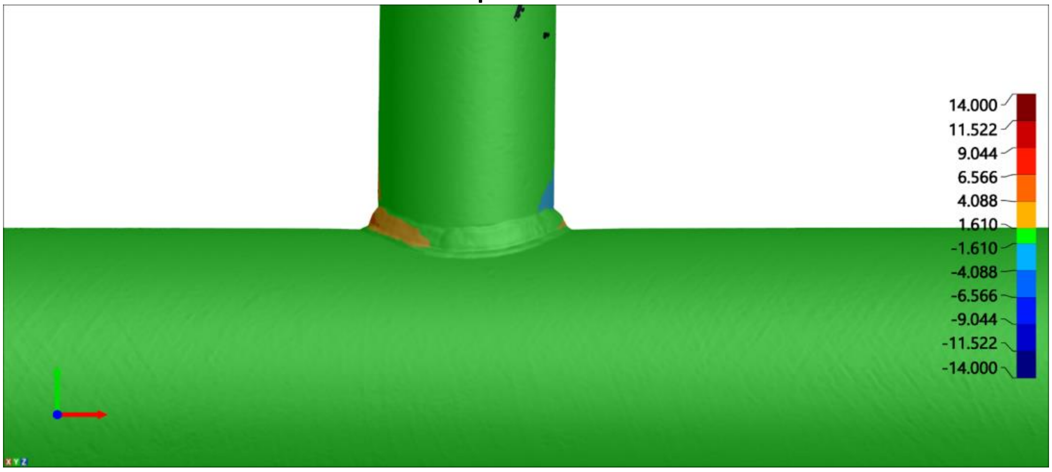
Color map 1 - Scan6

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-4,613	-4,613	**-3,003**
Max.	1,610	0,000	5,733	5,733	**4,123**
±	3,220	0,000	10,345	10,345	**7,125**
SD	1,000	0,000	0,813	0,813	

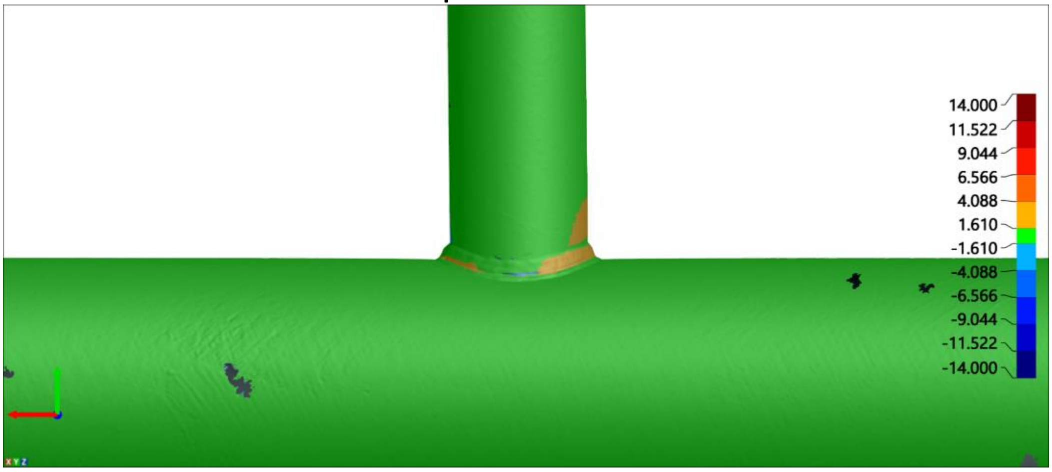
extremes at MMC



colormap side view MMC



colormap other side view MMC



Cylinder 1 - Scan6

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,443	0,343	

GD&T	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
⌭ 4.380	4,380		2,146		

Cylinder 2 - Scan6

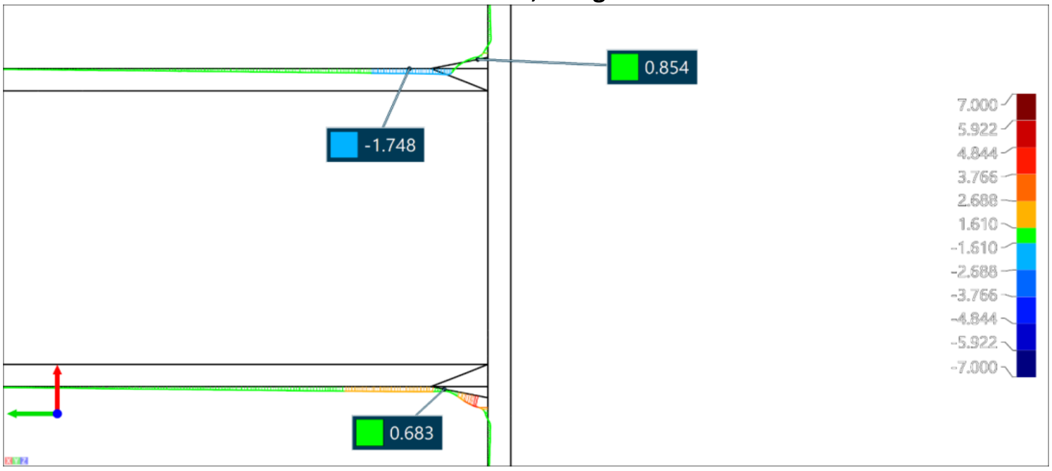
Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,608	0,308	

GD&T	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
⌭ 2.290	2,290		11,325		**9,035**

Angle [°] - Scan6

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,329	-0,671	**-0,338**
∠XZ	+0.333 -0.333	0,000	8,989	8,989	**8,656**
∠YZ	+0.333 -0.333	0,000	5,700	5,700	**5,367**

crowns, 0 deg



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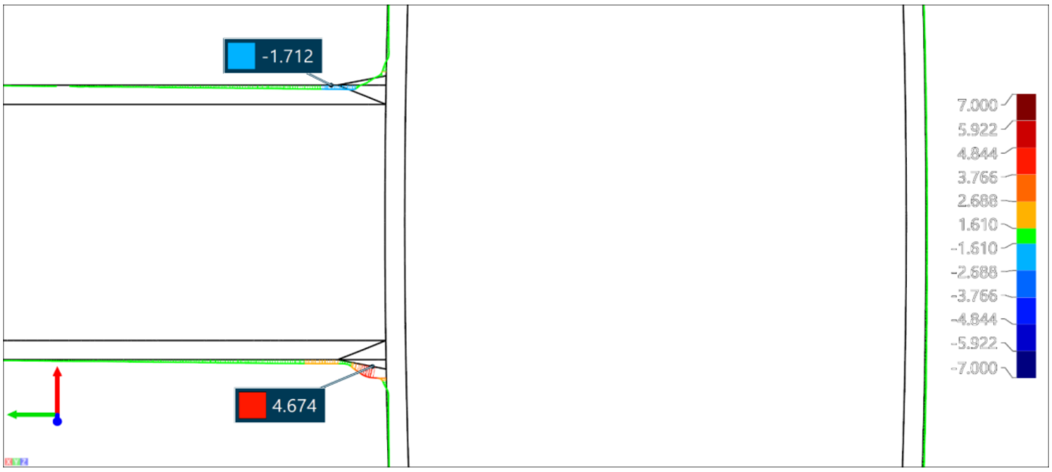

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1.610
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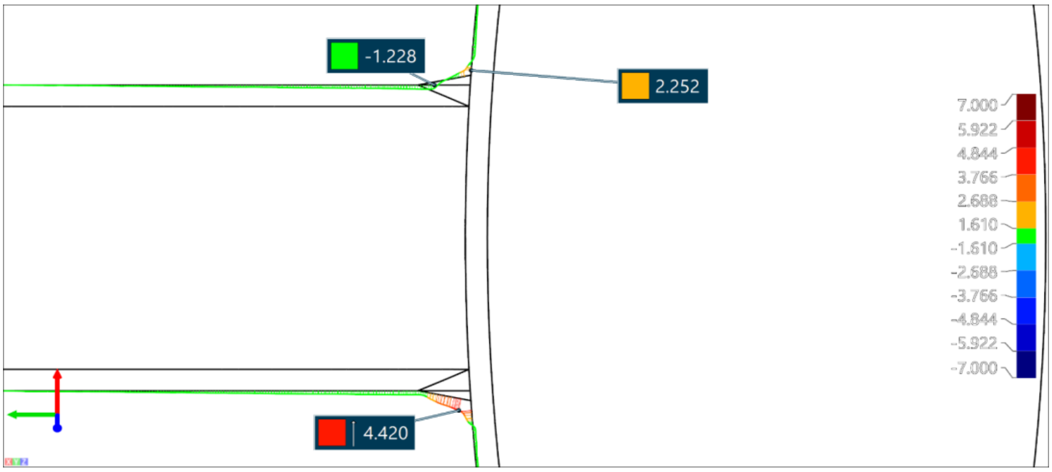
-4.844
-5.922
-7.000

20



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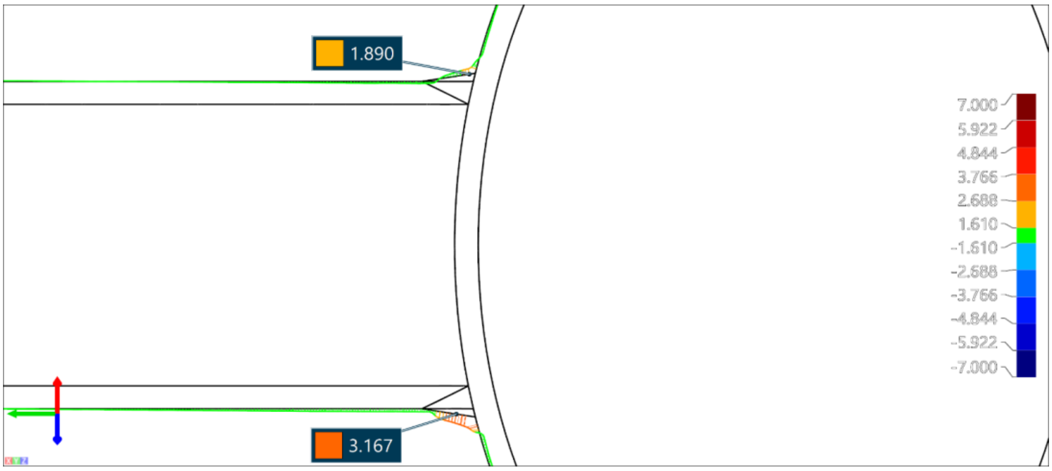
-5.922
-7.000

30



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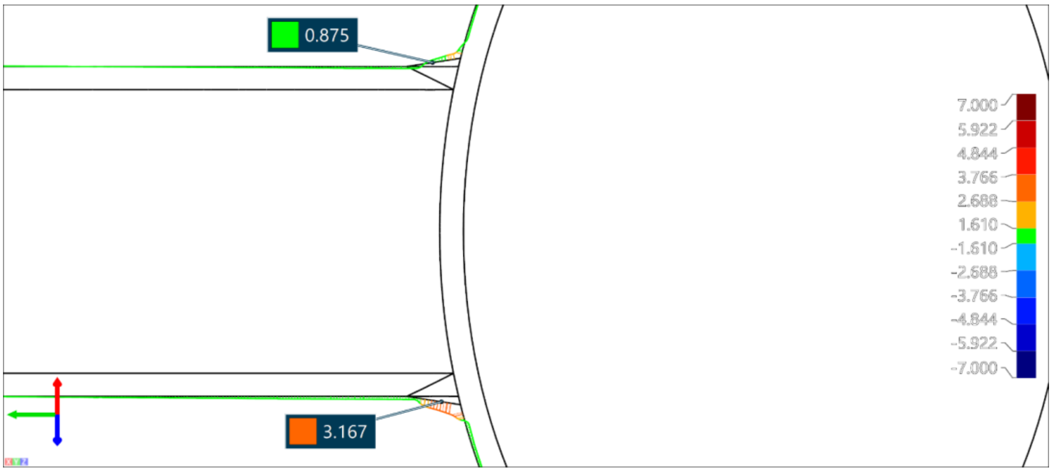
-5.922
-7.000

40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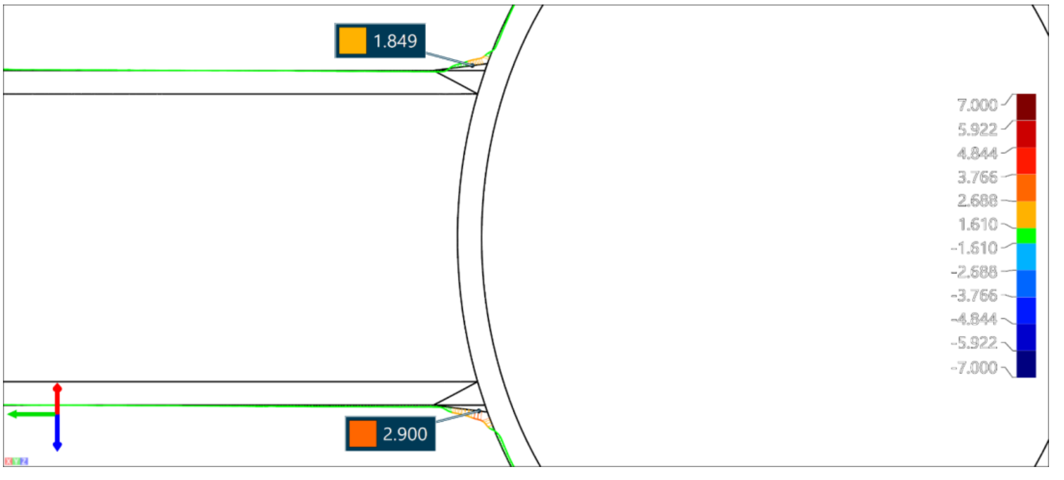
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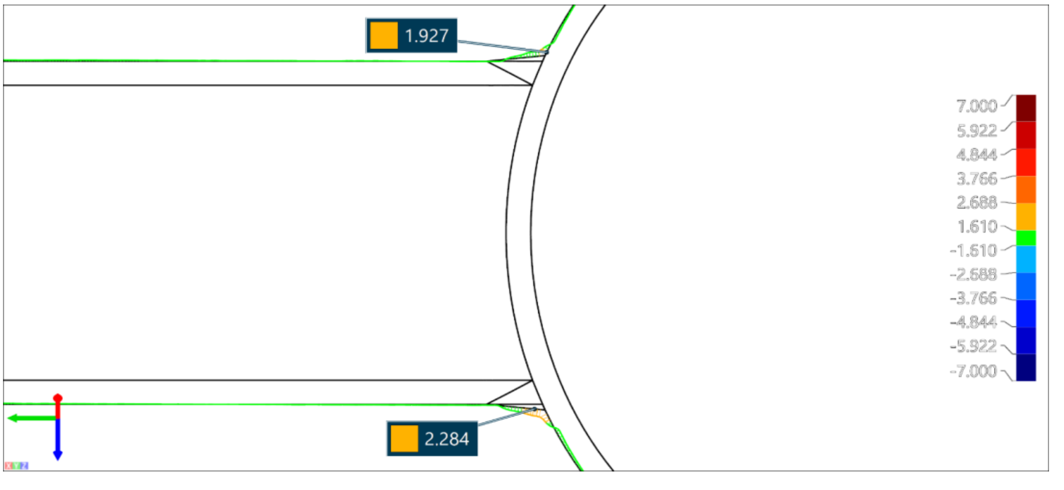
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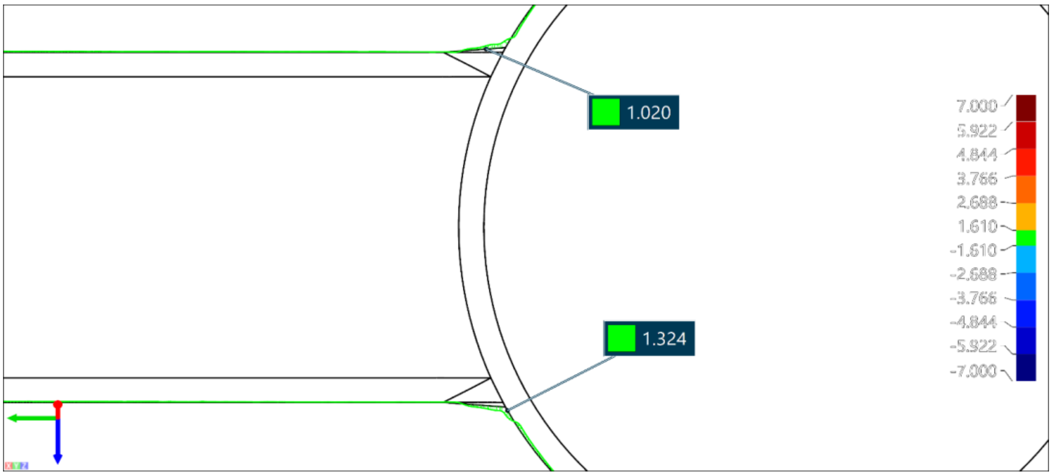
-7.000

70



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-2.688
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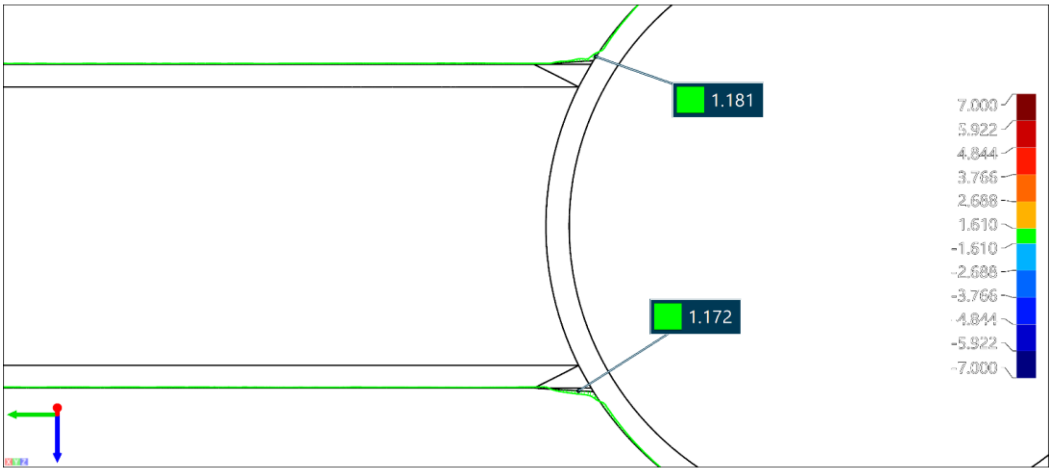
-4.844
-5.922
-7.000

80



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-4.844
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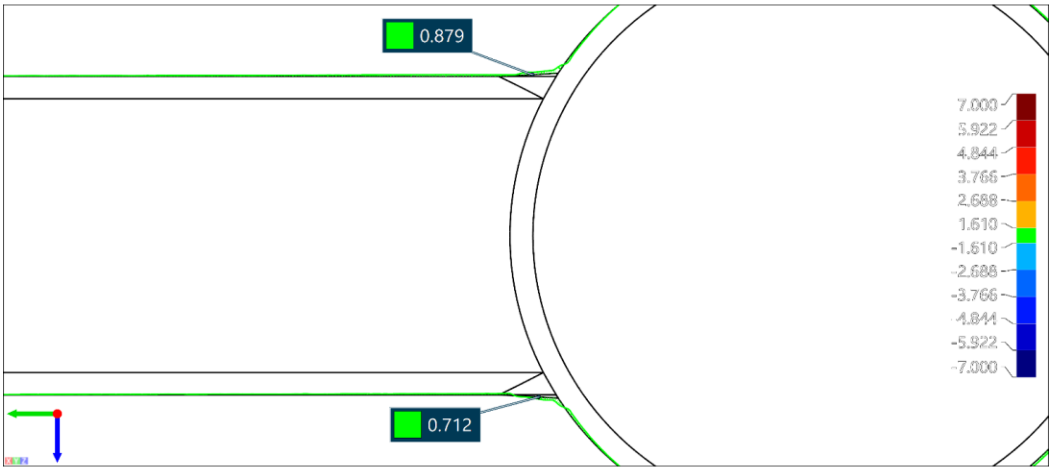
-7.000

saddle



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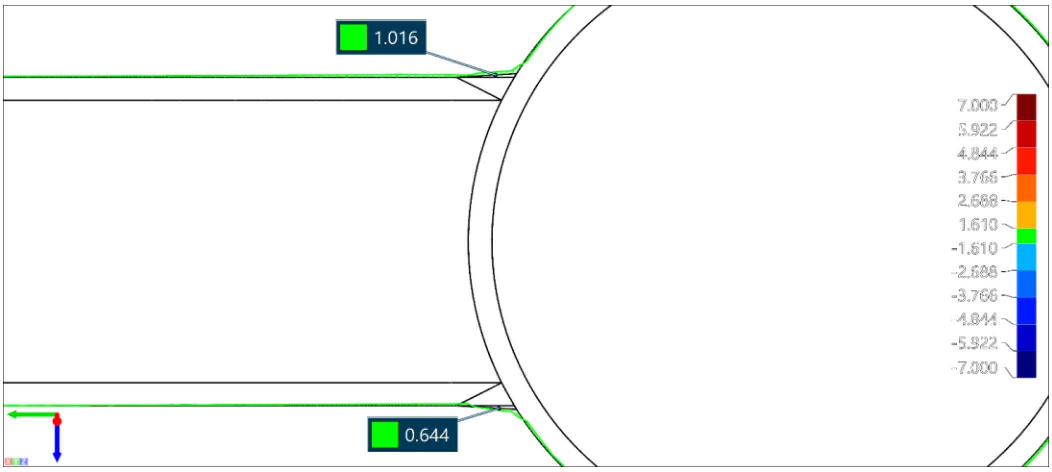
-7.000

100



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-2.688
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-7.000

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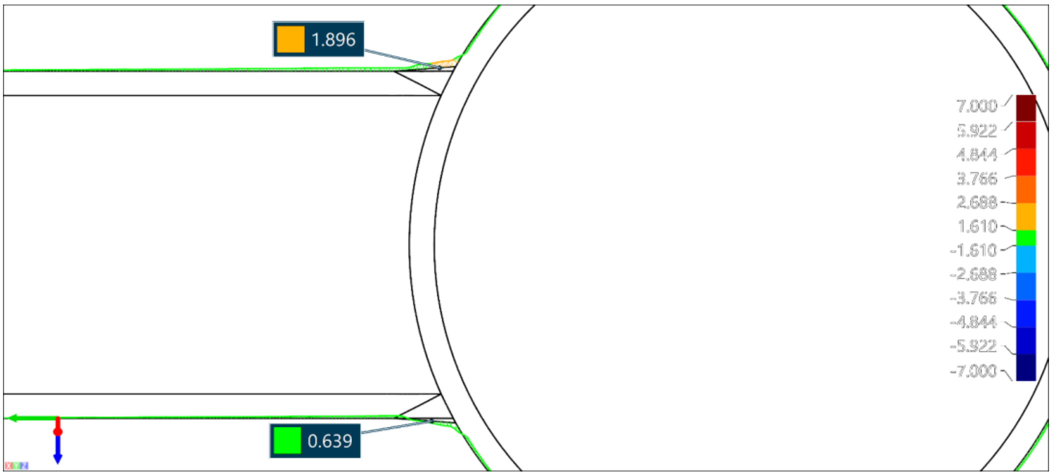

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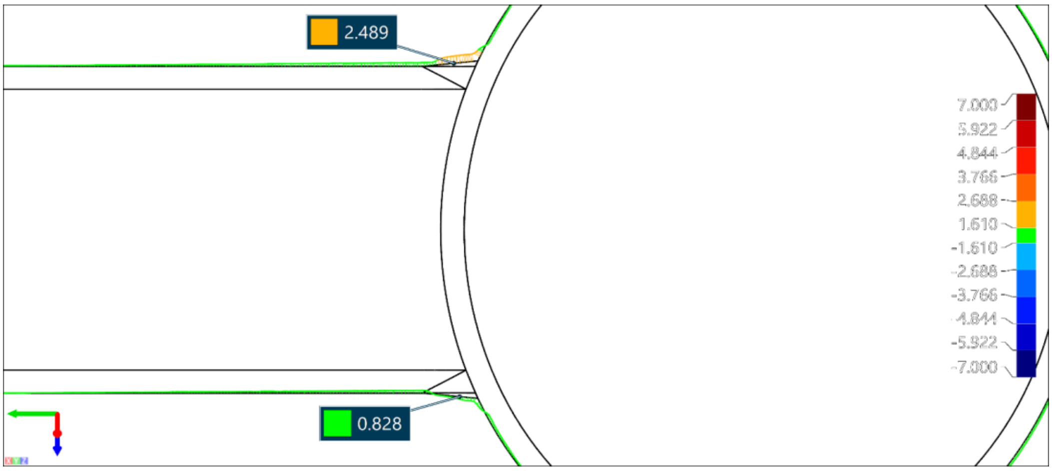

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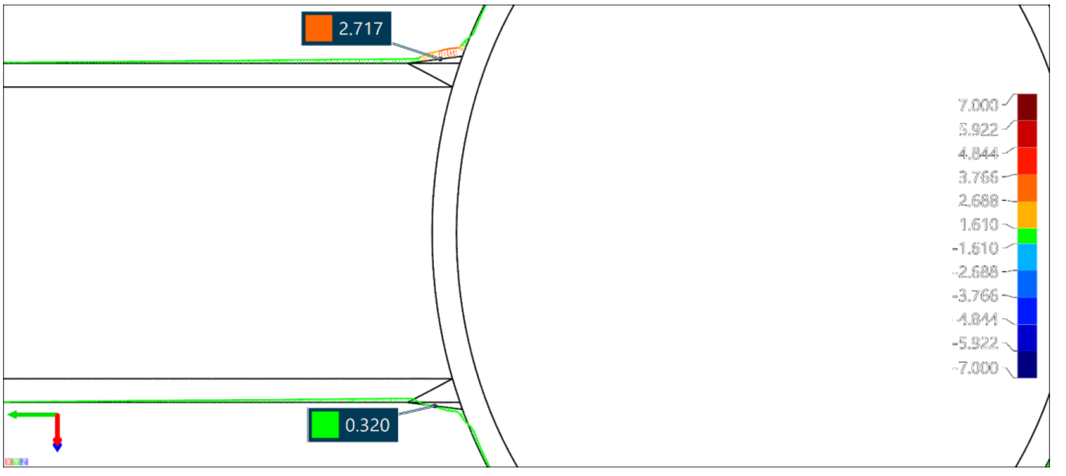
130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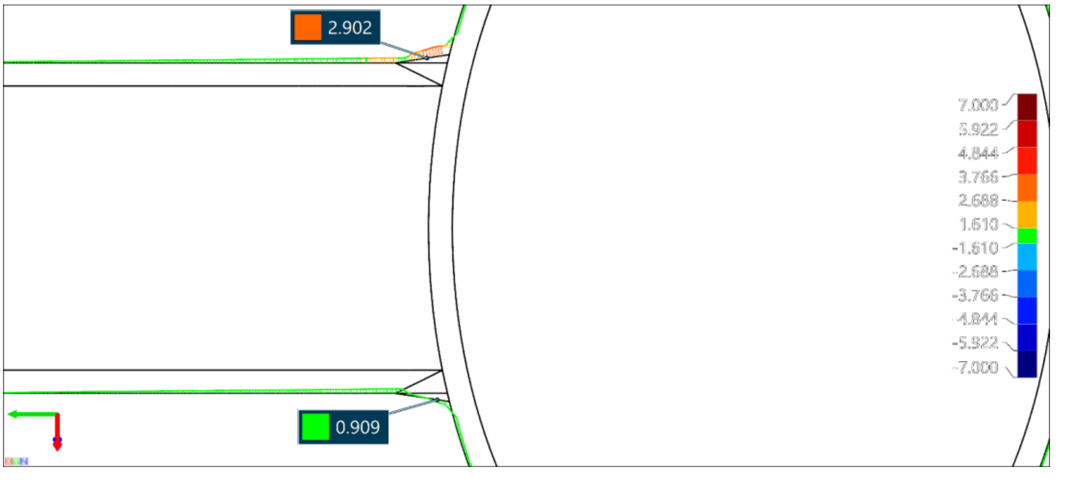
140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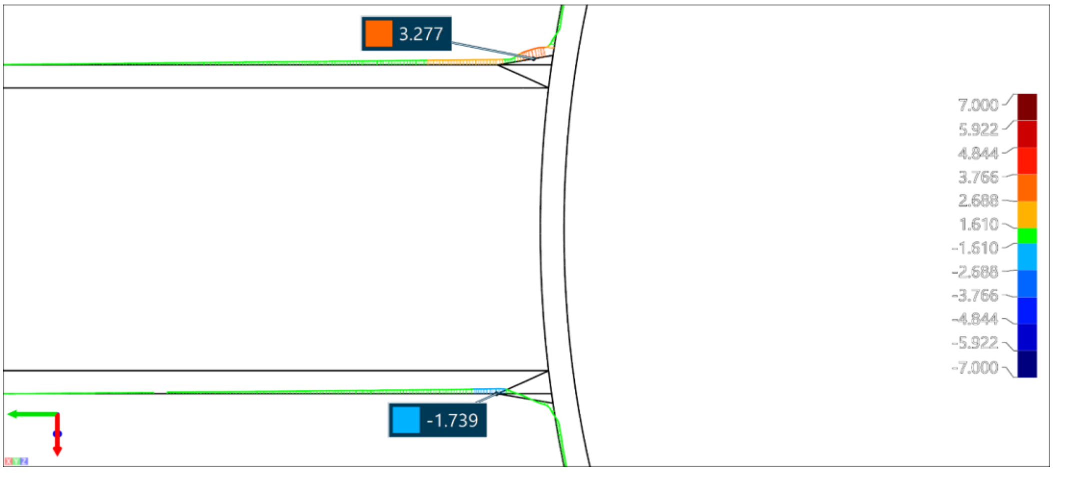
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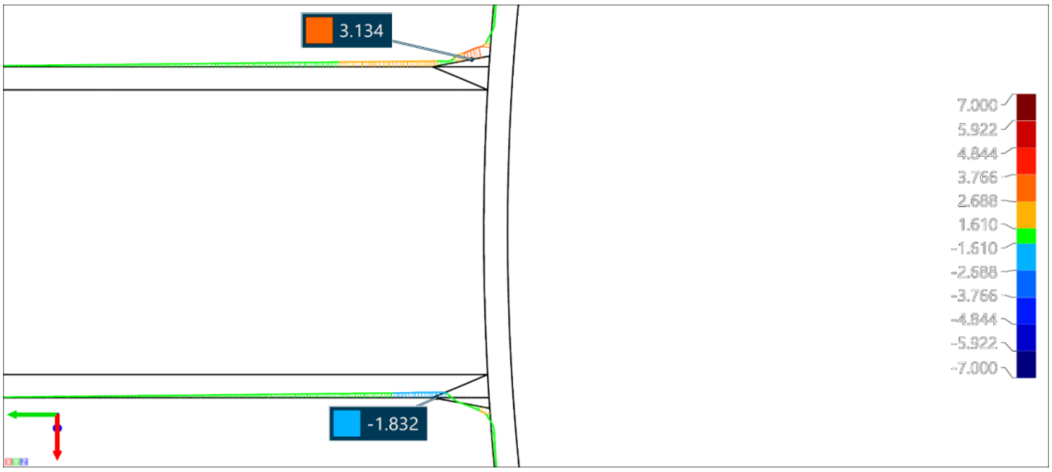
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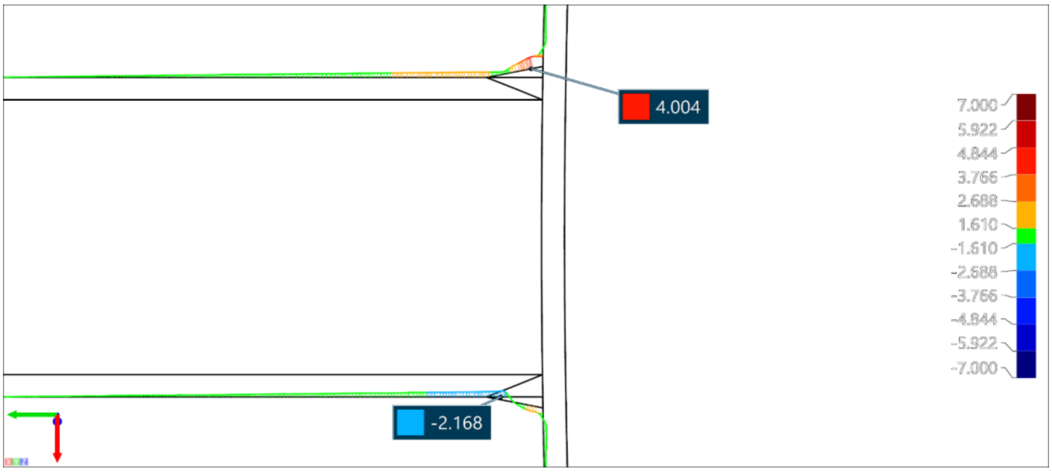
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-7.000

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Report prepared by
Name ____

Date ____

Signature ____

Report reviewed by
Name ____

Date ____

Signature ____

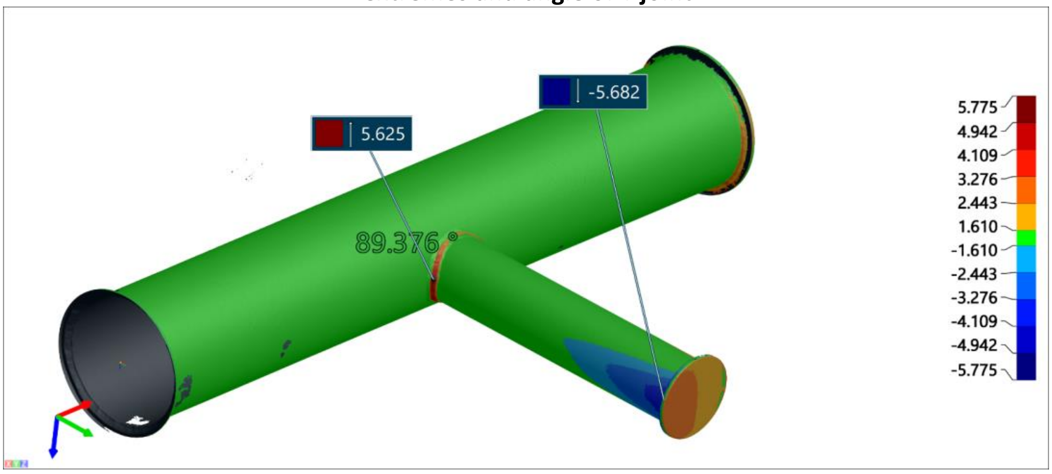
Project information

Organization	UIS
Units	mm

Part information

Part name	S31655-4000-T-03
Operator name	Kris Kolos

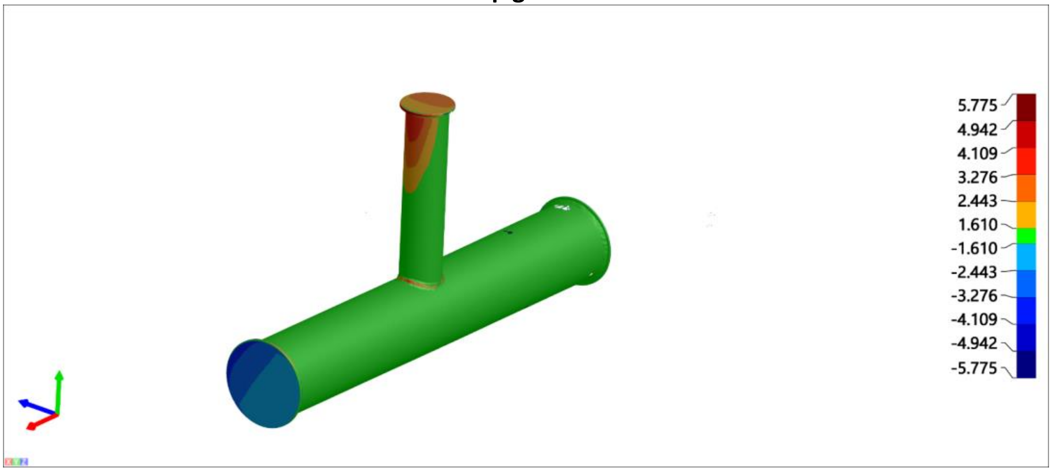
extremes and angle of T joint



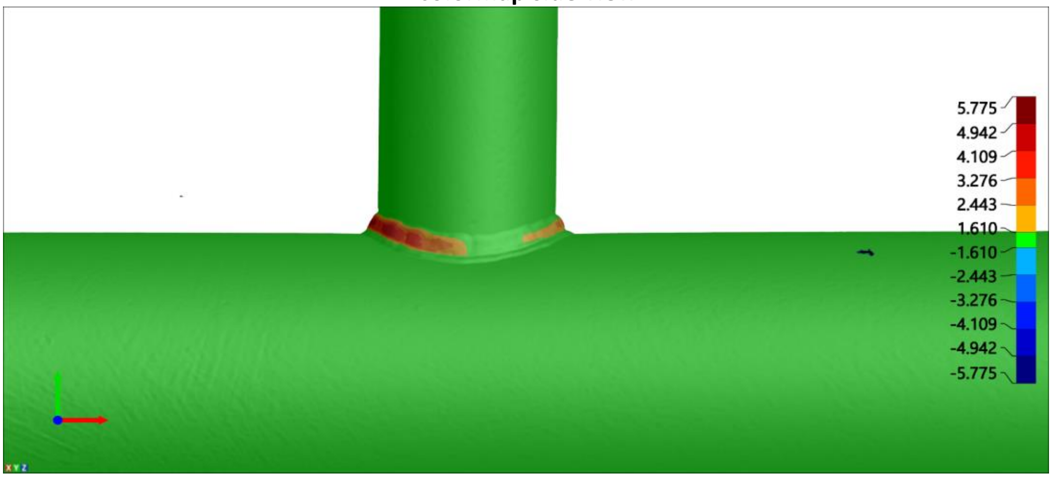
Color map 1 - Scan1

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-5,682	-5,682	**-4,072**
Max.	1,610	0,000	5,625	5,625	**4,015**
±	3,220	0,000	11,307	11,307	**8,087**
SD	1,000	0,000	0,912	0,912	

colormap general view



colormap side view



Cylinder 1 - Scan1

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,291	0,191	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		2,435		

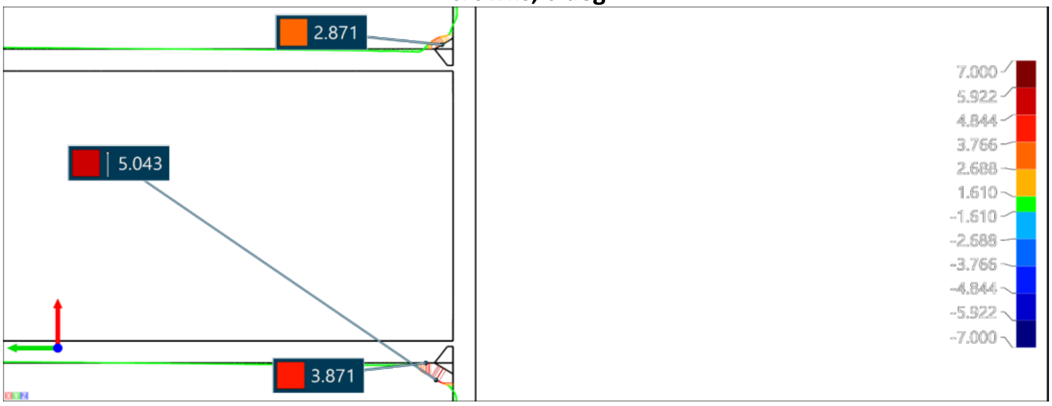
Cylinder 2 - Scan1

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,717	0,417	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		7,131		**4,841**

Angle [°] - Scan1

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,376	-0,624	**-0,291**
∠XZ	+0.333 -0.333	0,000	1,890	1,890	**1,557**
∠YZ	+0.333 -0.333	0,000	2,602	2,602	**2,269**

crowns, 0 deg



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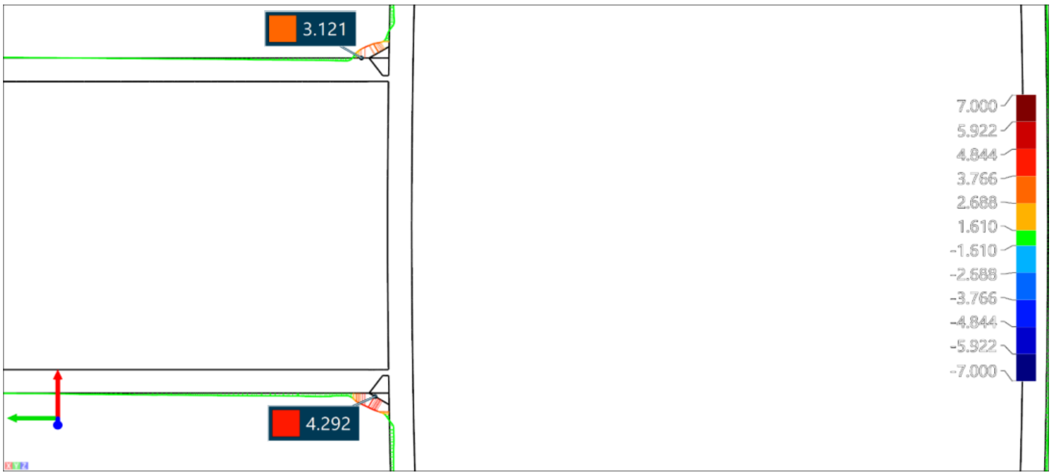

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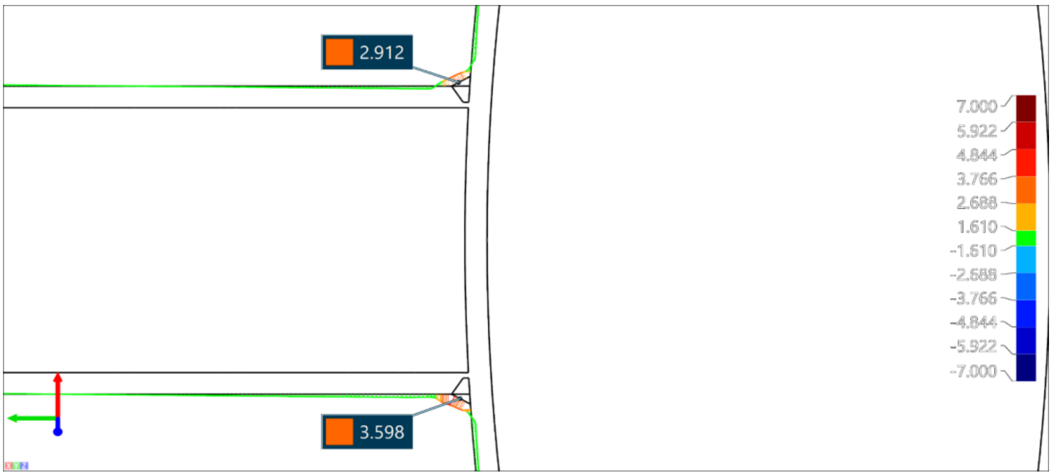

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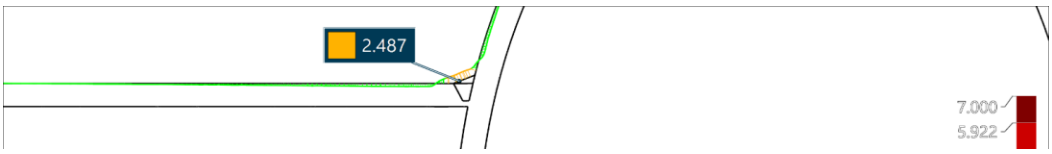

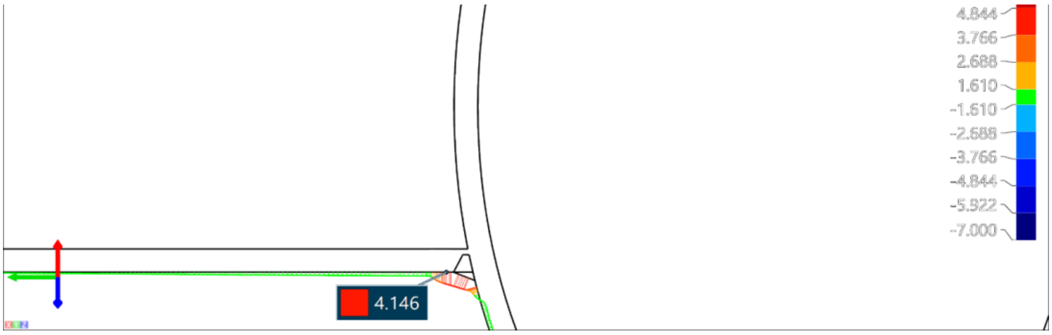
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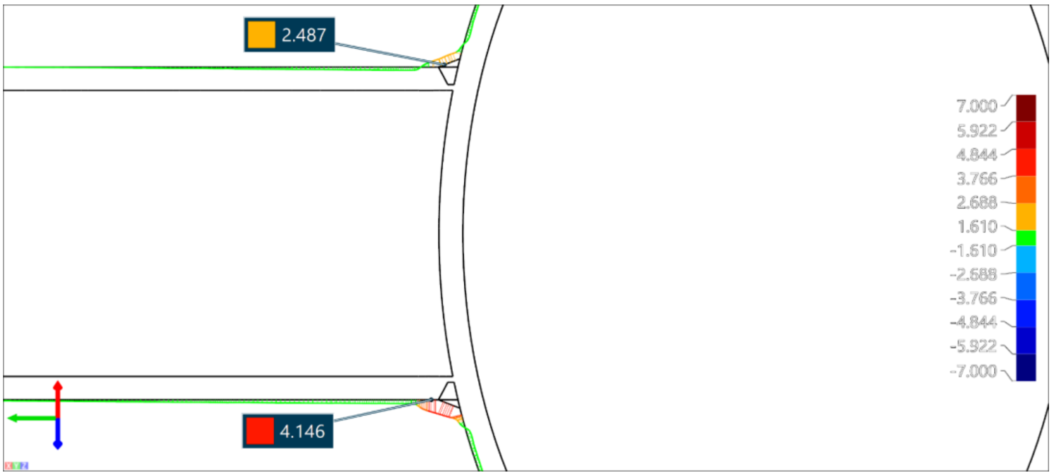
4.146

40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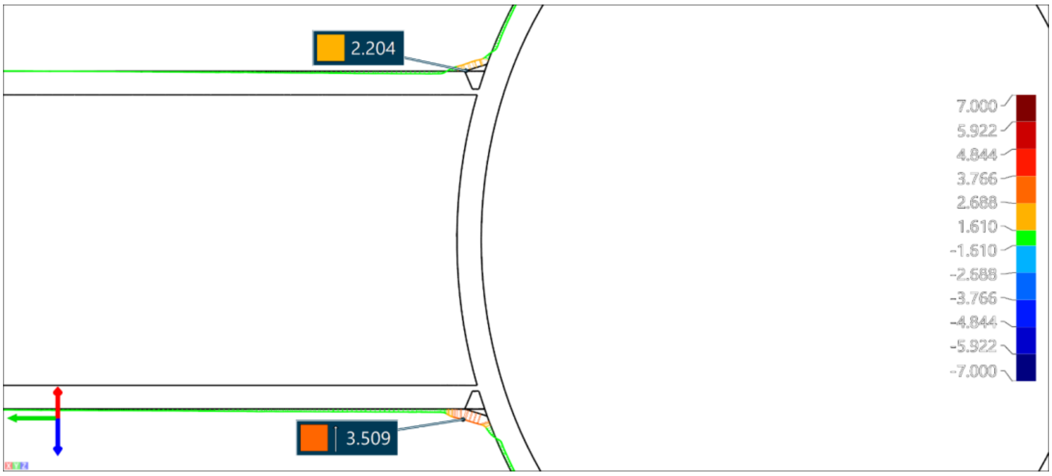
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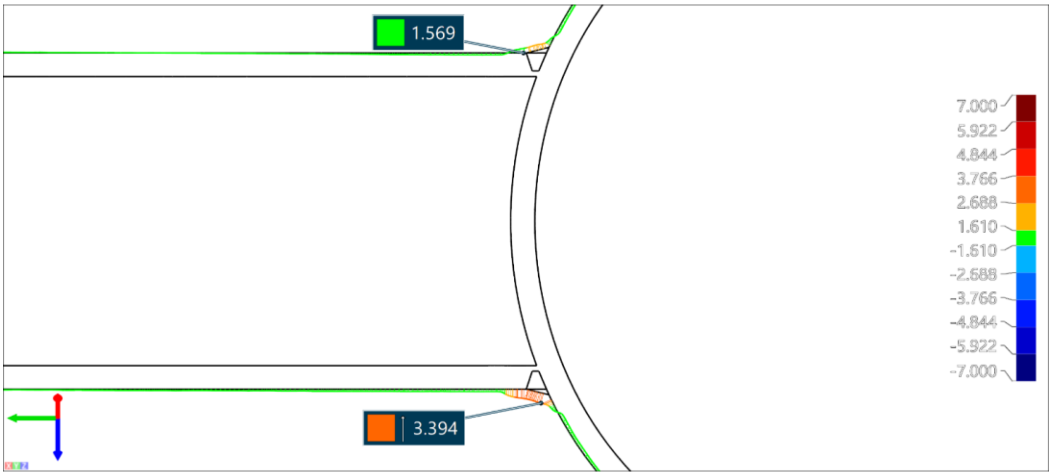
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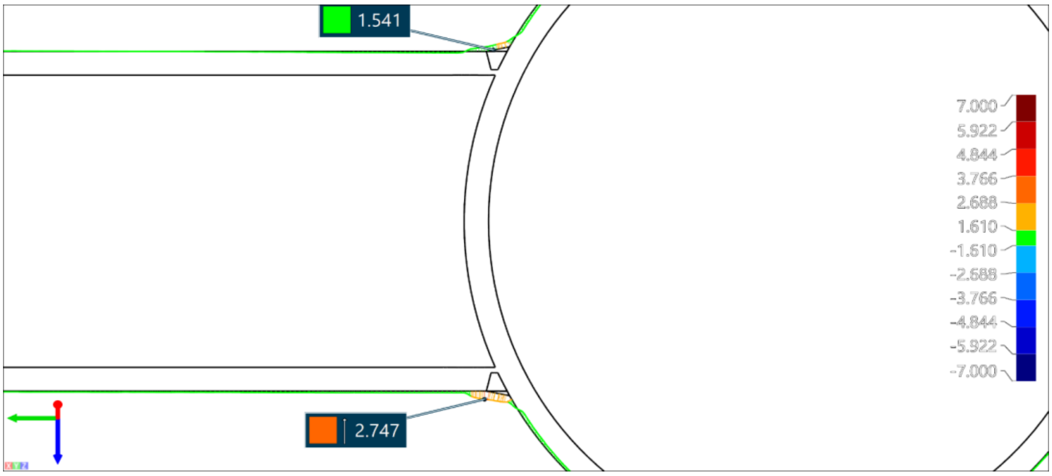
70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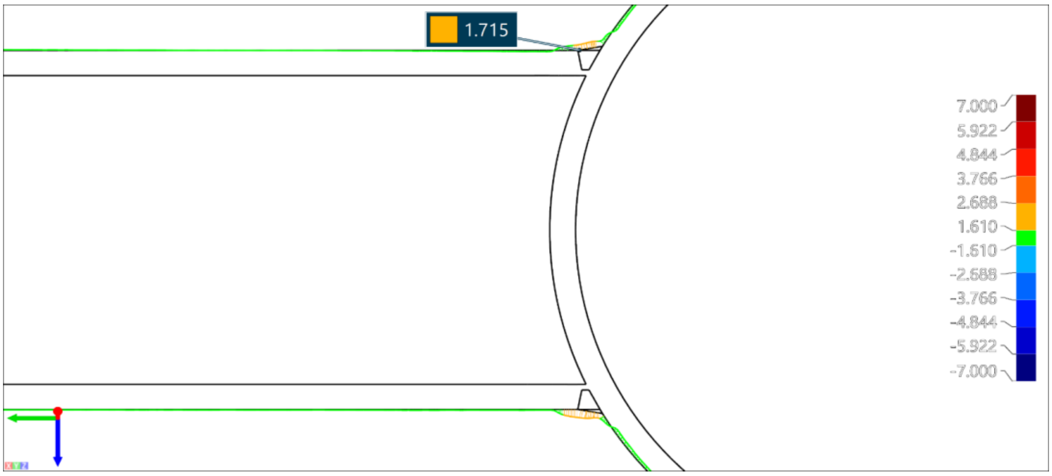
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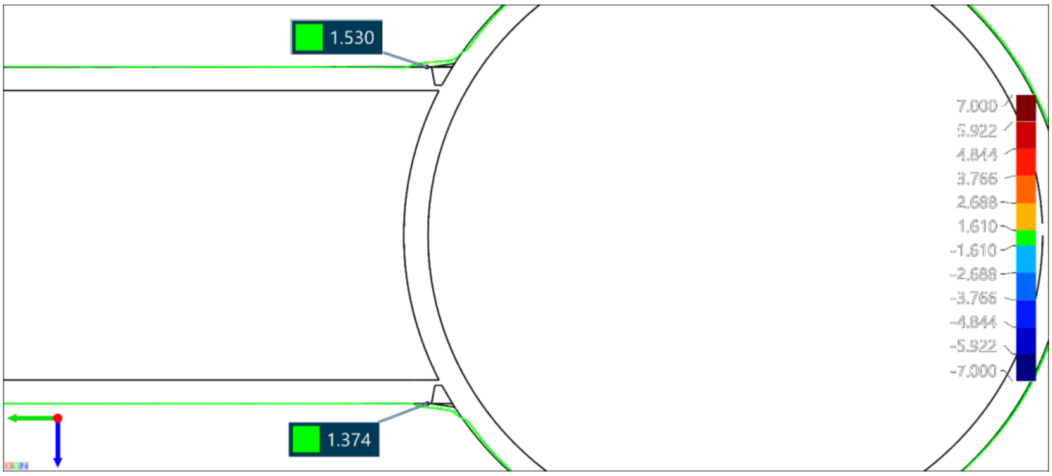
saddle



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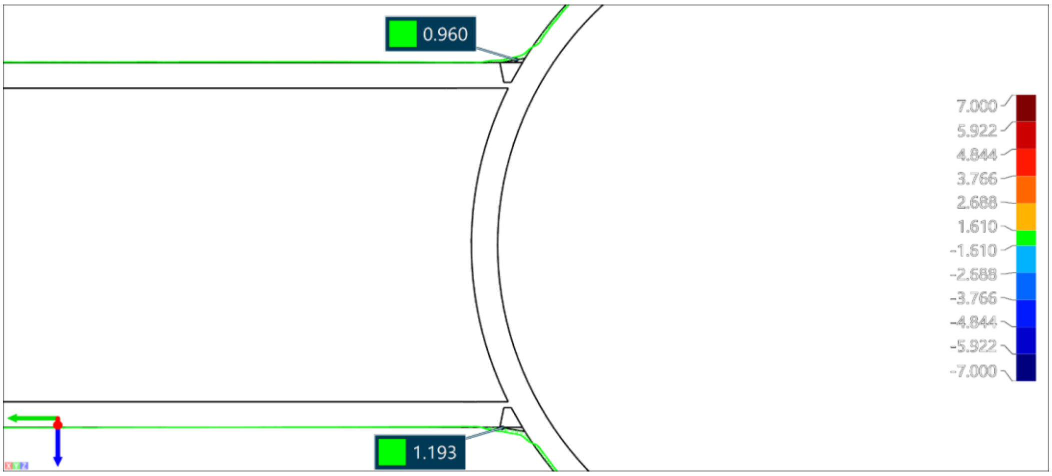

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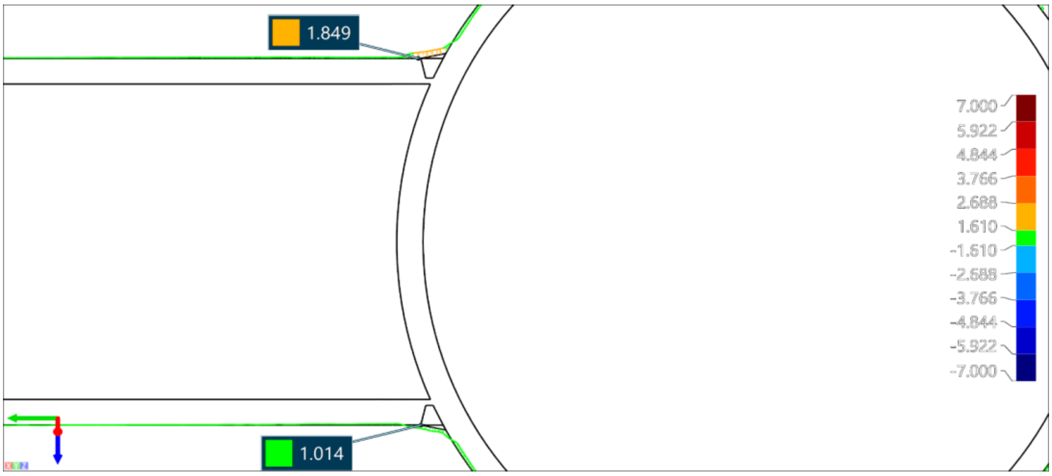

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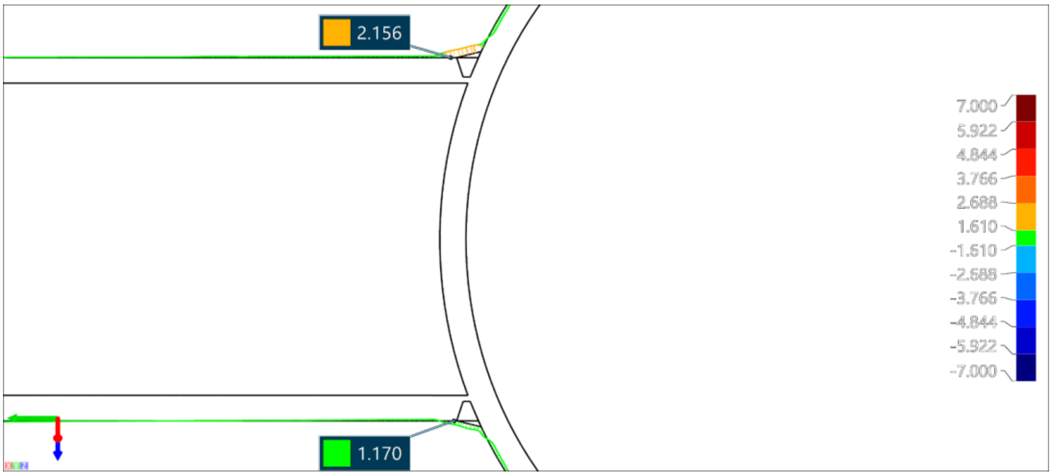
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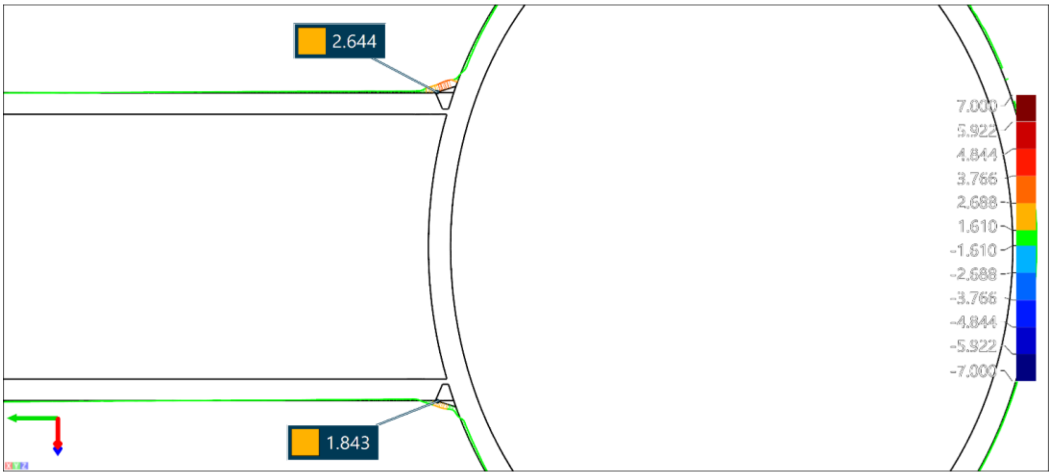
130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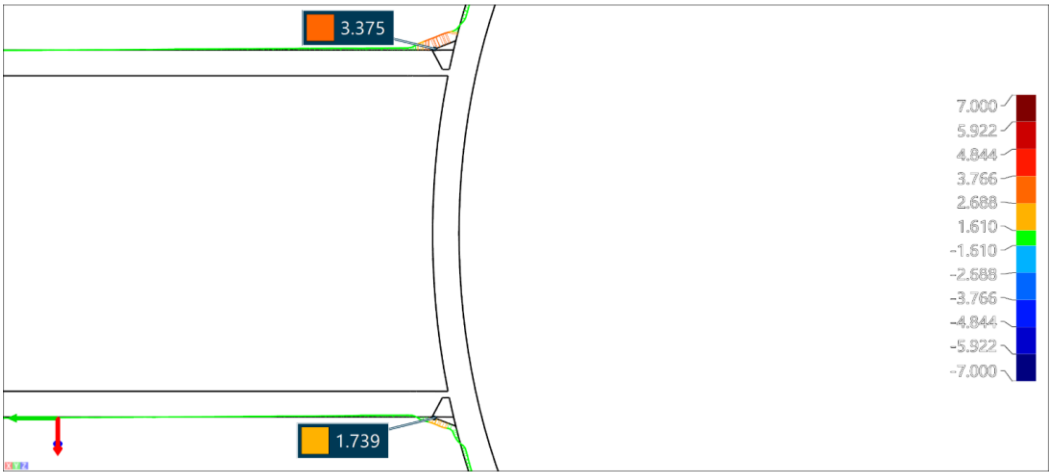
140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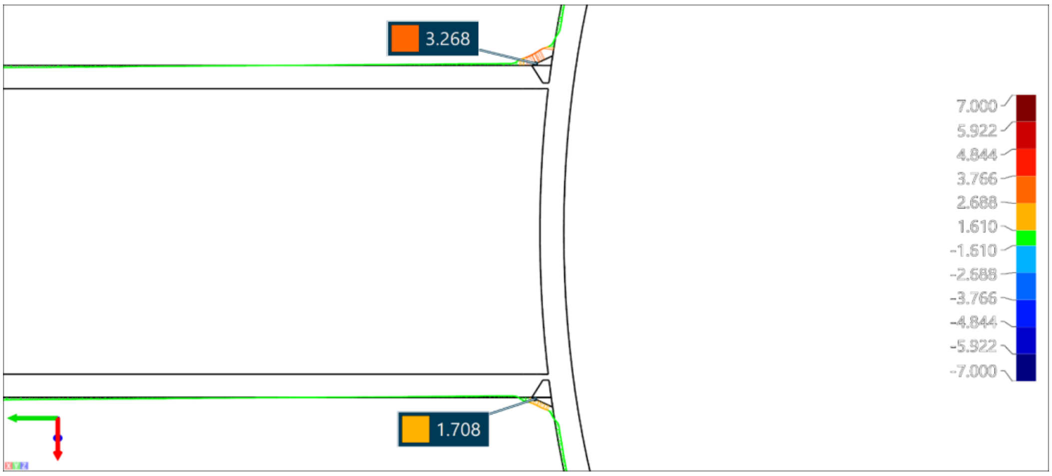
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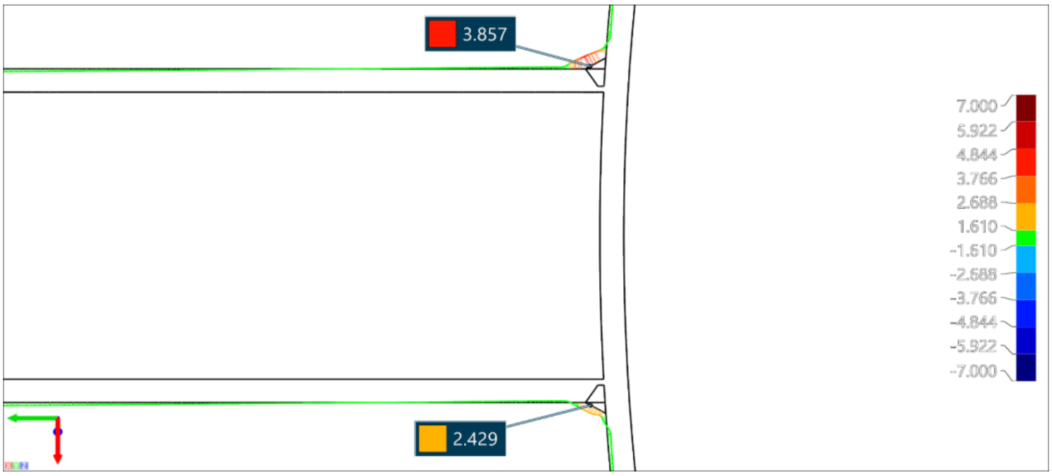
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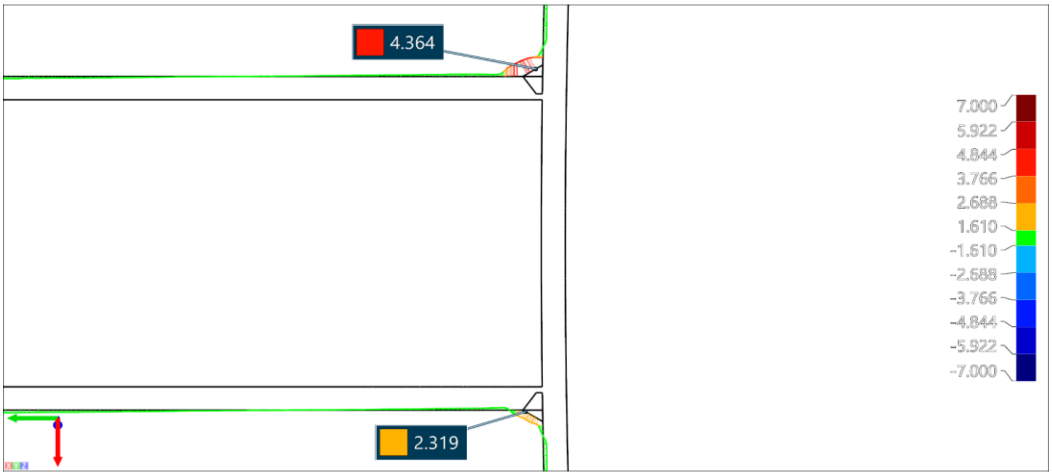
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1.610
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-4.844
-5.922
-7.000

MMC

Project information

Organization	UIS
Units	mm

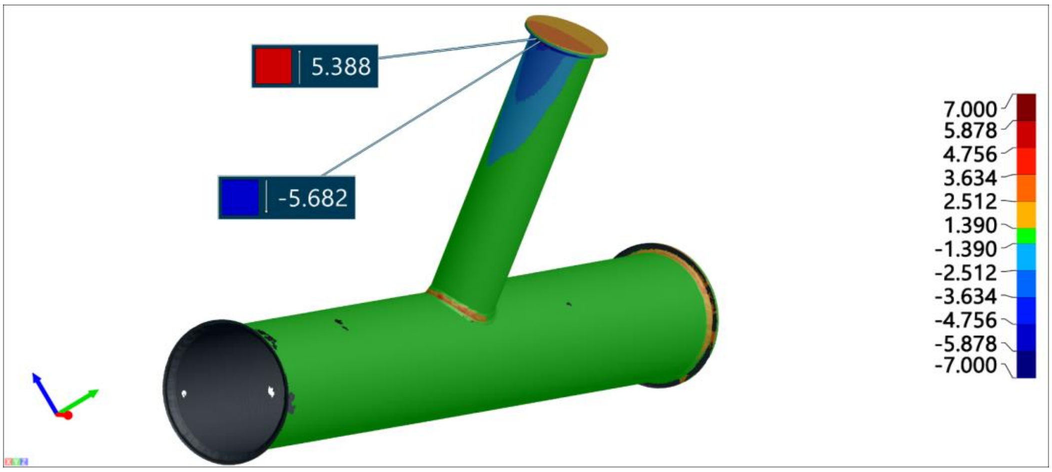
Part information

Part name	S31655-4000-T-03
Operator name	Kris Kolos

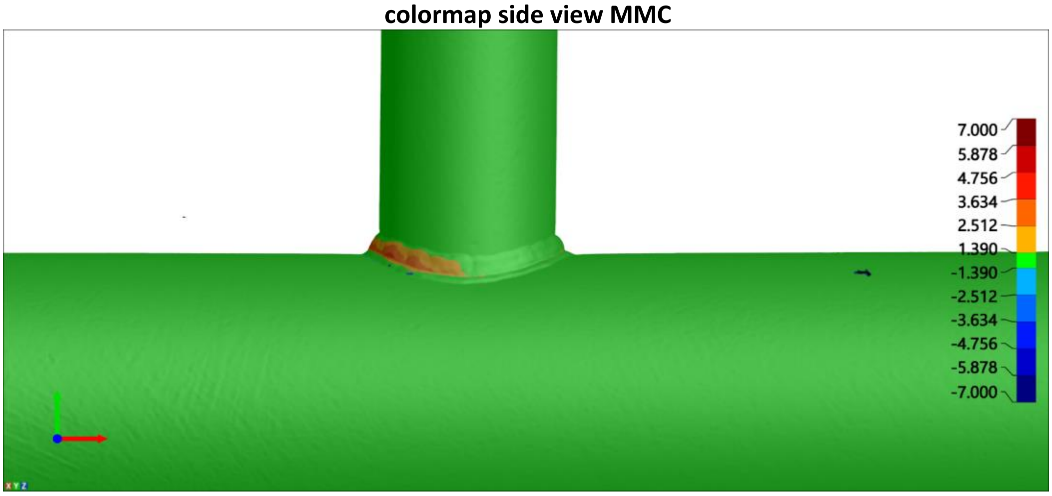
Color map 1 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-5,682	-5,682	**-4,072**
Max.	1,610	0,000	5,388	5,388	**3,778**
±	3,220	0,000	11,070	11,070	**7,850**
SD	1,000	0,000	0,904	0,904	

extremes at MMC

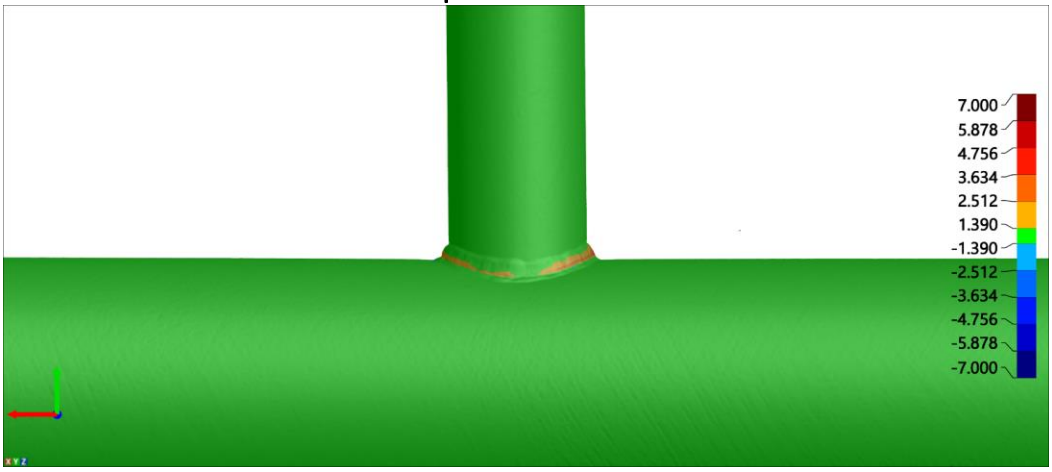


colormap side view MMC



CREAFORM AMETEK® ULTRA PRECISION TECHNOLOGIES

colormap other side view MMC



Cylinder 1 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,291	0,191	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		2,435		

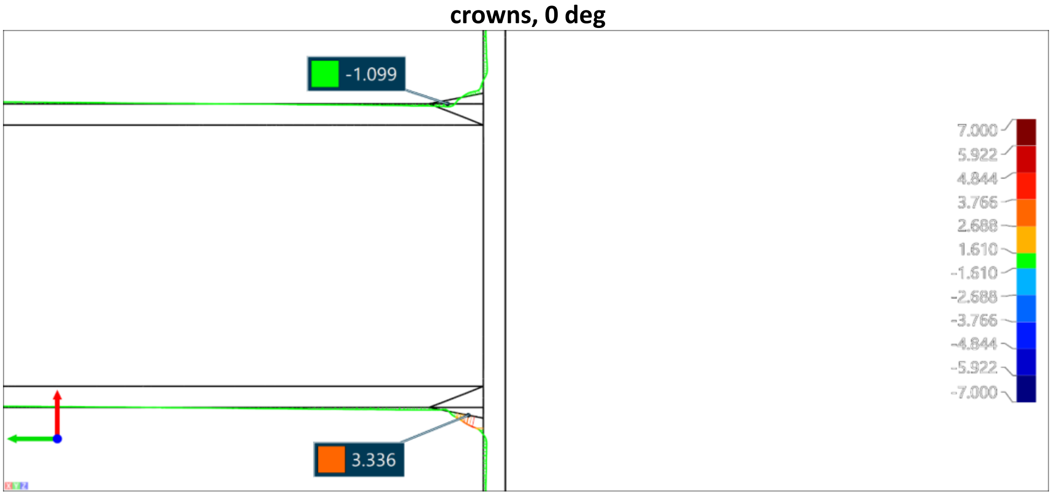
Cylinder 2 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,717	0,417	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		7,131		**4,841**

Angle [°] - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,376	-0,624	**-0,291**
∠XZ	+0.333 -0.333	0,000	1,893	1,893	**1,560**
∠YZ	+0.333 -0.333	0,000	2,599	2,599	**2,266**

crowns, 0 deg



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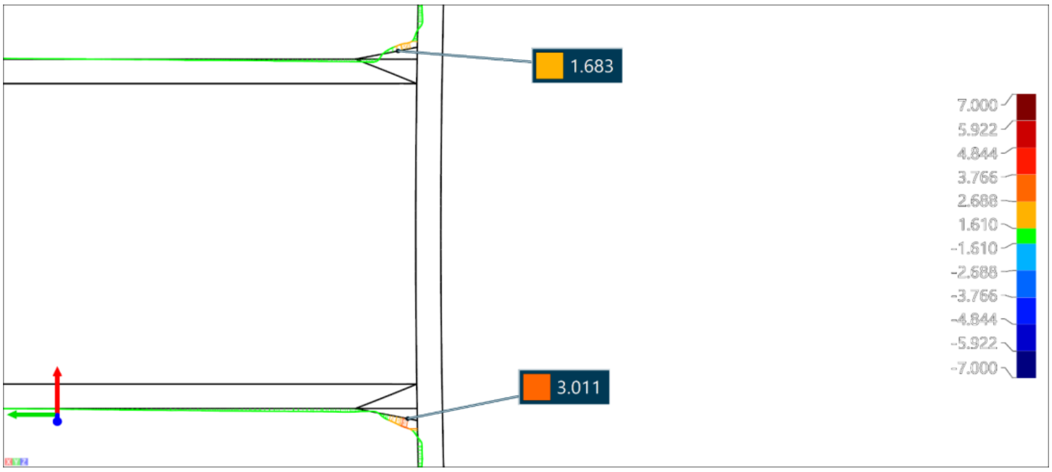
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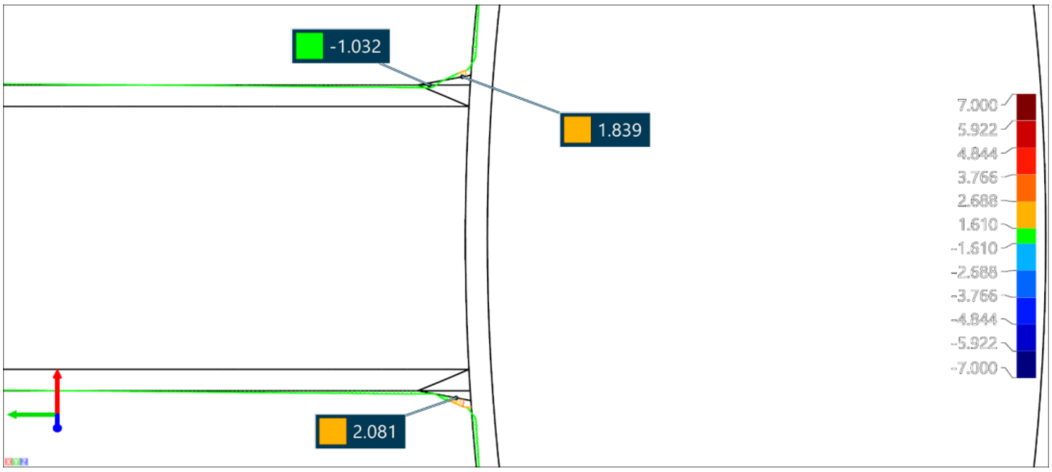
-7.000

20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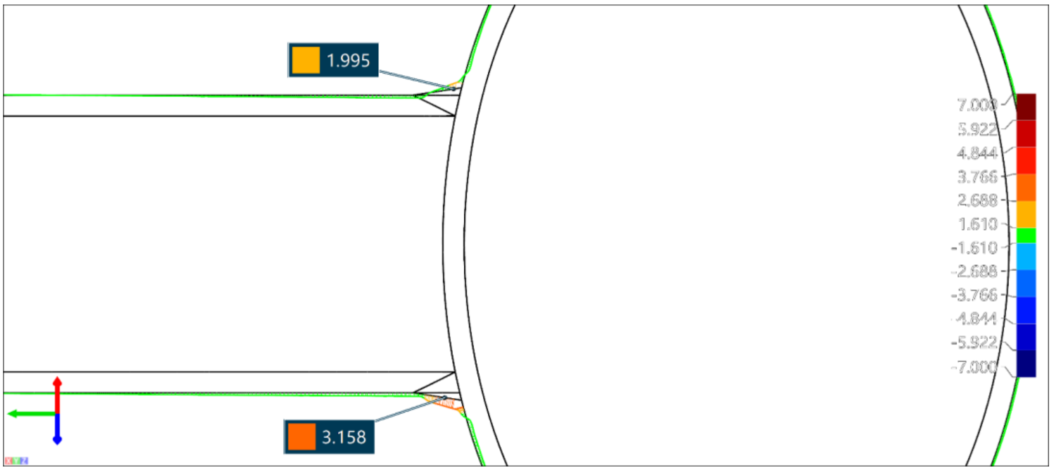
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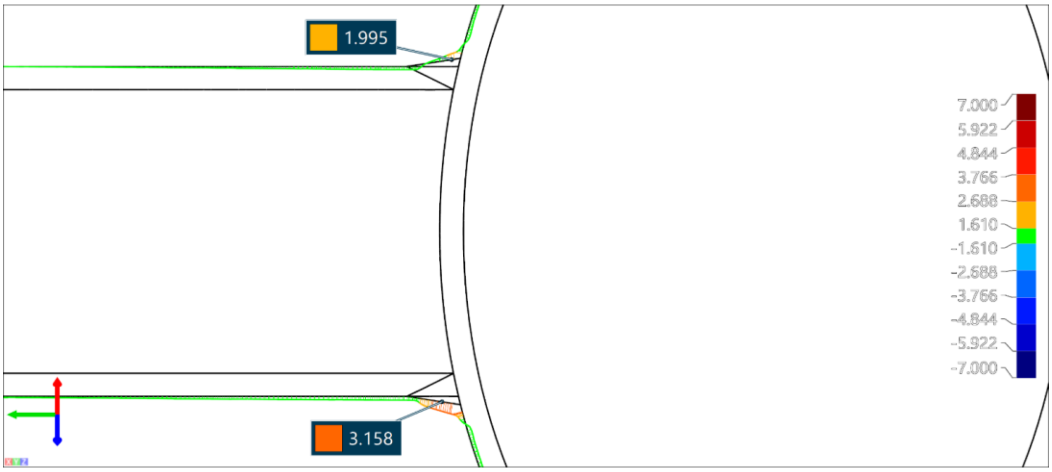
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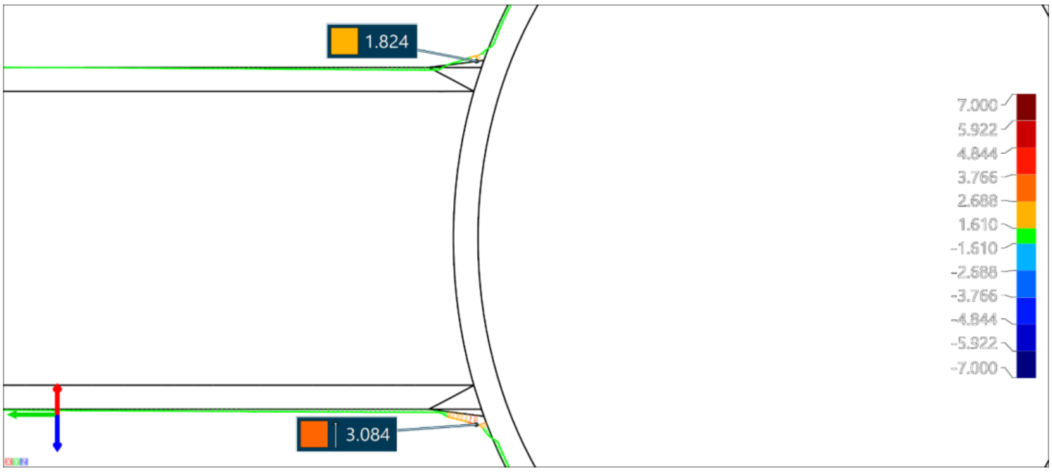
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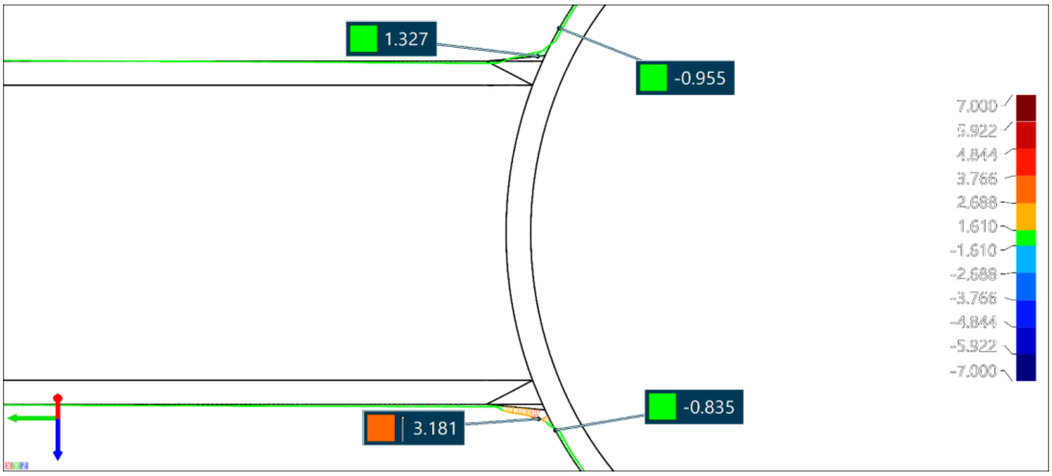
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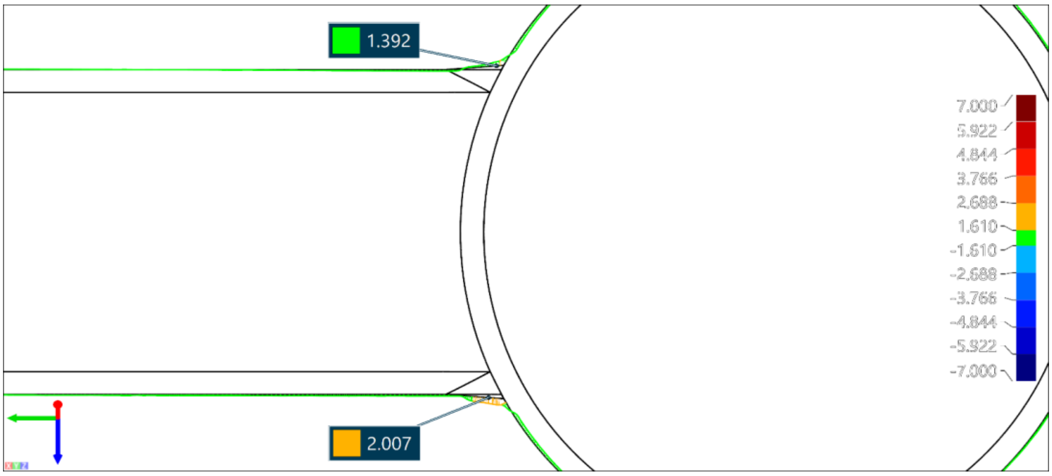
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-5.922
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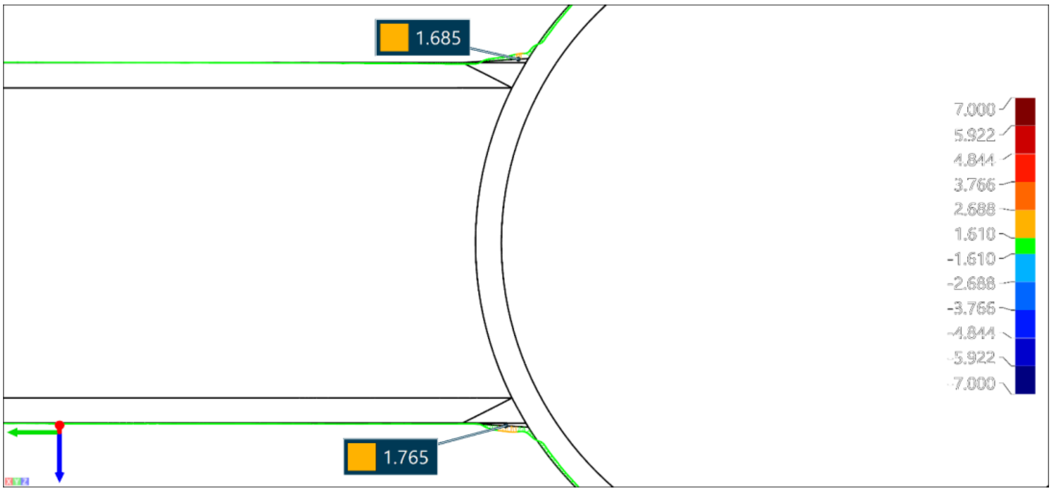
80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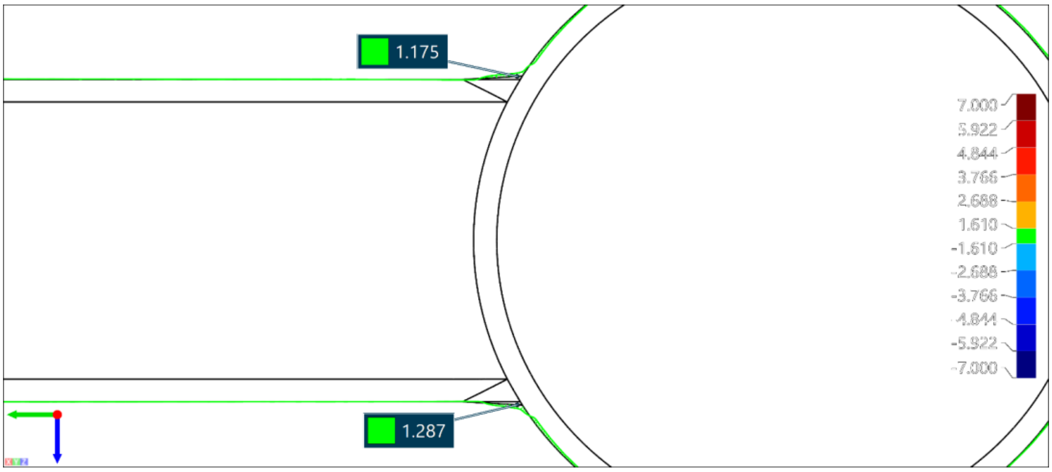
saddle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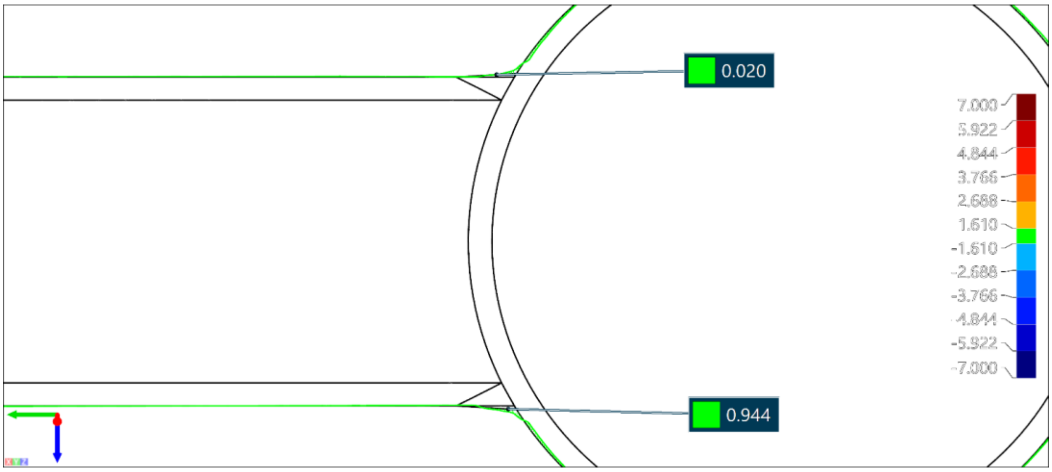
100



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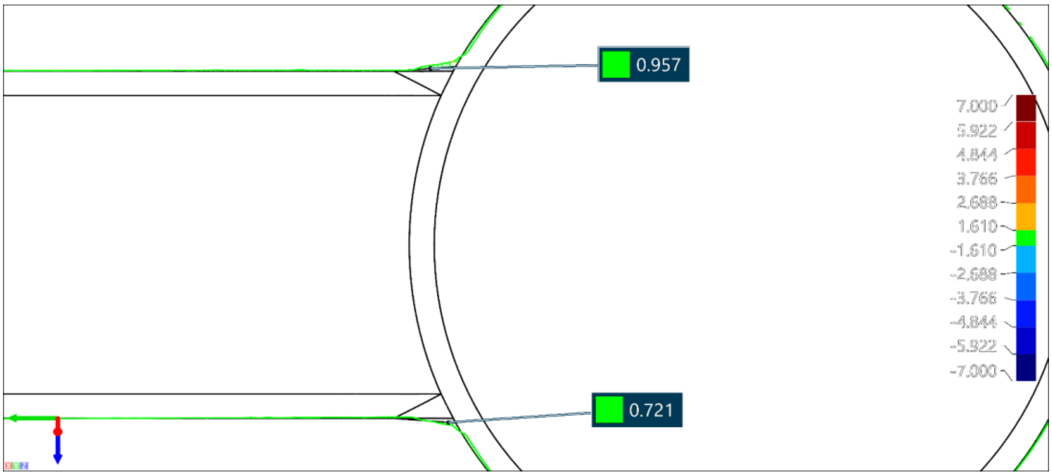

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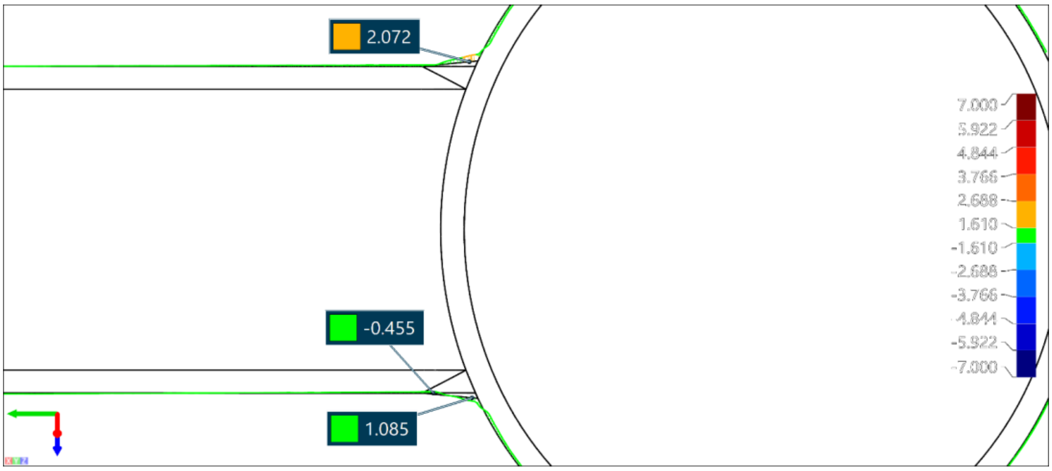
120



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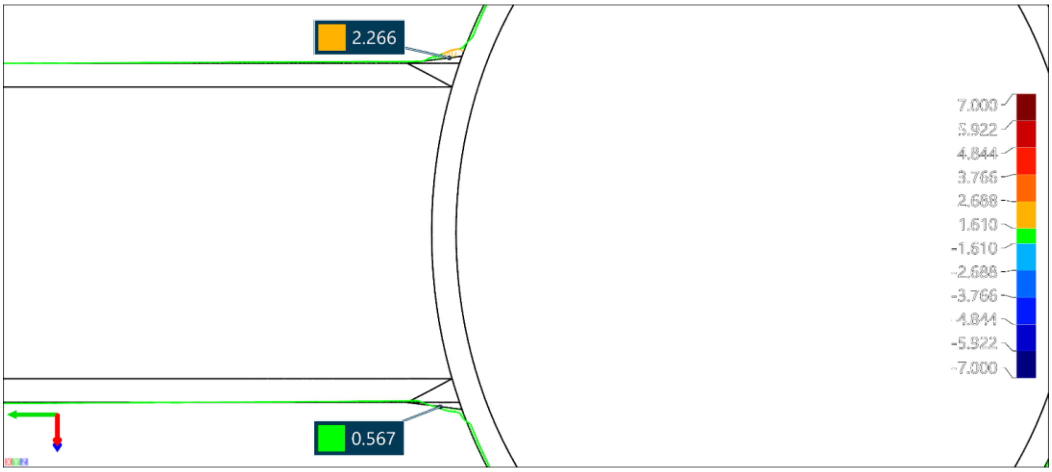
130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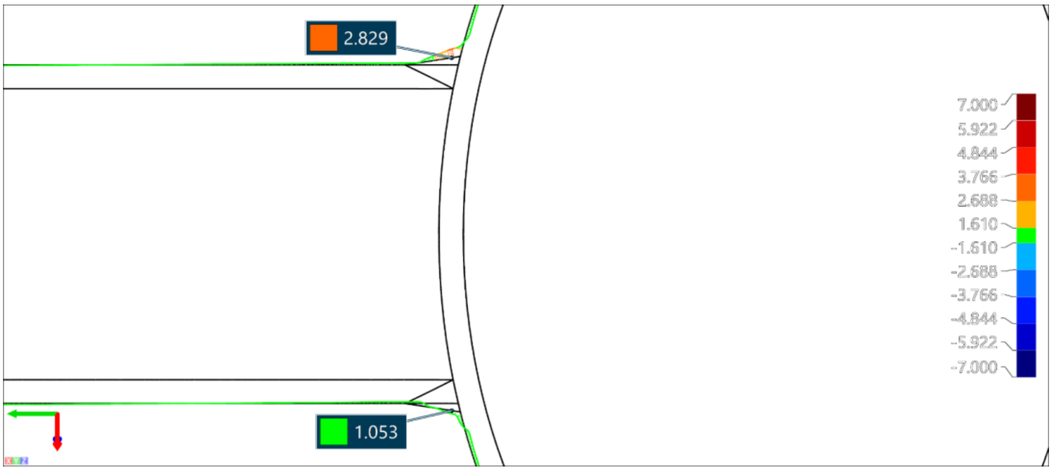
140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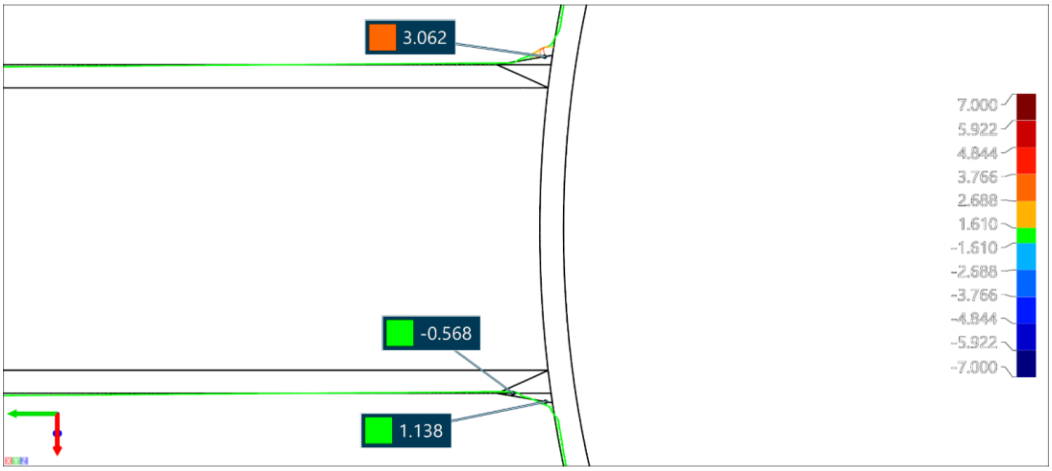
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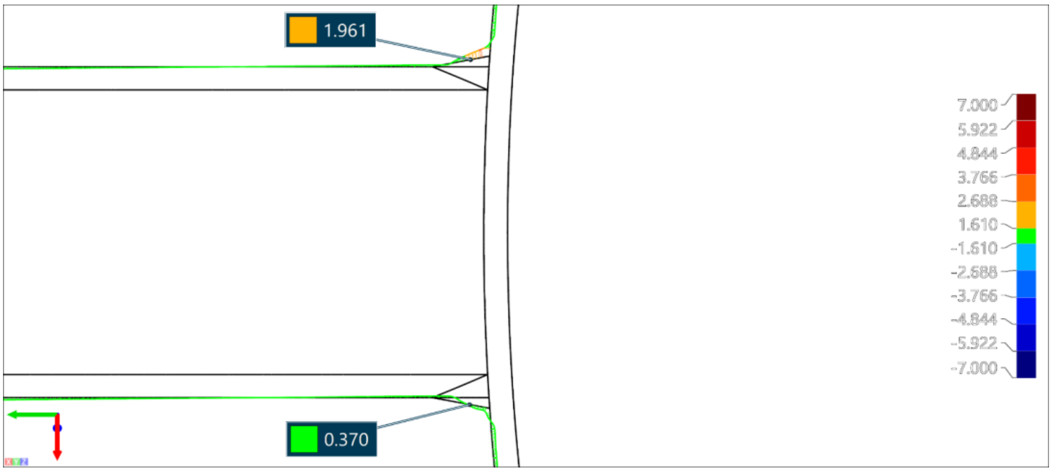
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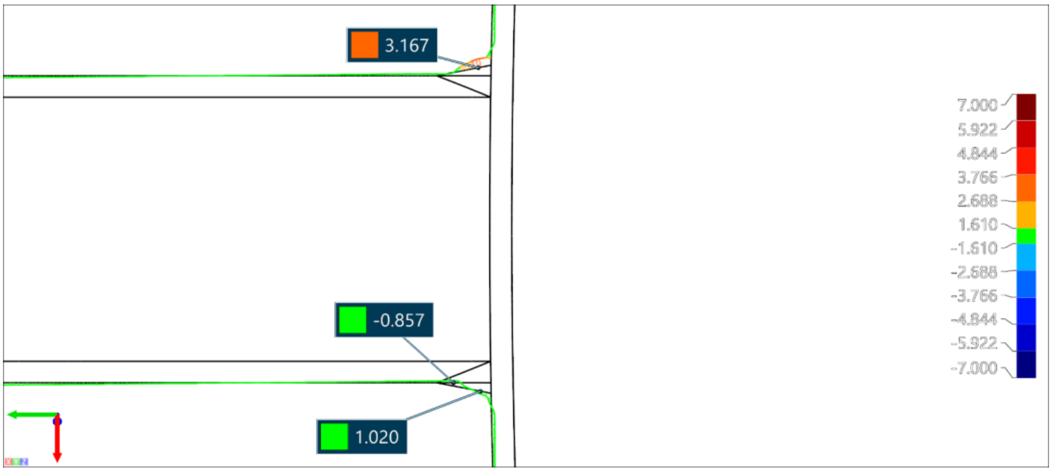
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Report prepared by
Name ____

Date ____

Signature ____

Report reviewed by
Name ____

Date ____

Signature ____

Specimen 2

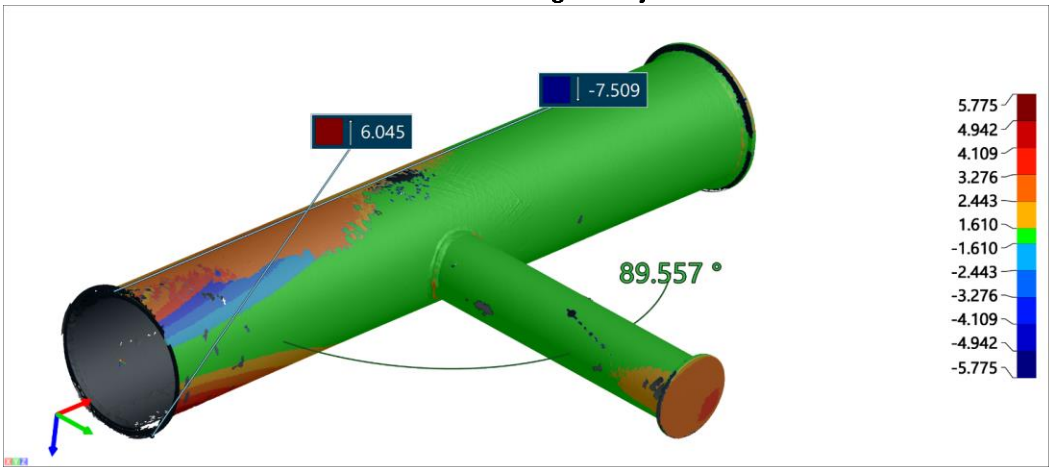
Project information

Organization	UIS
Units	mm

Part information

Part name	S31655-4000-T-04
Operator name	Kris Kolos

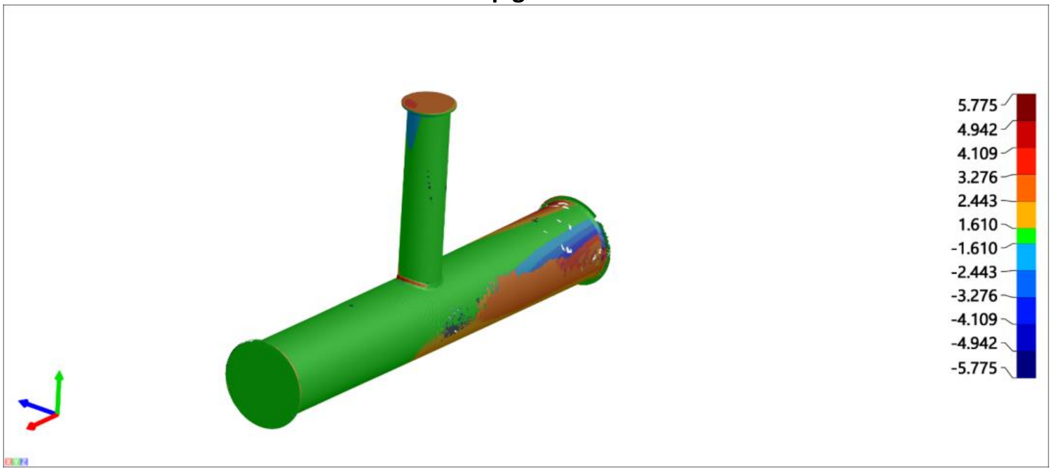
extremes and angle of T joint



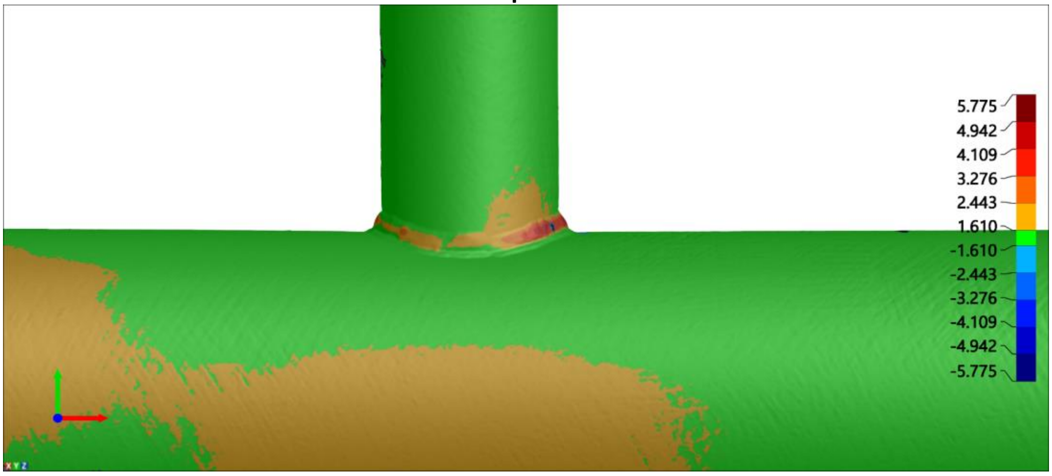
Color map 1 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-7,509	-7,509	**-5,899**
Max.	1,610	0,000	6,045	6,045	**4,435**
±	3,220	0,000	13,554	13,554	**10,334**
SD	1,000	0,000	1,395	1,395	**0,395**

colormap general view



colormap side view



Cylinder 1 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	220,224	1,124	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4,380	4,380		9,918		**5,538**

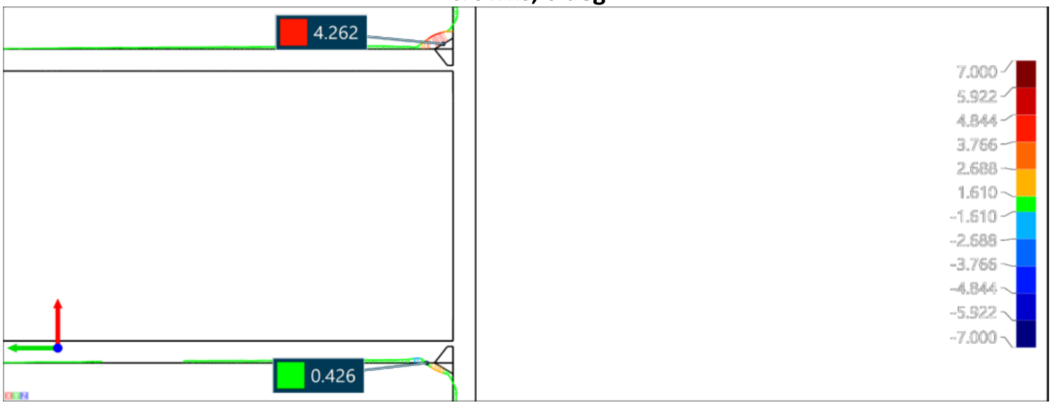
Cylinder 2 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,518	0,218	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2,290	2,290		6,377		**4,087**

Angle [°] - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,557	-0,443	**-0,110**
∠XZ	+0.333 -0.333	0,000	25,356	25,356	**25,023**
∠YZ	+0.333 -0.333	0,000	63,646	63,646	**63,313**

crowns, 0 deg



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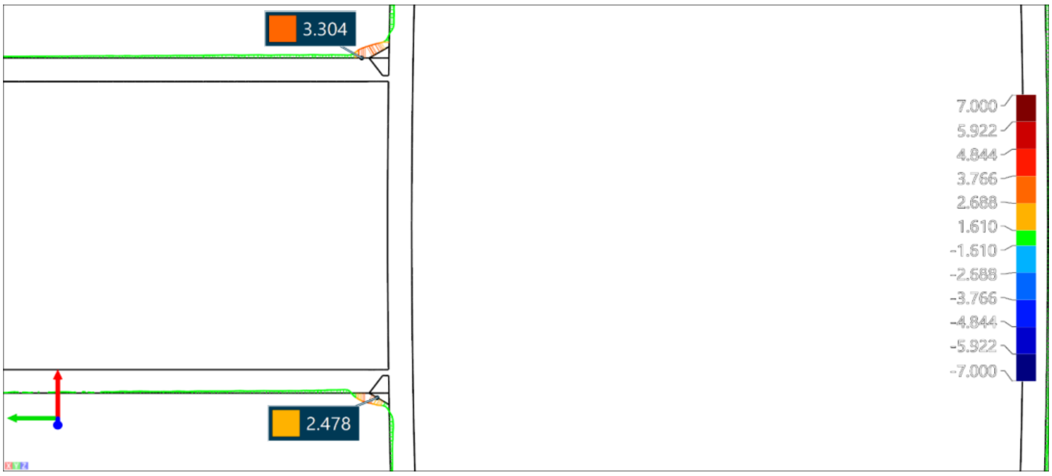

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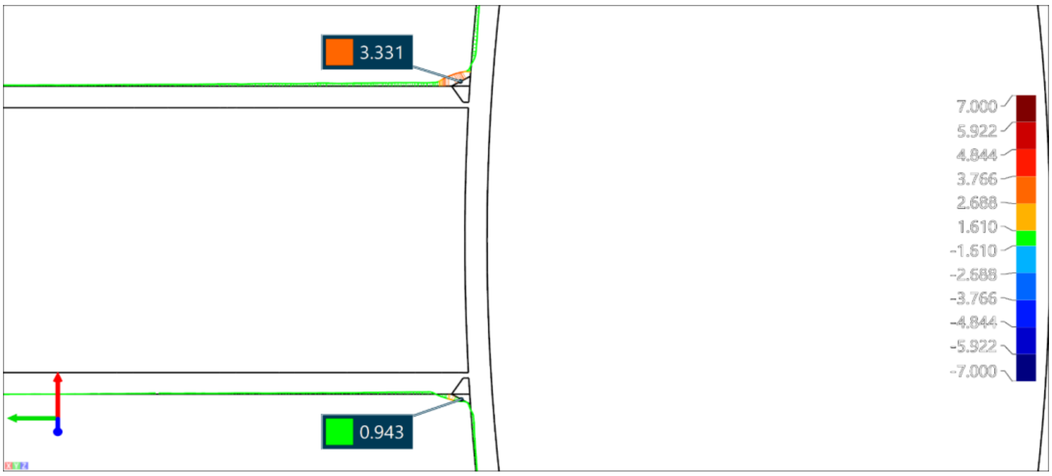

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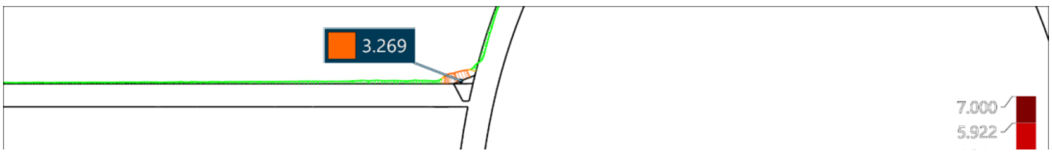

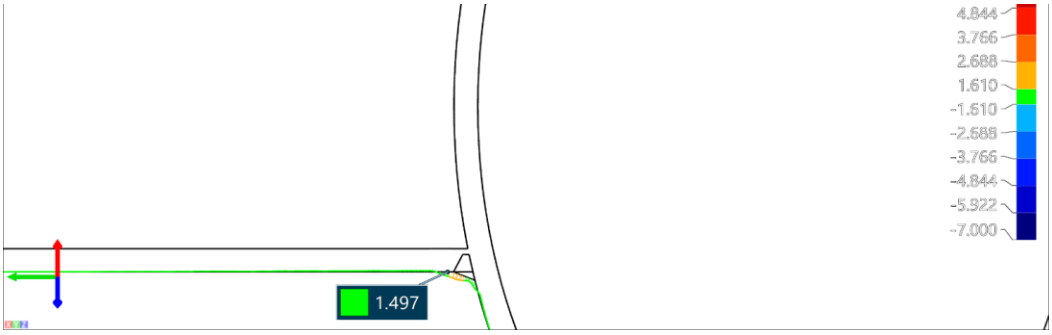
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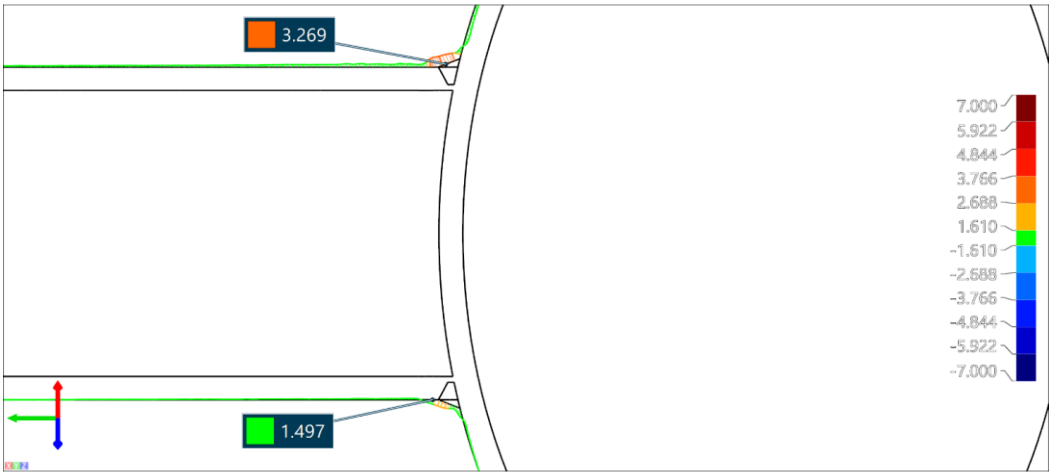
40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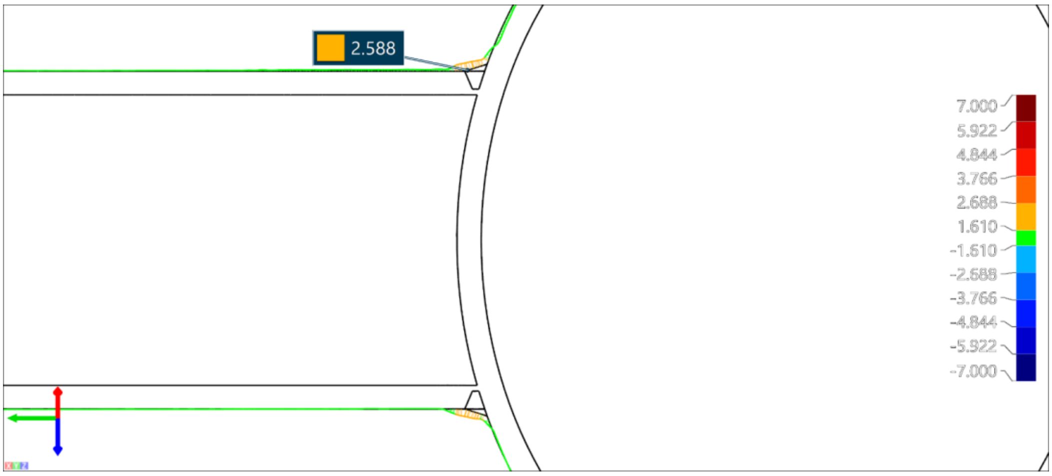
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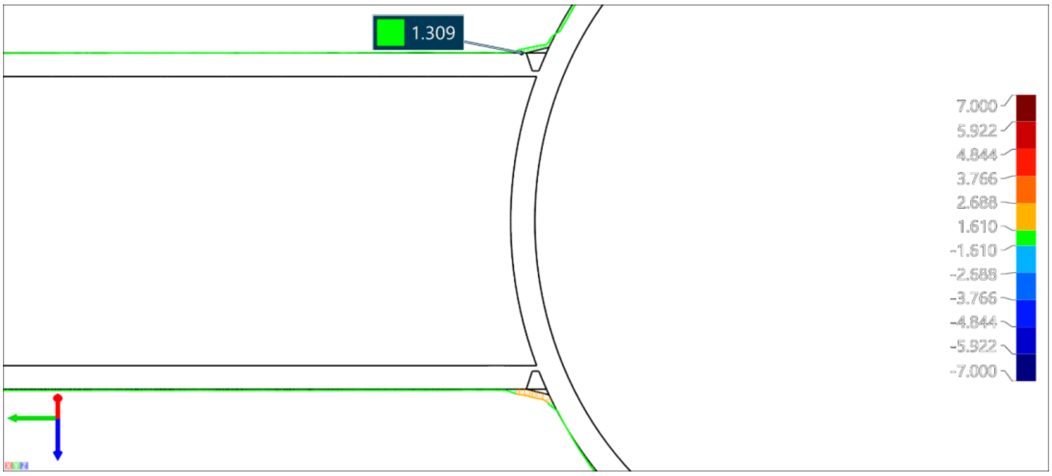
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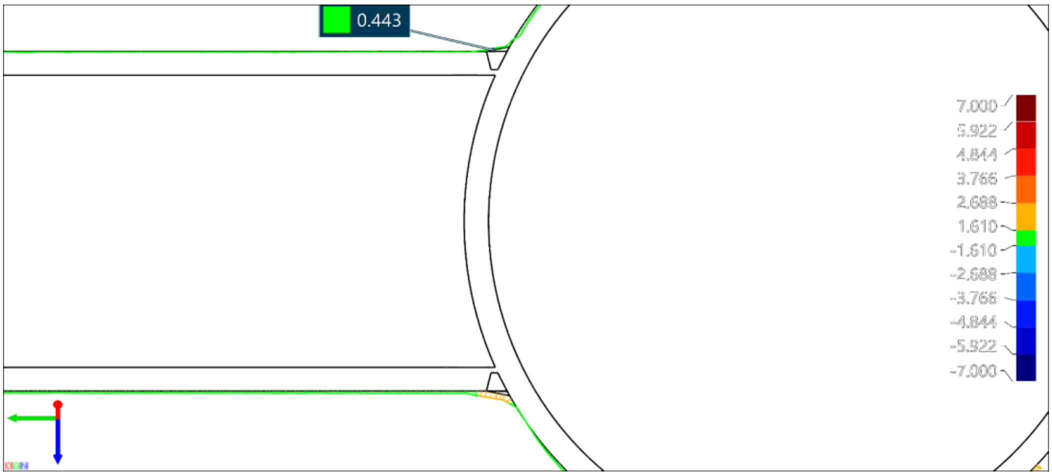
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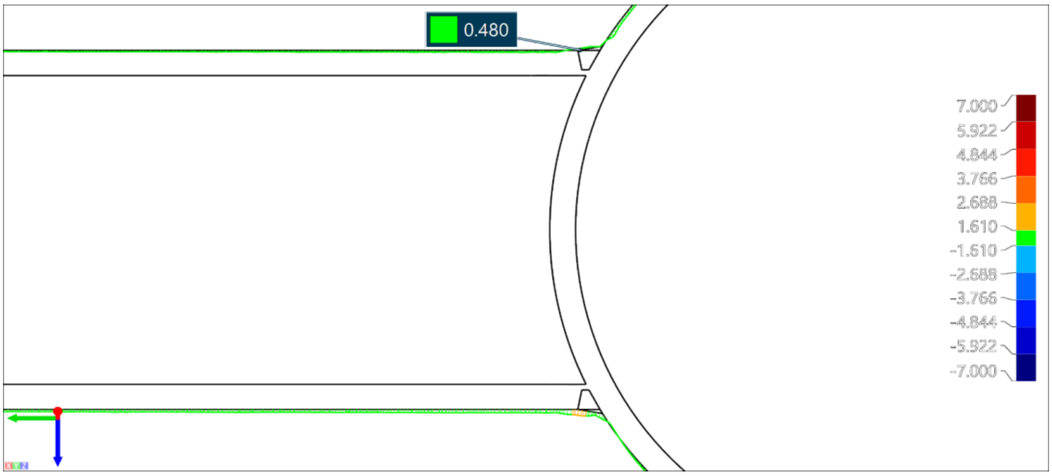
80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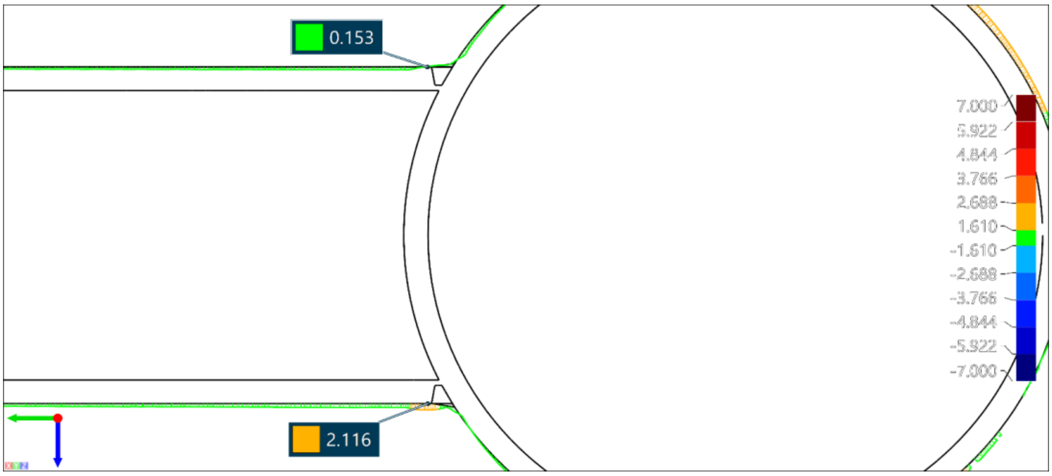
saddle



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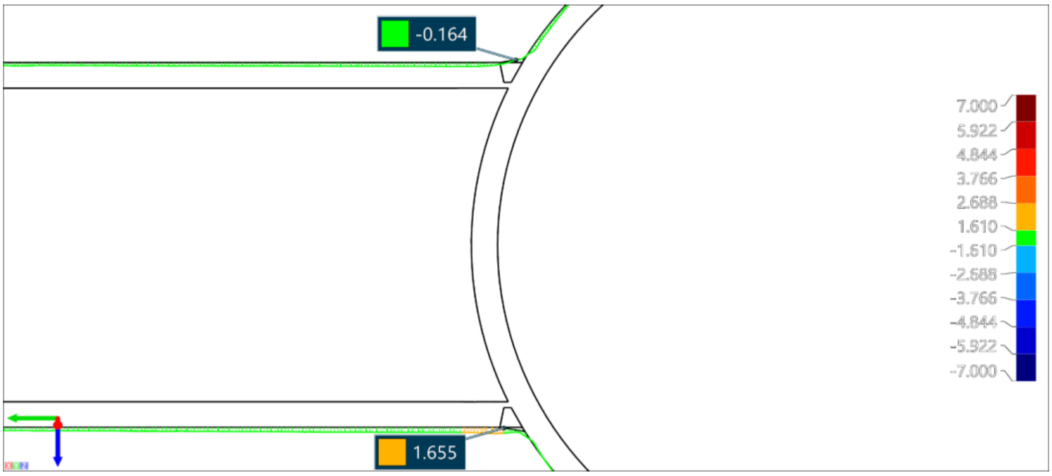

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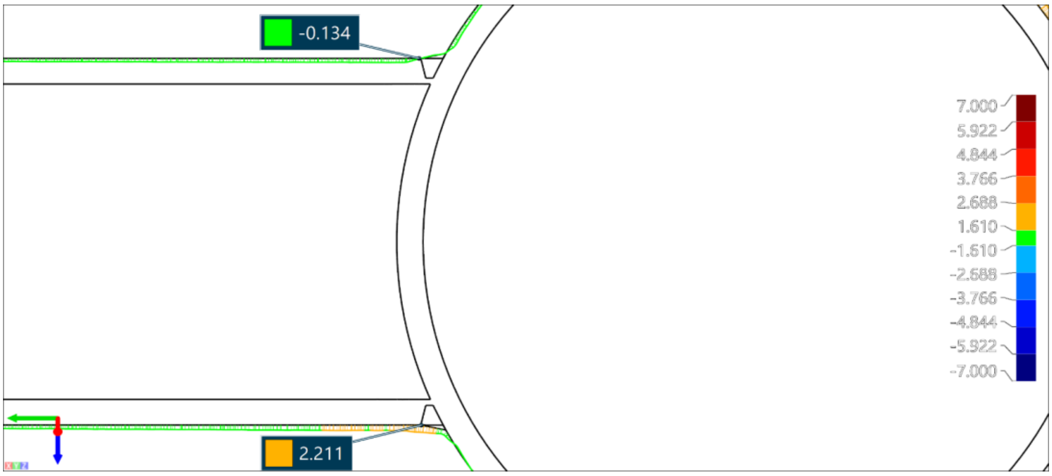

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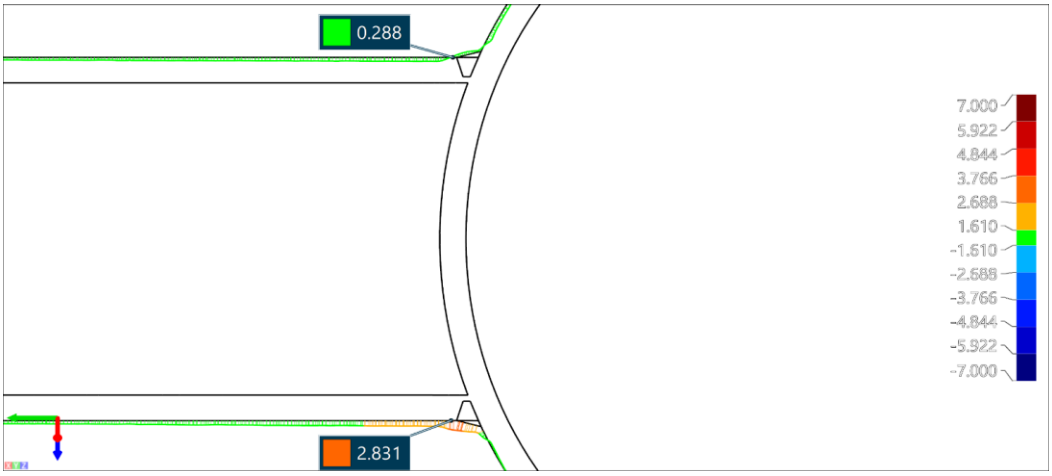

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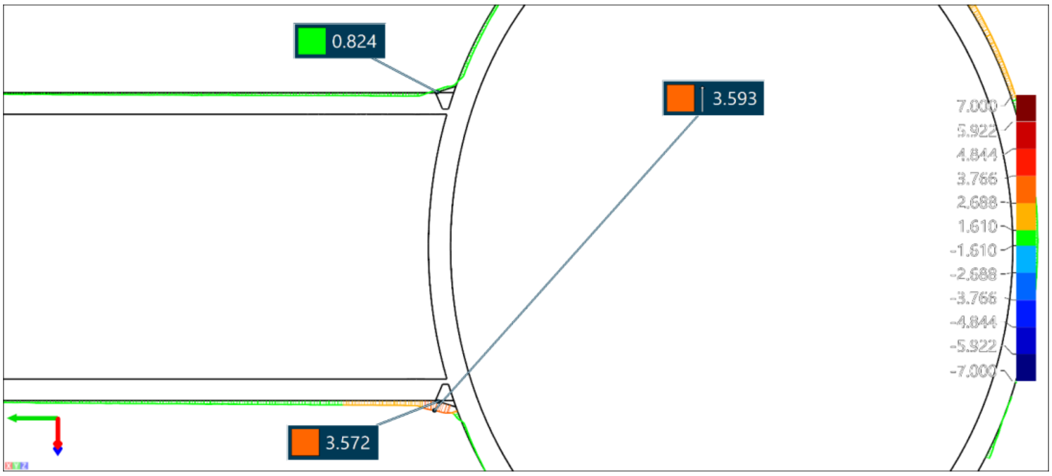

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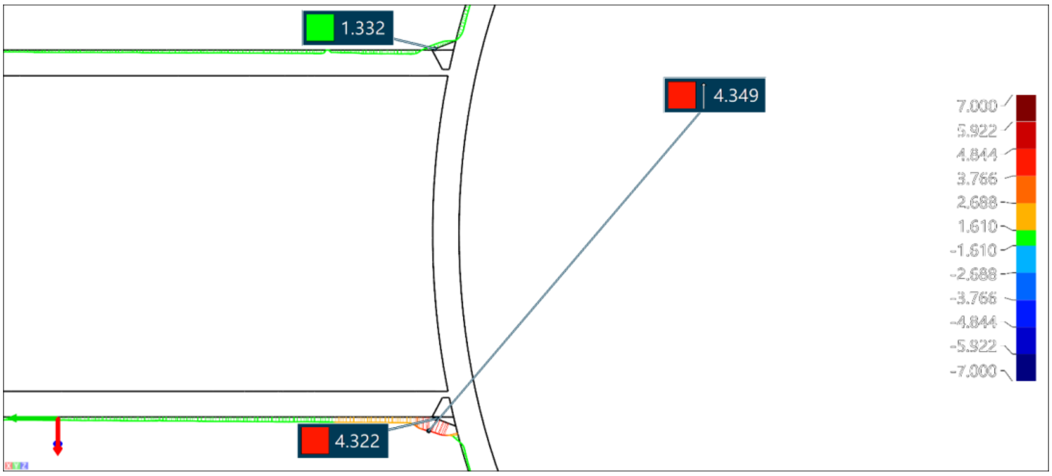

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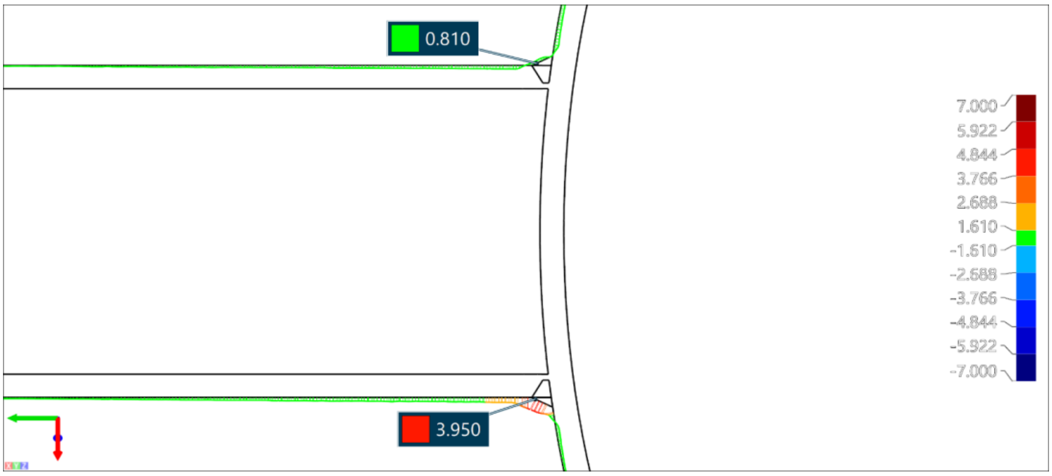
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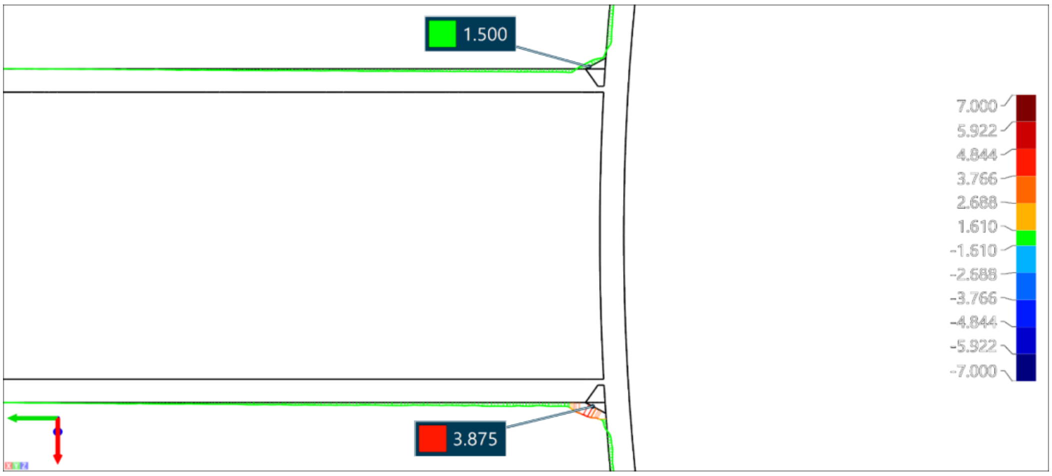
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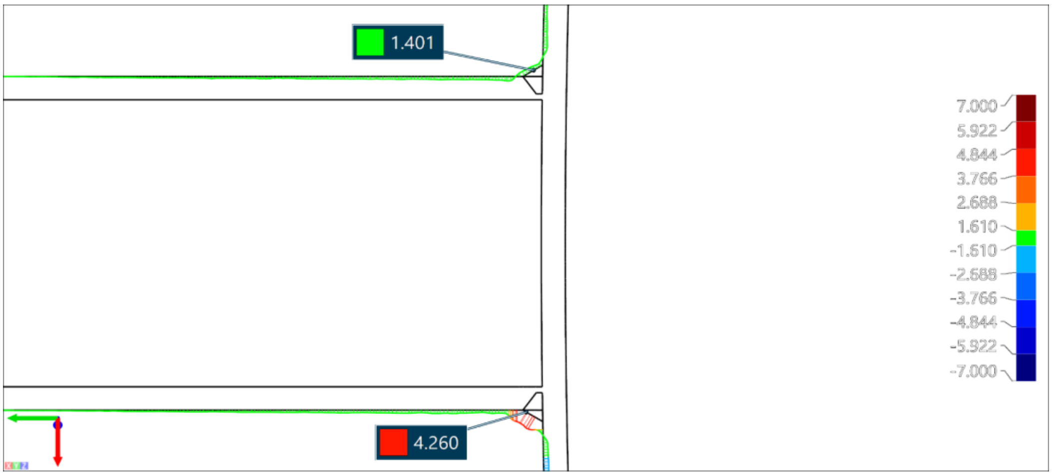
170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2.688
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-4.844
-5.922
-7.000

MMC

Project information

Organization	UIS
Units	mm

Part information

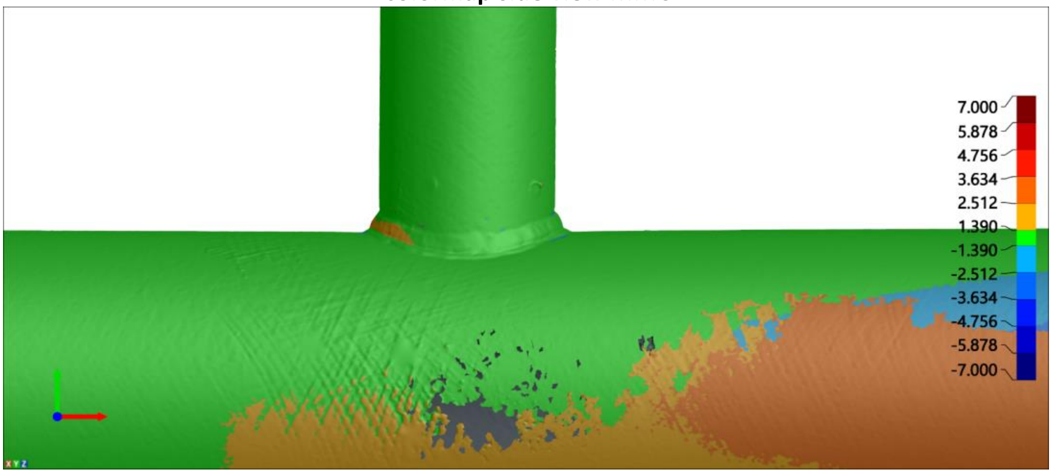
Part name	S31655-4000-T-04
Operator name	Kris Kolos

Color map 1 - Scan2

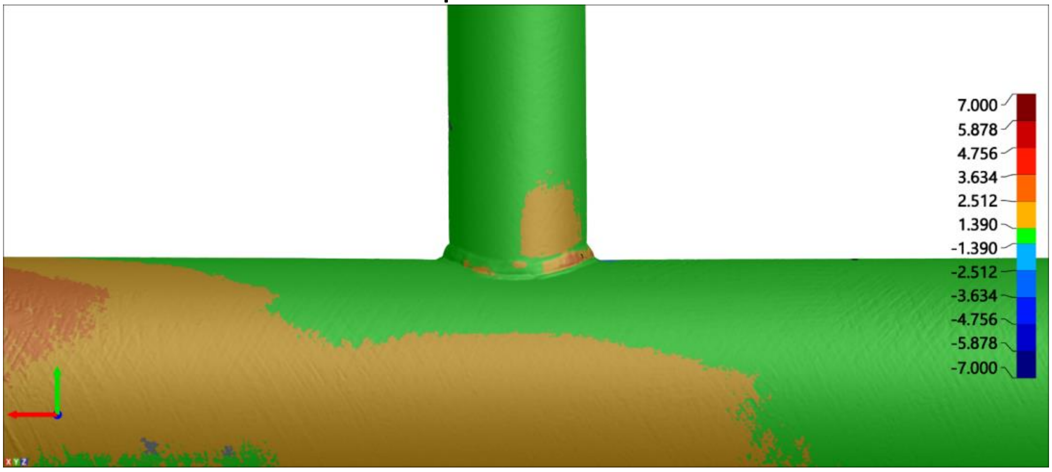
Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-22,953	-22,953	**-21,343**
Max.	1,610	0,000	22,979	22,979	**21,369**
±	3,220	0,000	45,933	45,933	**42,713**
SD	1,000	0,000	1,438	1,438	**0,438**

extremes at MMC

colormap side view MMC



colormap other side view MMC



Cylinder 1 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	220,224	1,124	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		9,918		**5,538**

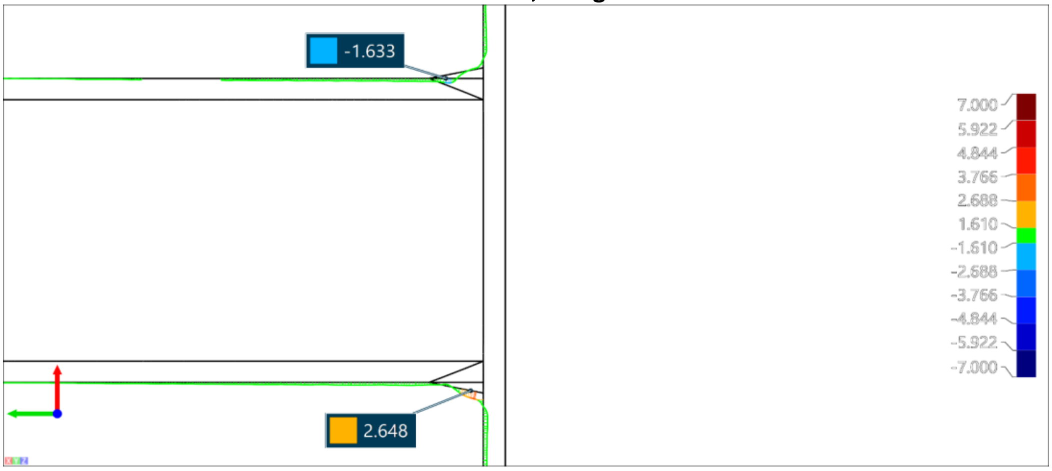
Cylinder 2 - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,518	0,218	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		6,377		**4,087**

Angle [°] - Scan2

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,557	-0,443	**-0,110**
∠XZ	+0.333 -0.333	0,000	25,345	25,345	**25,012**
∠YZ	+0.333 -0.333	0,000	63,664	63,664	**63,331**

crowns, 0 deg



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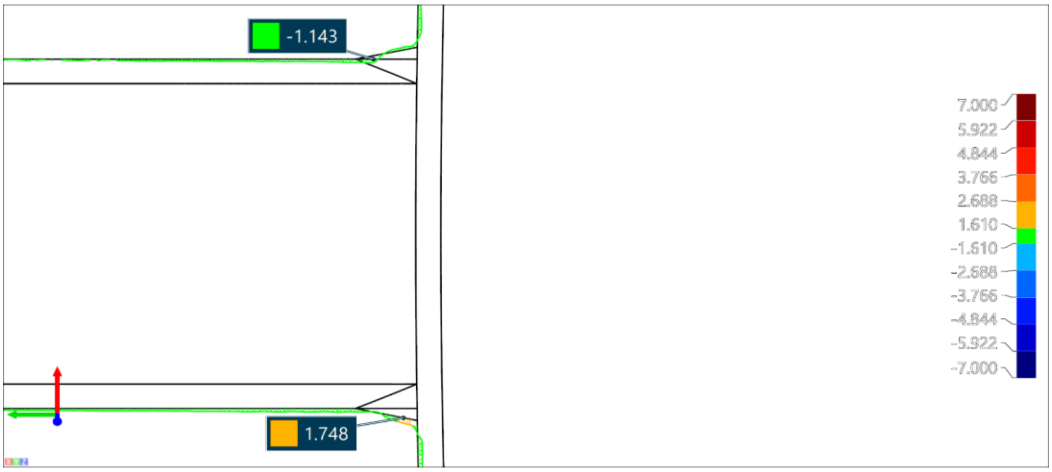
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-5.922
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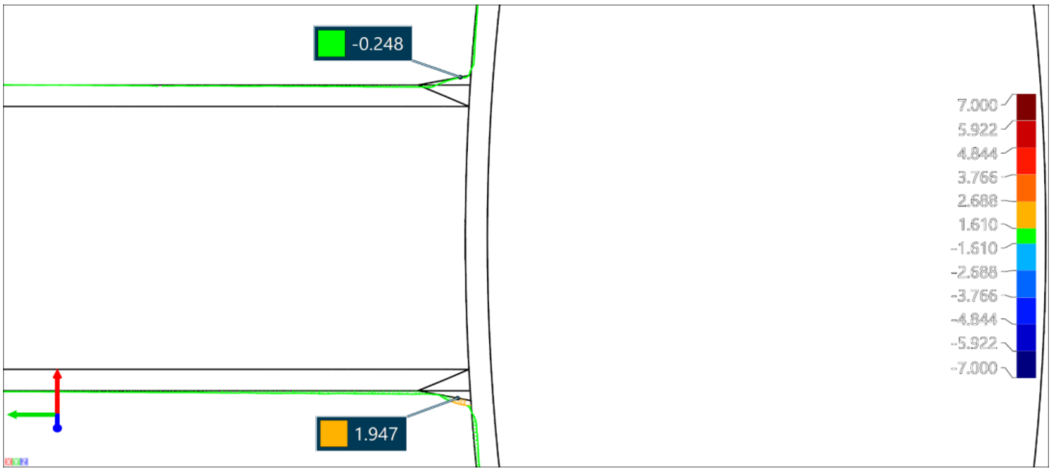
20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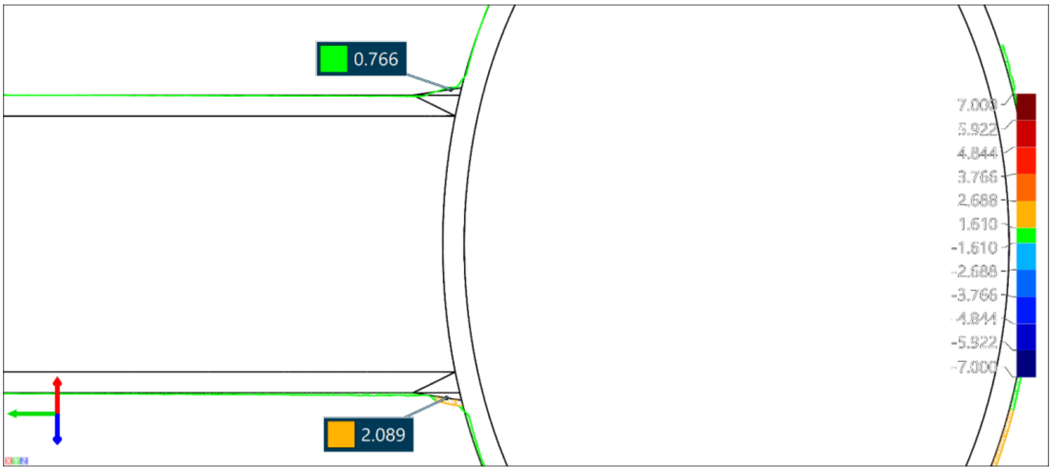
30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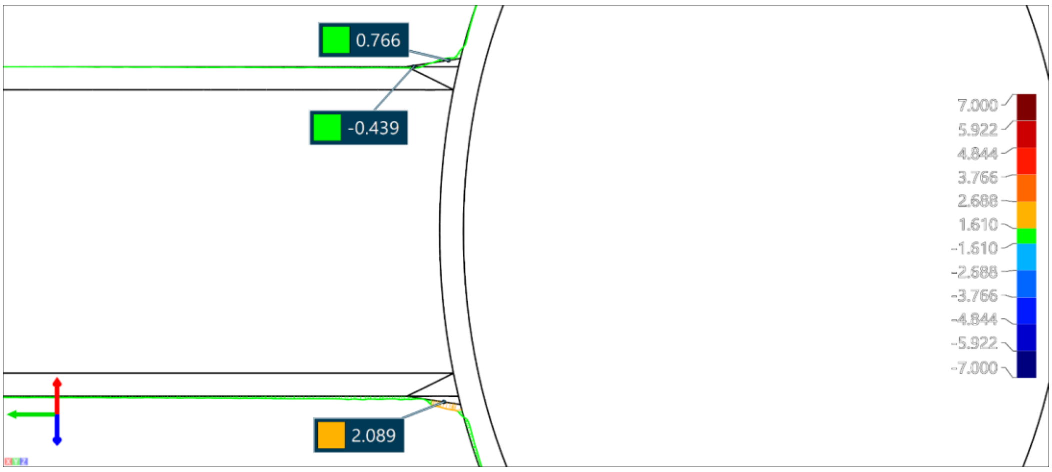
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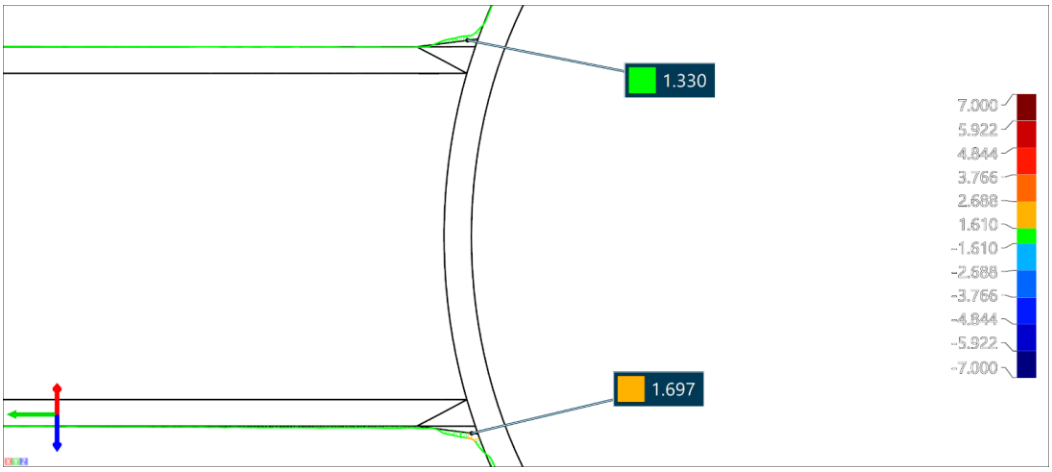
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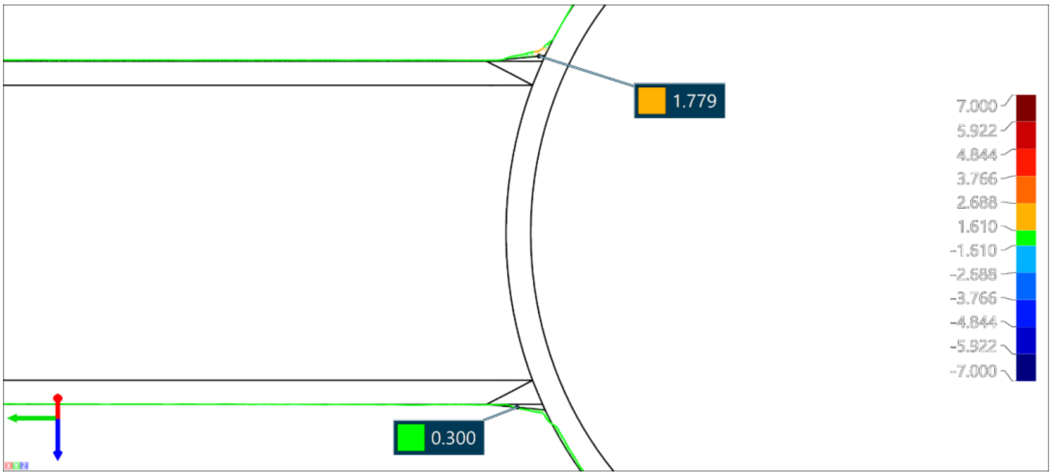
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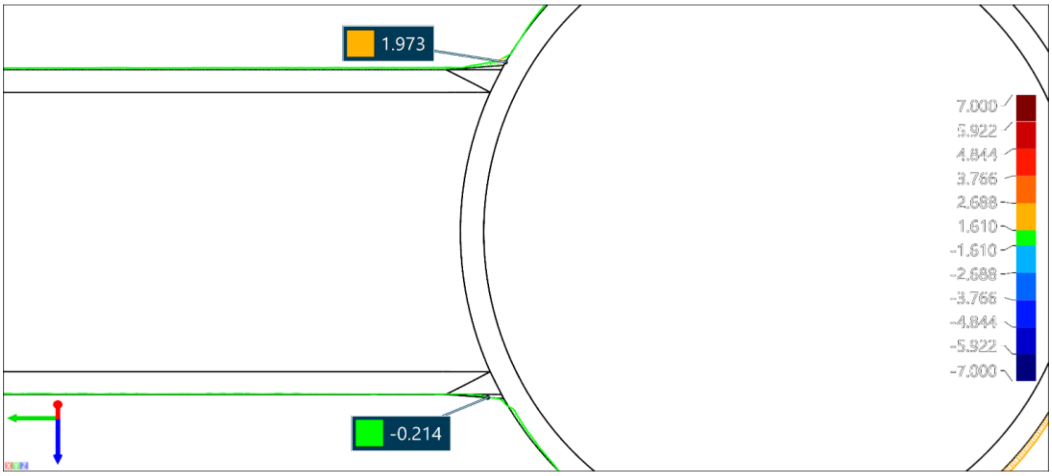
70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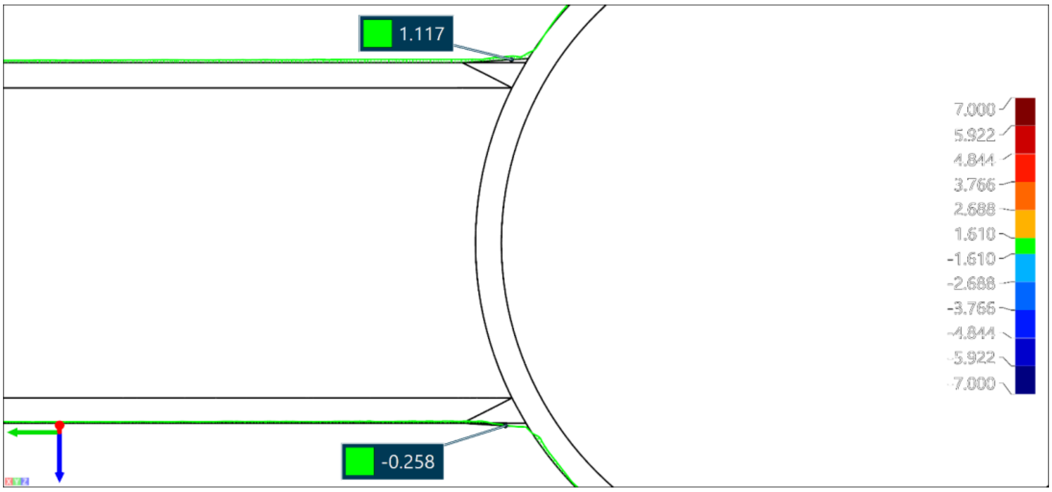
80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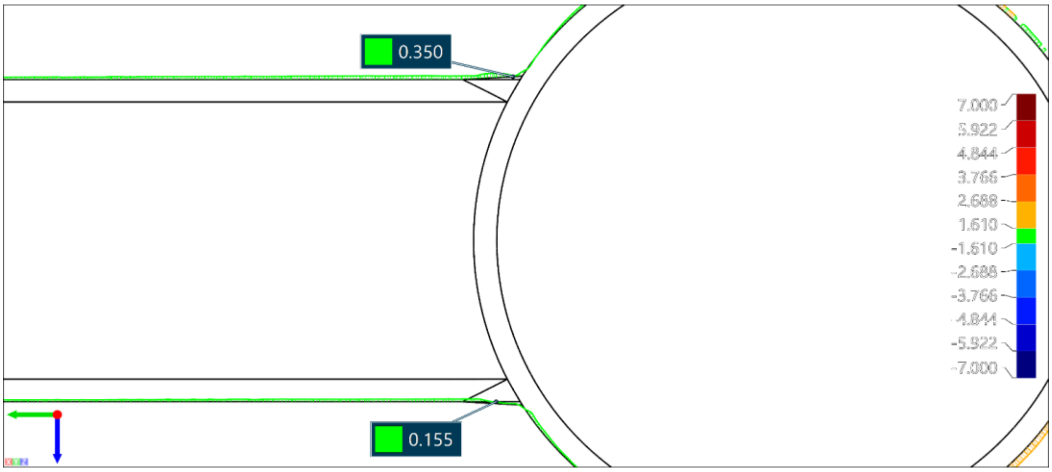
-7.000

saddle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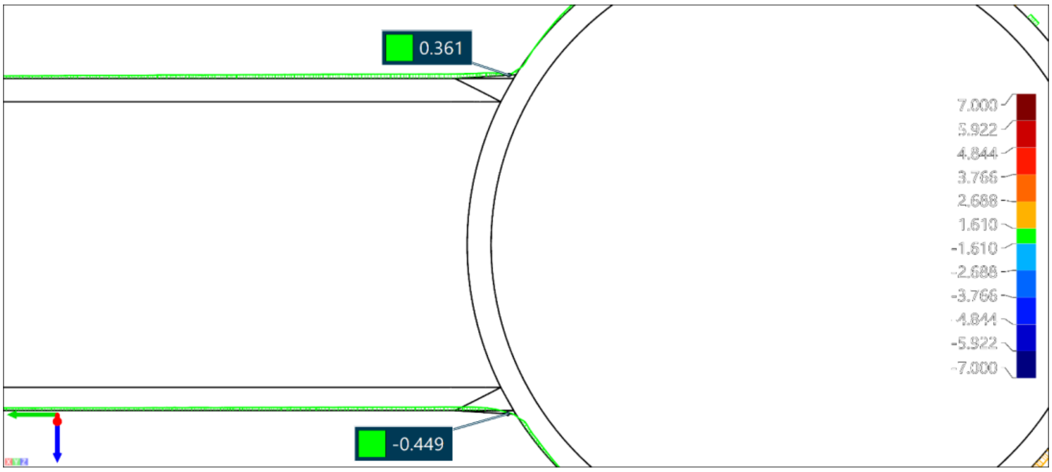
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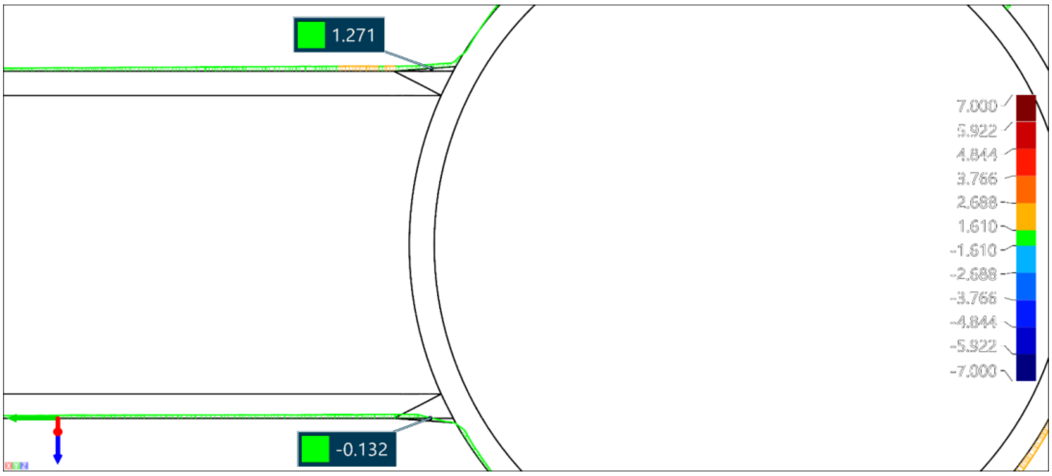
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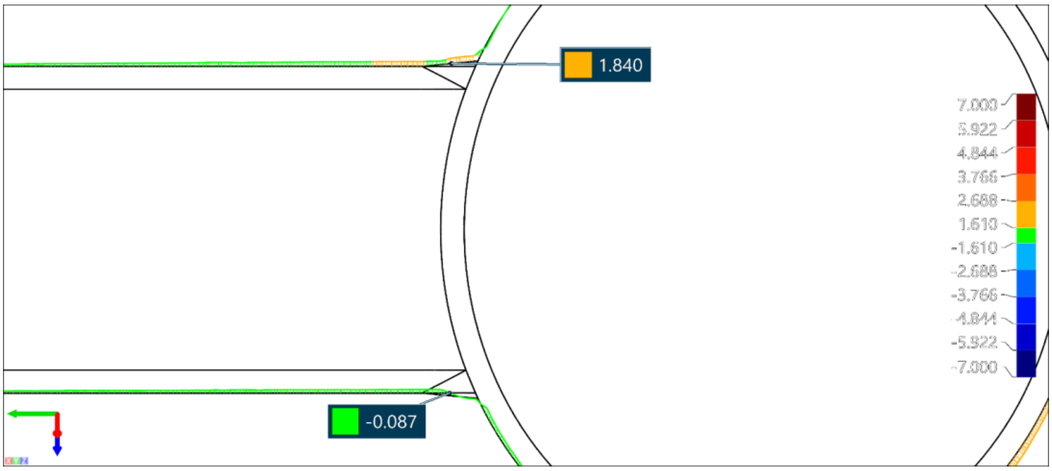
120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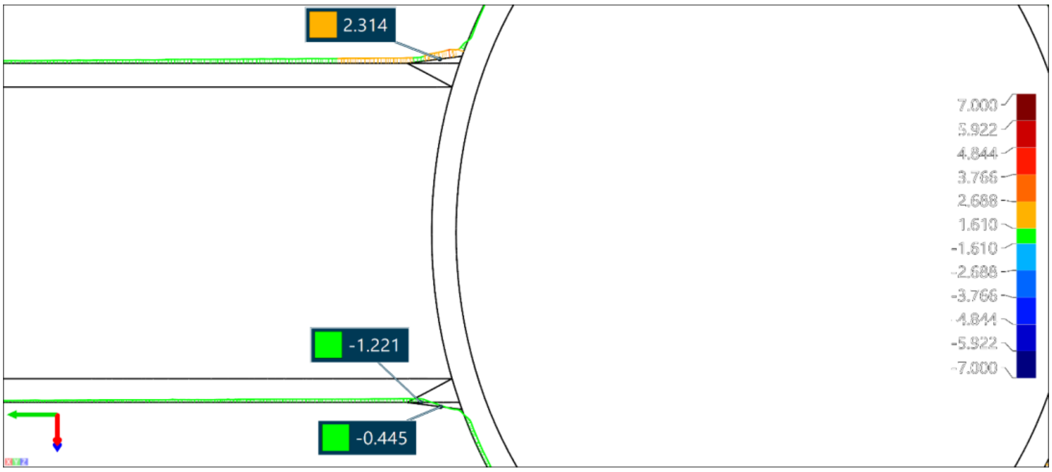
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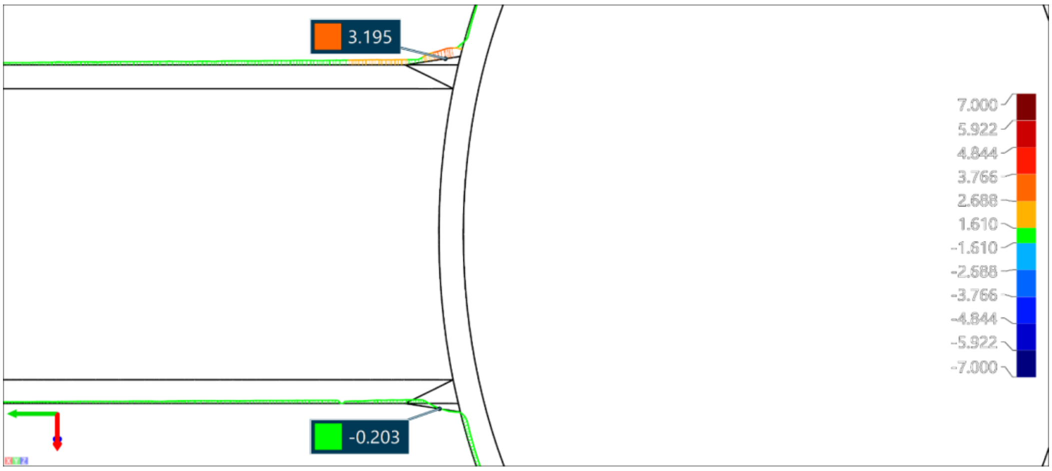
140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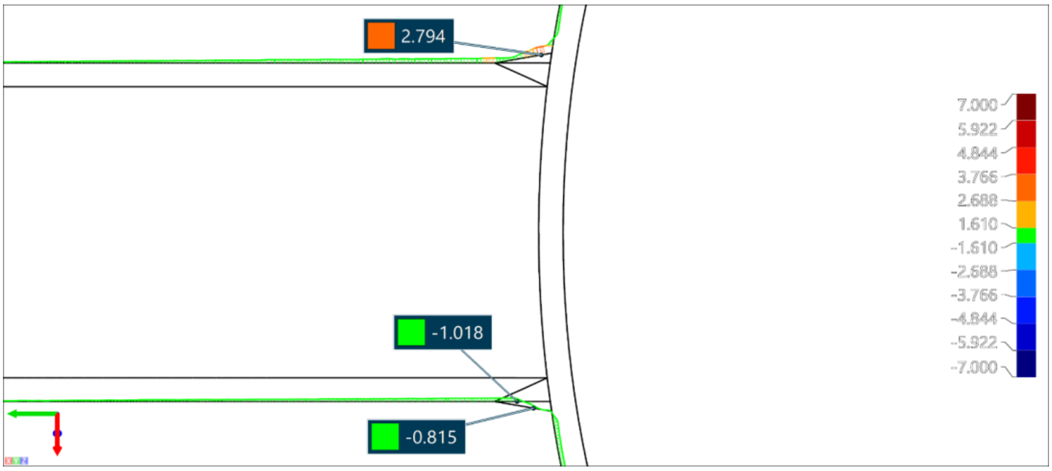
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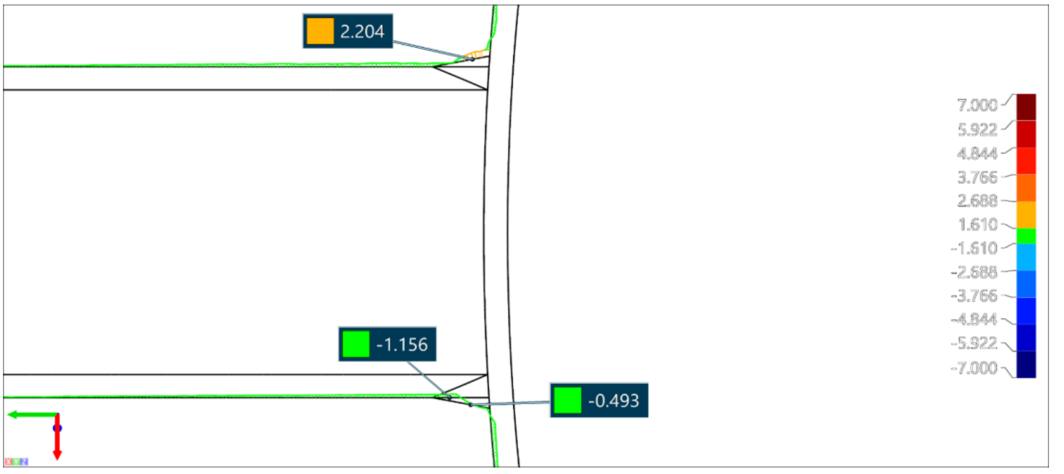
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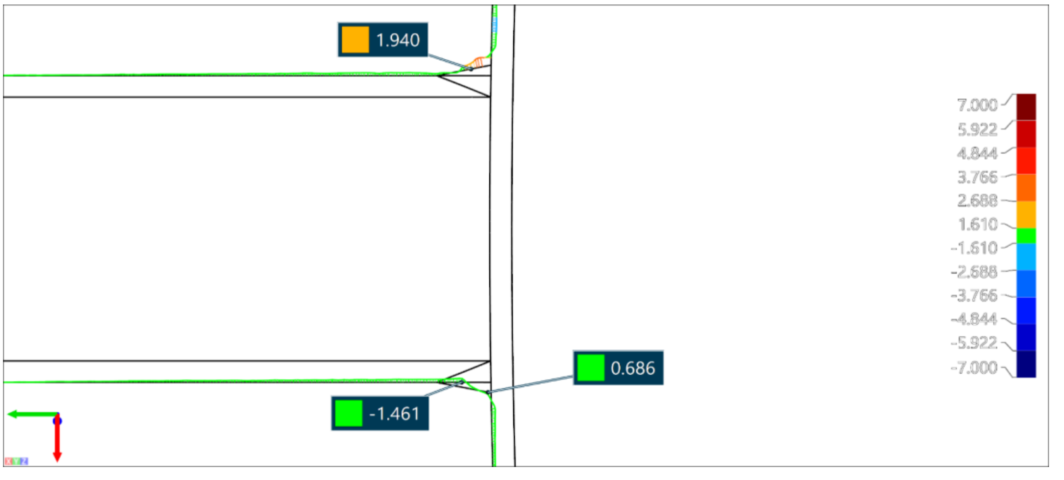
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-5.922
-7.000

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Report prepared by
Name ____

Date ____

Signature ____

Report reviewed by
Name ____

Date ____

Signature ____

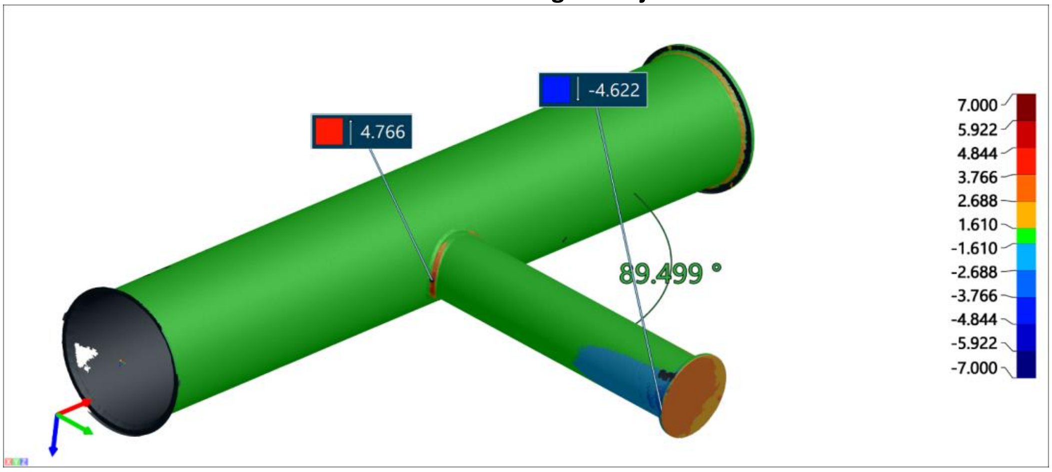
Project information

Organization	UIS
Units	mm

Part information

Part name	S31655-4000-T-05
Operator name	Kris Kolos

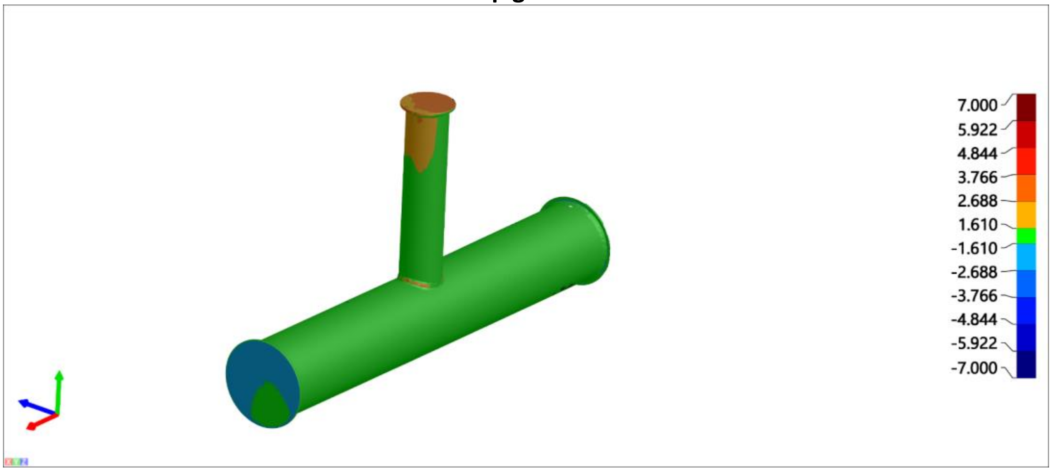
extremes and angle of T joint



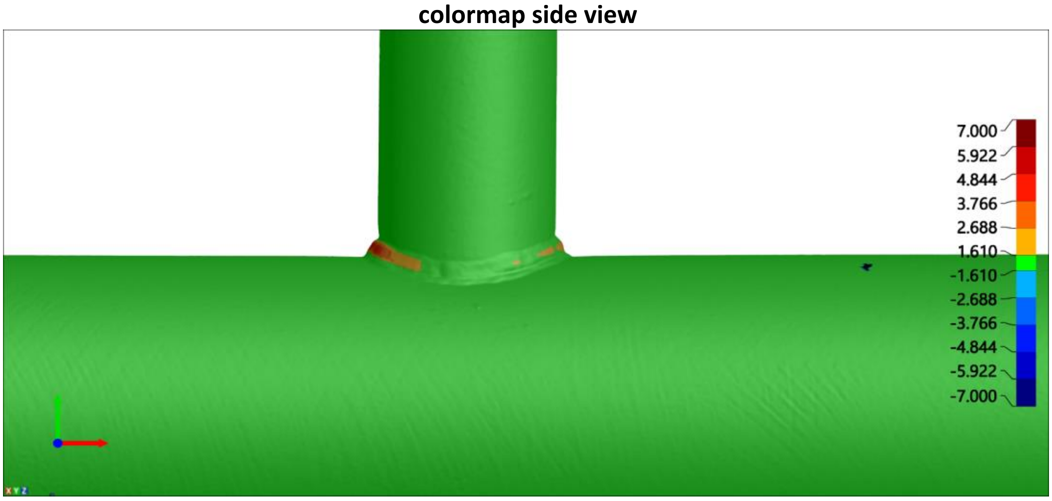
Color map 1 - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-4,622	-4,622	**-3,012**
Max.	1,610	0,000	4,766	4,766	**3,156**
±	3,220	0,000	9,388	9,388	**6,168**
SD	1,000	0,000	0,786	0,786	

colormap general view



colormap side view



Cylinder 1 - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,271	0,171	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		2,167		

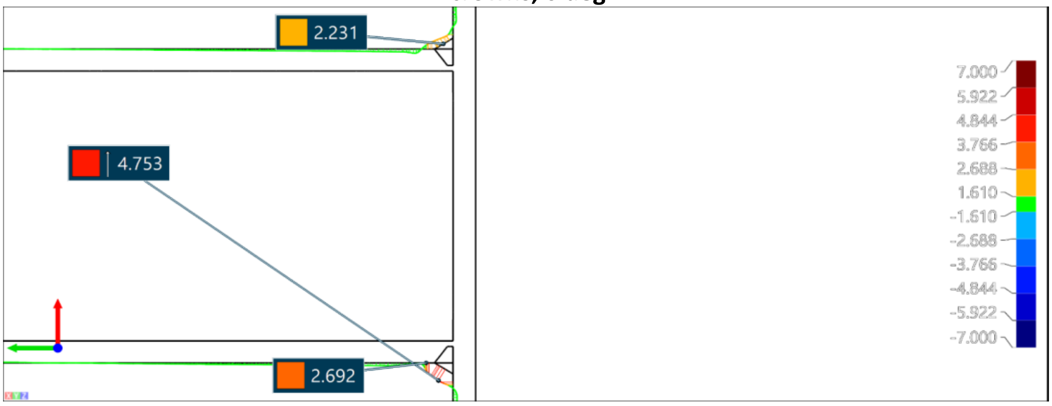
Cylinder 2 - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,348	0,048	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		7,521		**5,231**

Angle [°] - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,499	-0,501	**-0,168**
∠XZ	+0.333 -0.333	0,000	1,383	1,383	**1,050**
∠YZ	+0.333 -0.333	0,000	3,178	3,178	**2,845**

crowns, 0 deg



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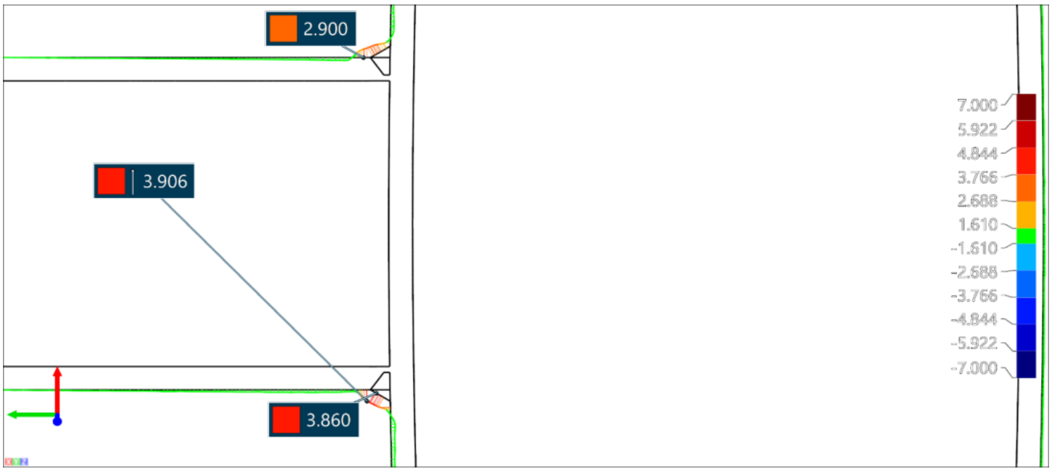

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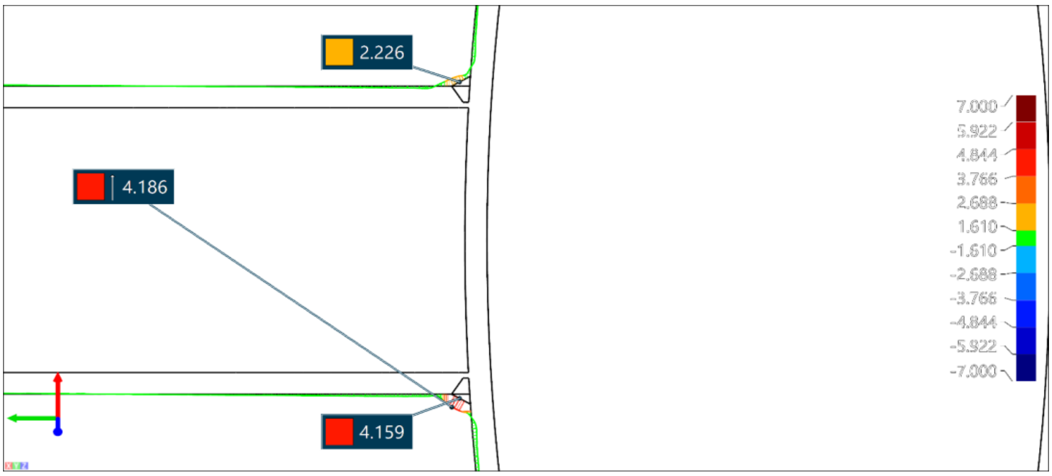

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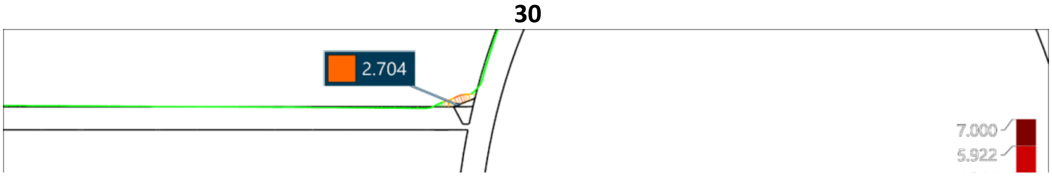

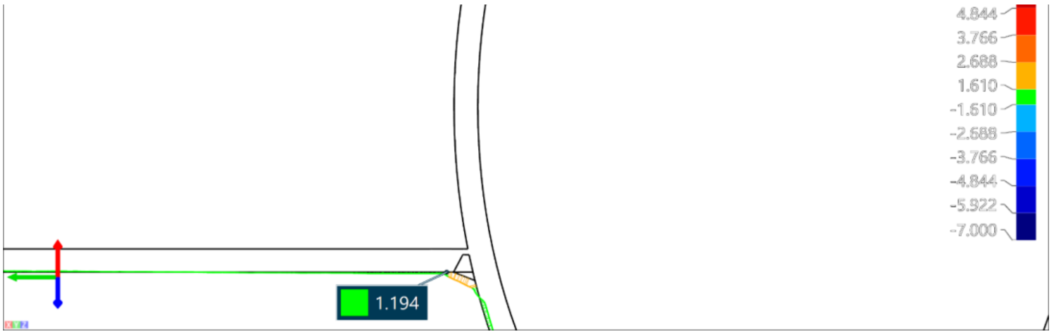
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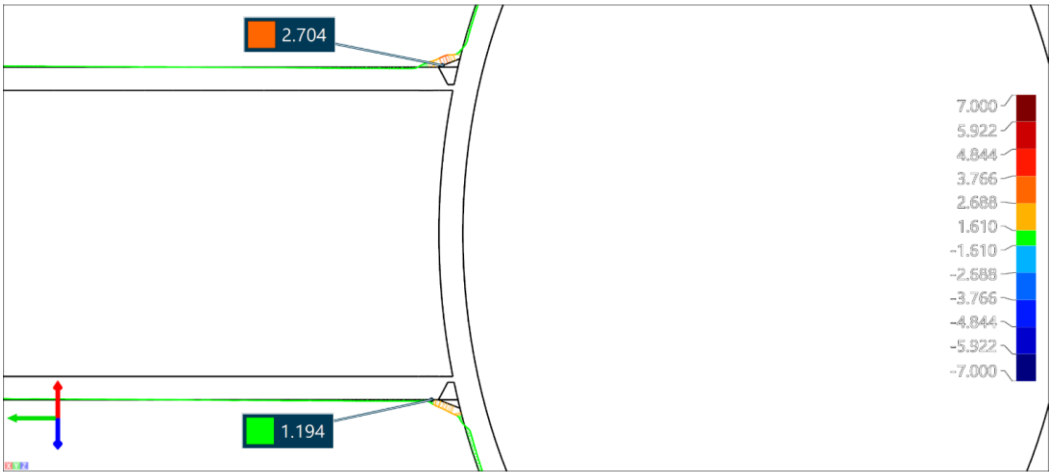
40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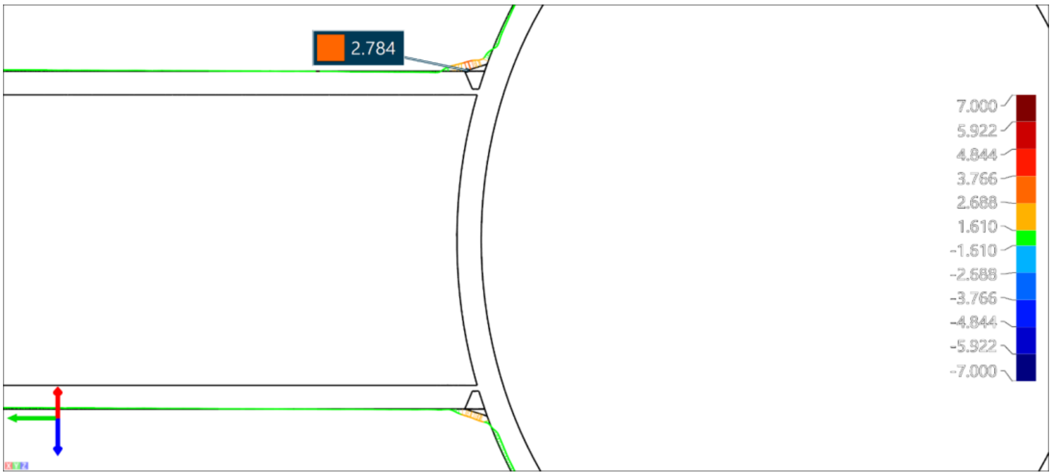
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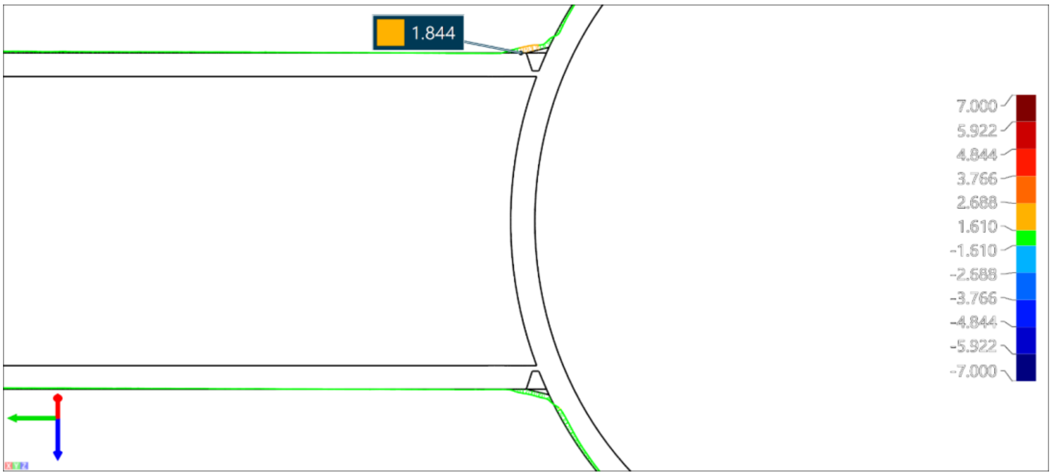
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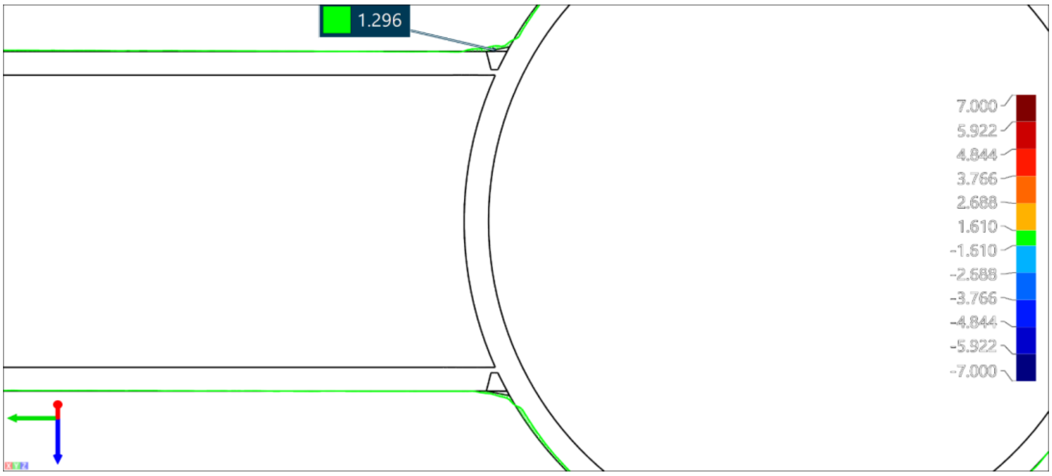
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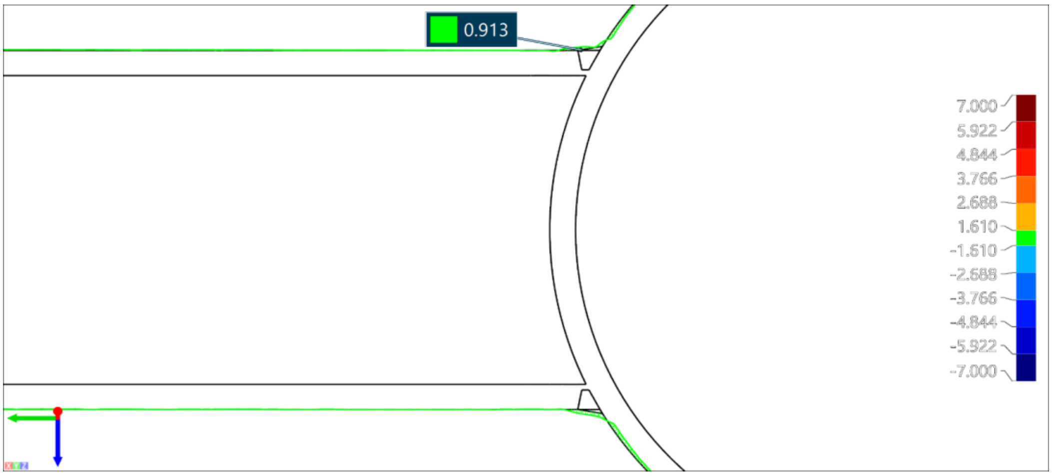
80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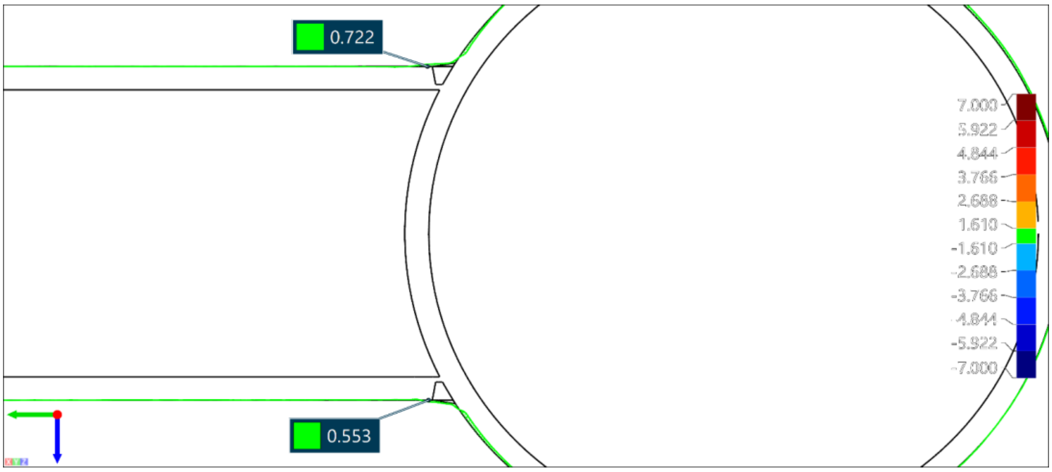
saddle



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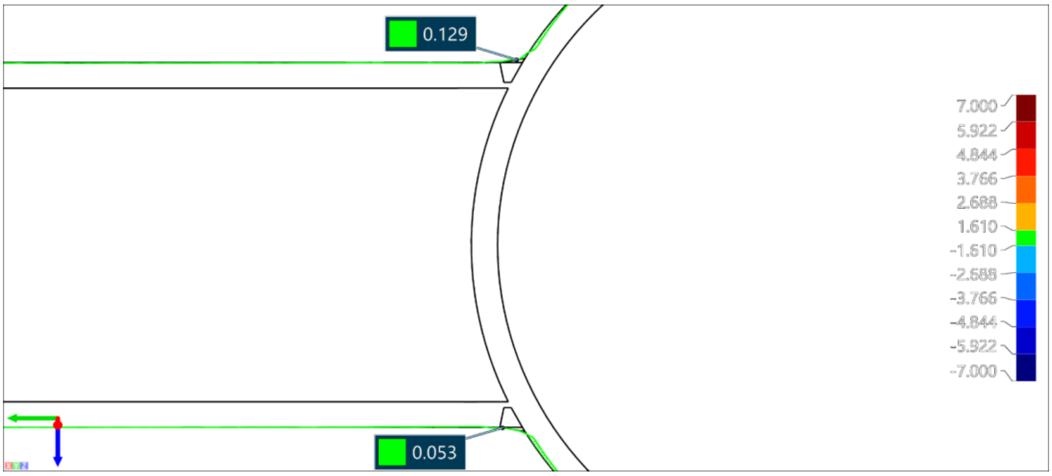

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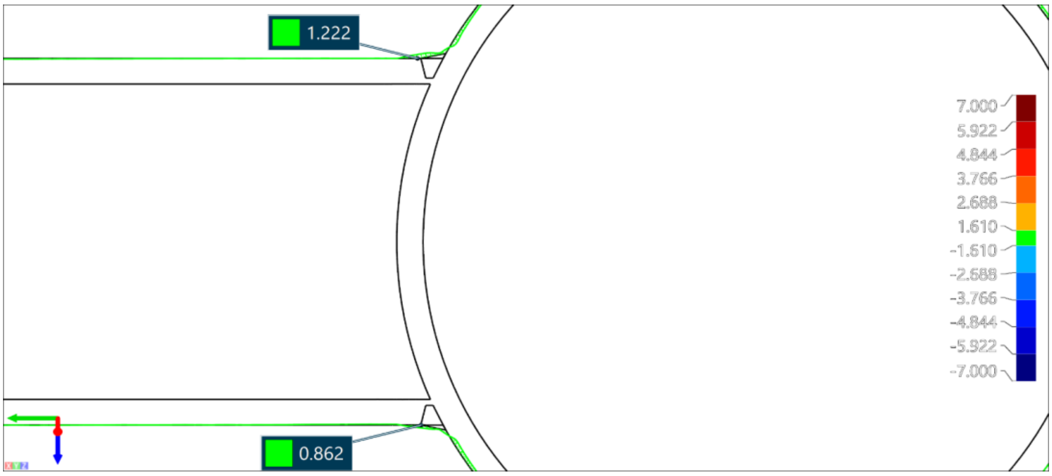

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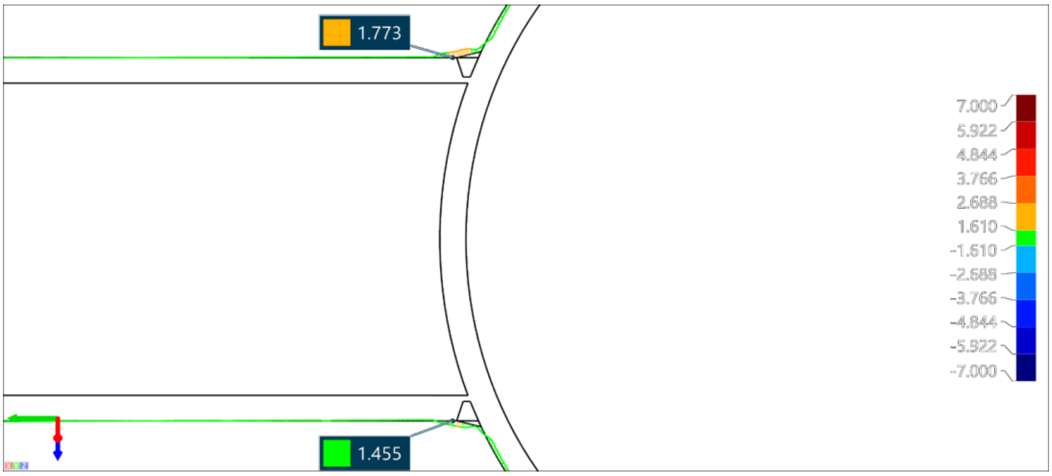
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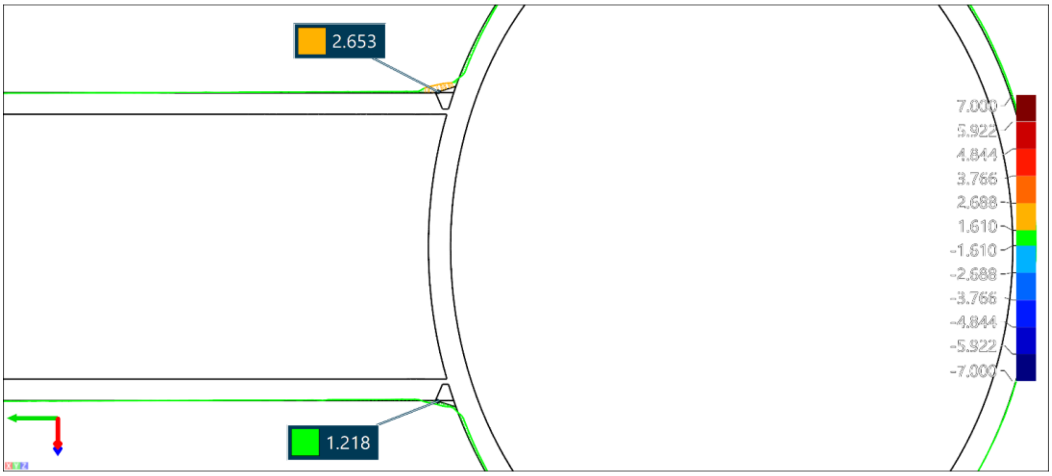
-2.688
-3.766
-4.844
-5.922
-7.000

130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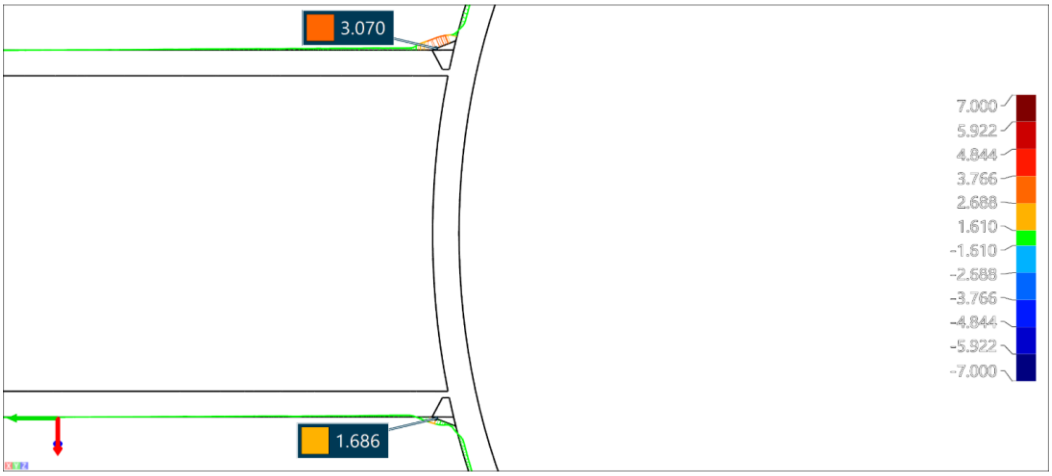
140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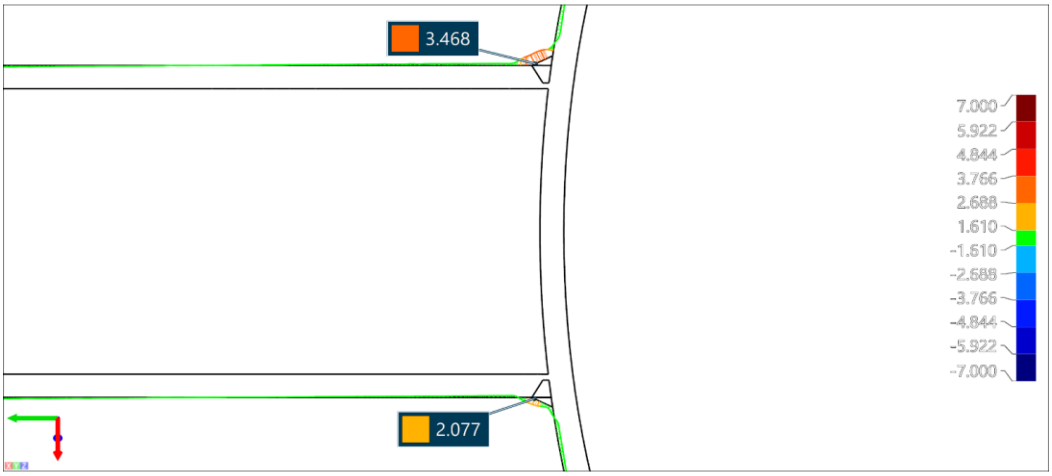

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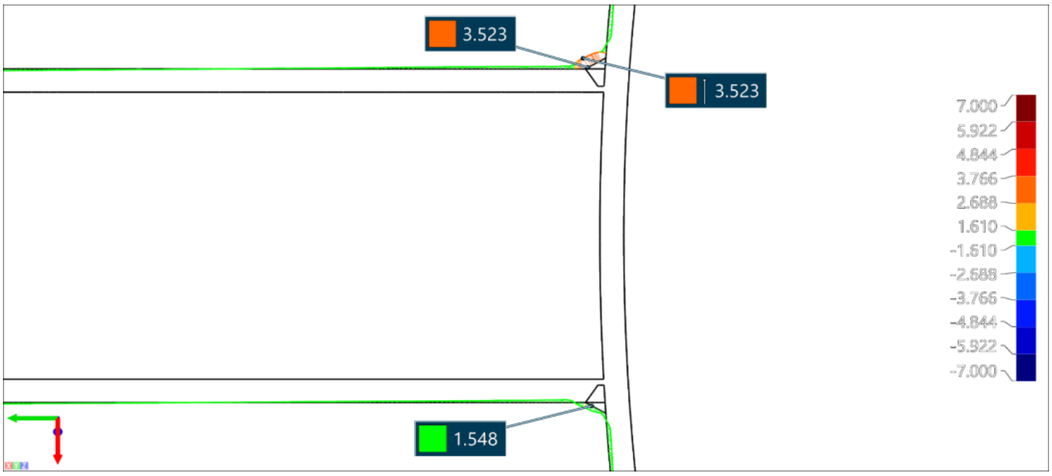

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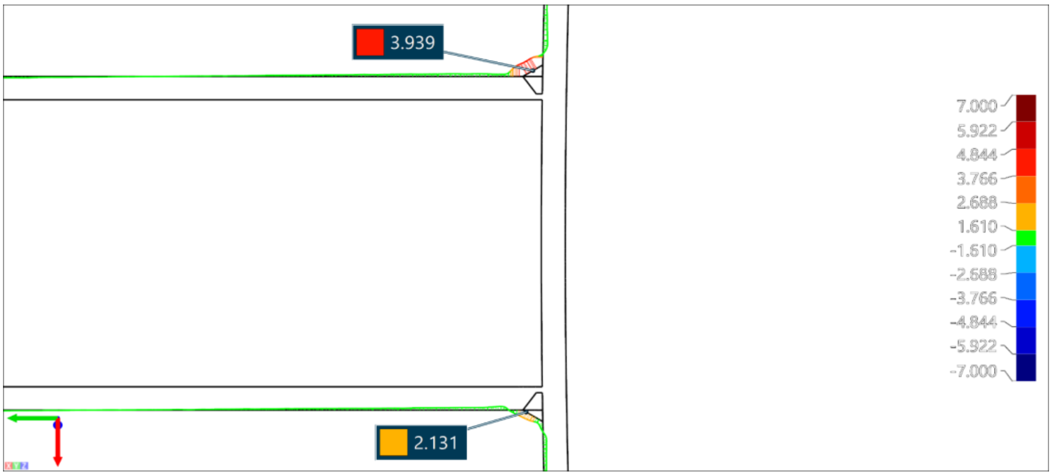
170



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-4.844
-5.922
-7.000

MMC

Project information

Organization	UIS
Units	mm

Part information

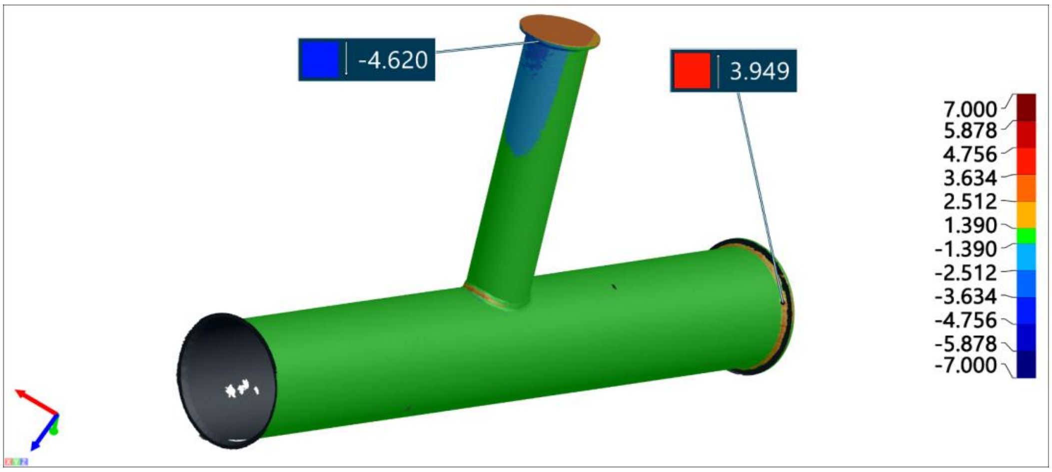
Part name	S31655-4000-T-05
Operator name	Kris Kolos

CREAFORM AMETEK ULTRA PRECISION TECHNOLOGIES

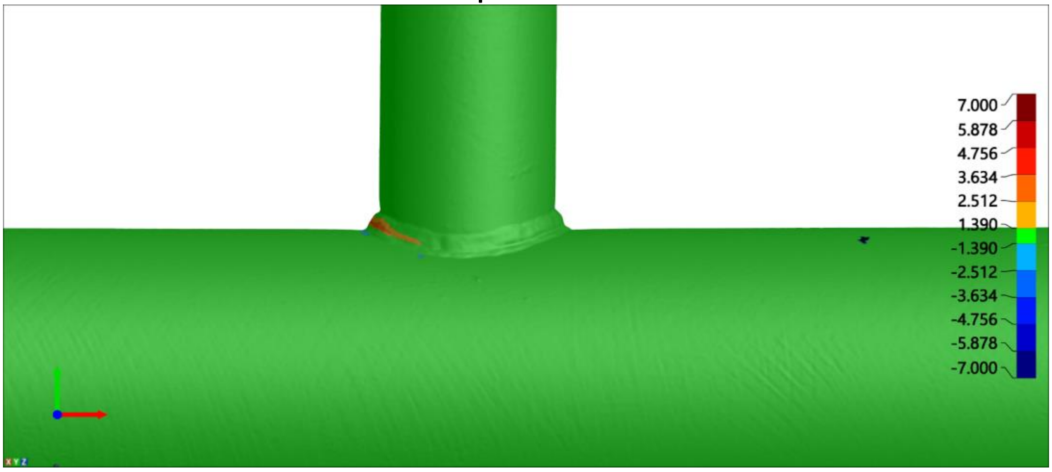
Color map 1 - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-4,620	-4,620	**-3,010**
Max.	1,610	0,000	3,949	3,949	**2,339**
±	3,220	0,000	8,569	8,569	**5,349**
SD	1,000	0,000	0,779	0,779	

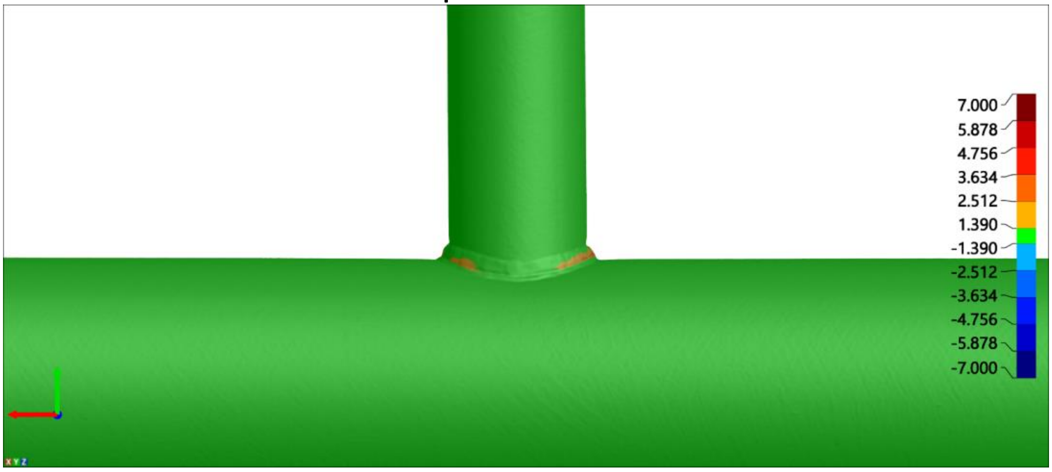
extremes at MMC



colormap side view MMC



colormap other side view MMC



Cylinder 1 - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,271	0,171	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		2,167		

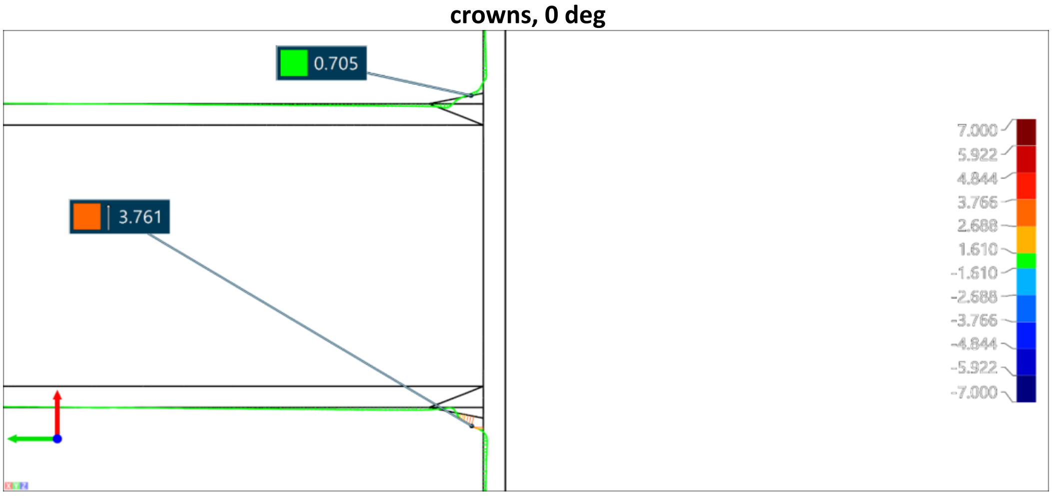
Cylinder 2 - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,348	0,048	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		7,521		**5,231**

Angle [°] - Scan3

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,499	-0,501	**-0,168**
∠XZ	+0.333 -0.333	0,000	1,388	1,388	**1,055**
∠YZ	+0.333 -0.333	0,000	3,184	3,184	**2,851**

crowns, 0 deg



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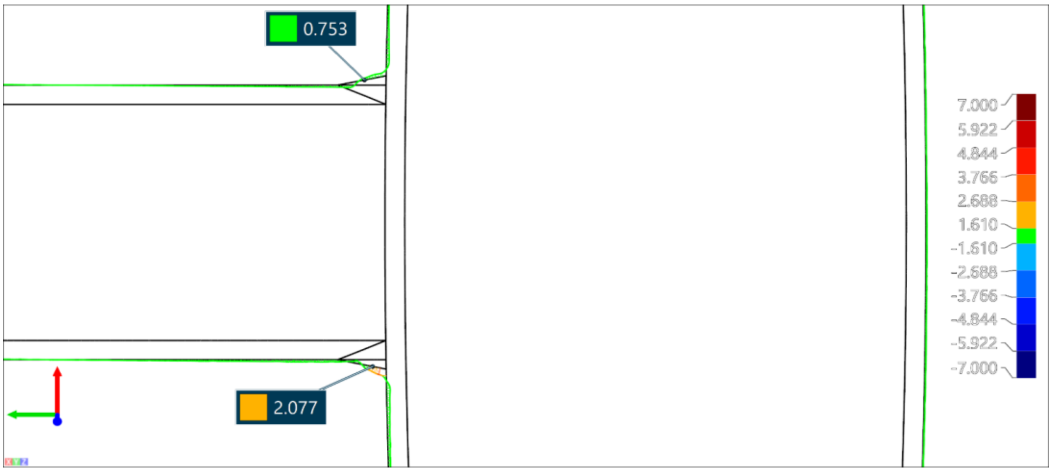
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-5.922
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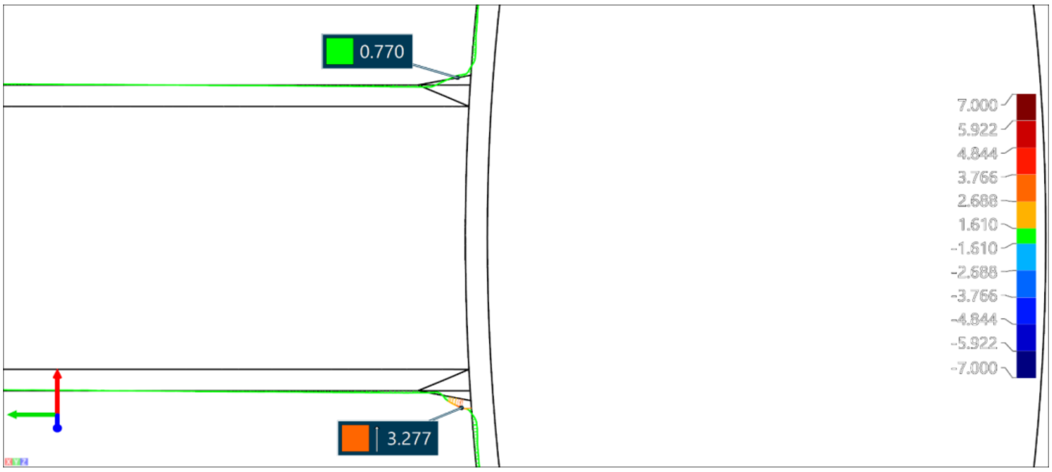
20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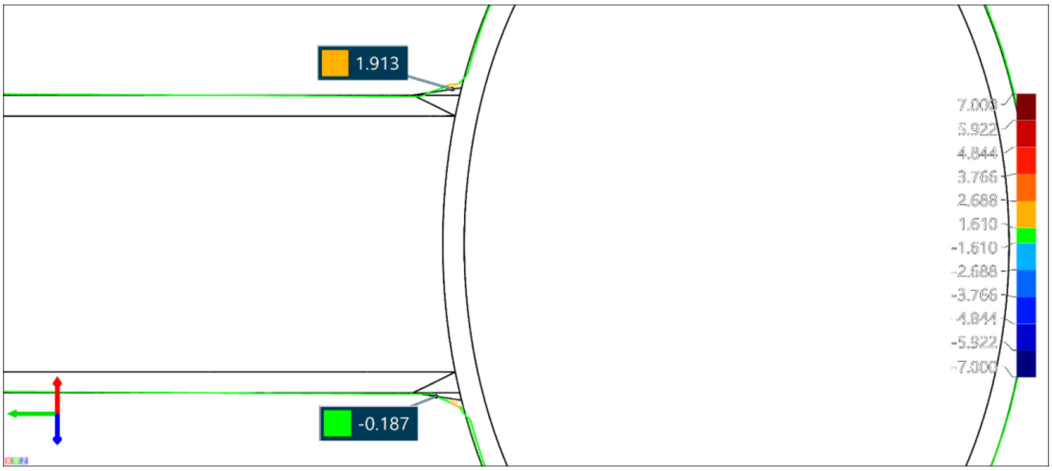
30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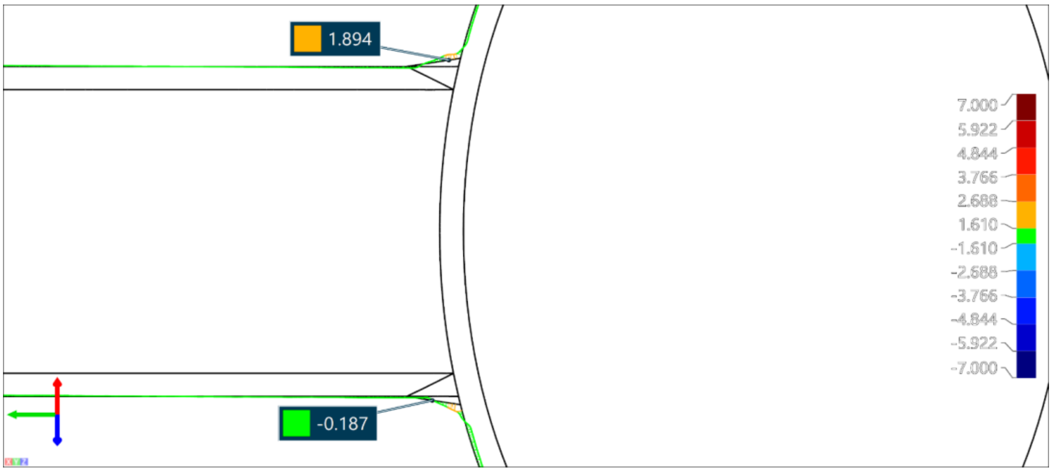
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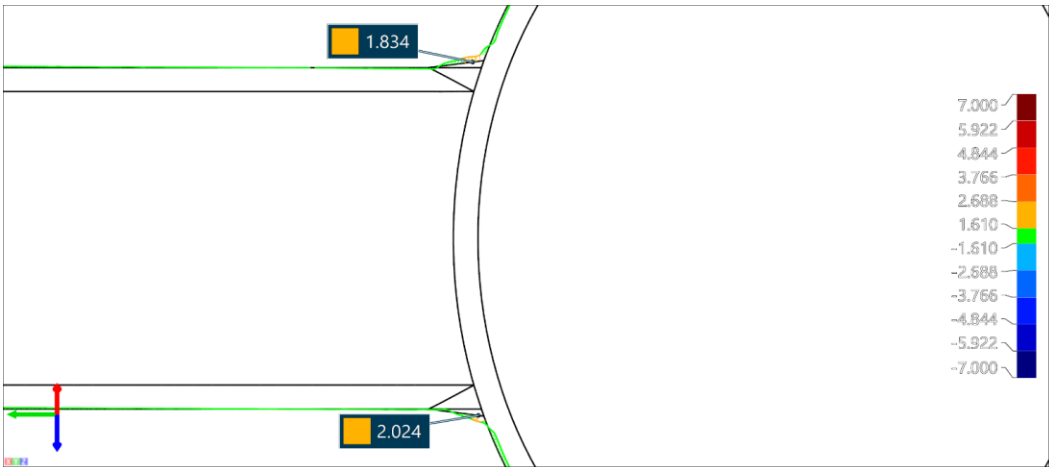
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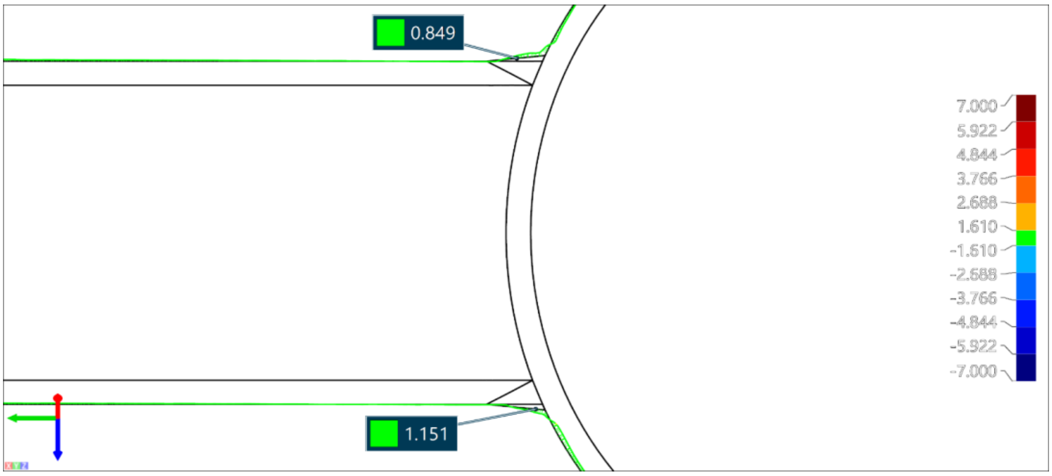
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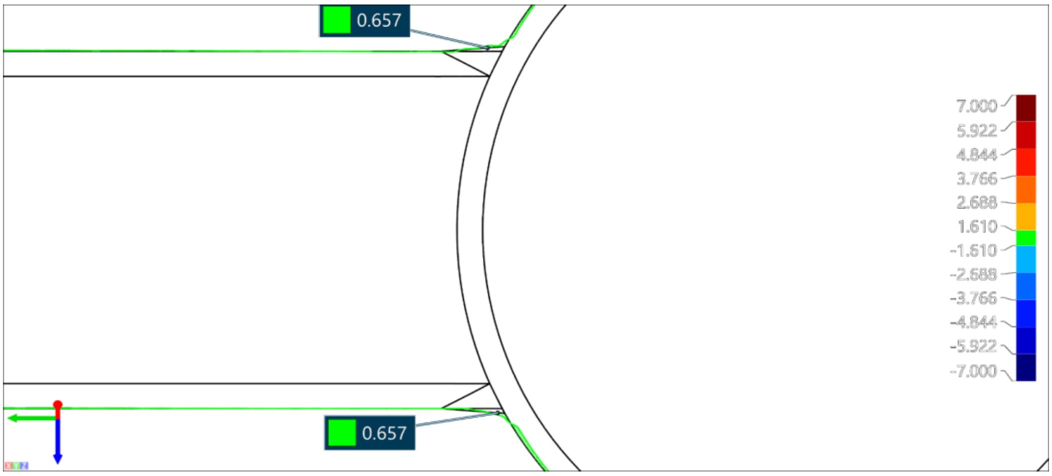
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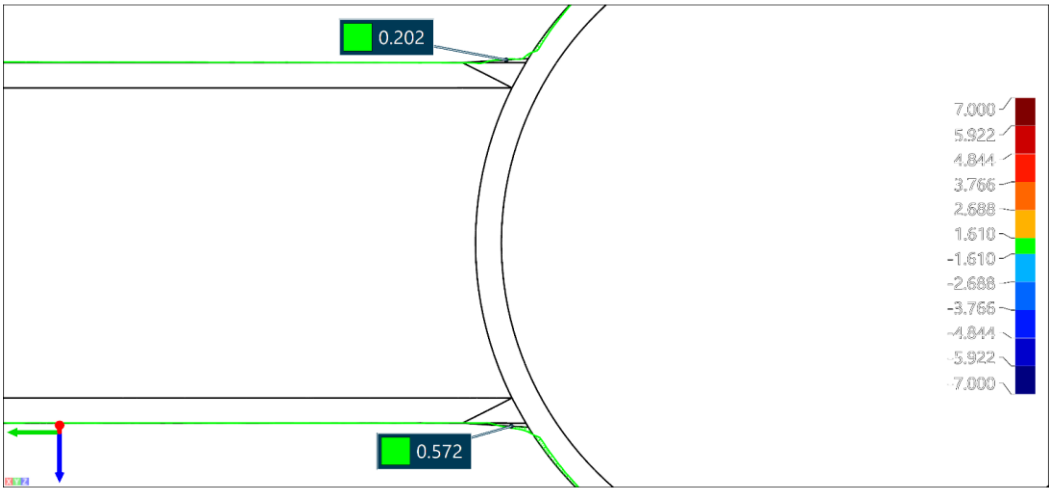
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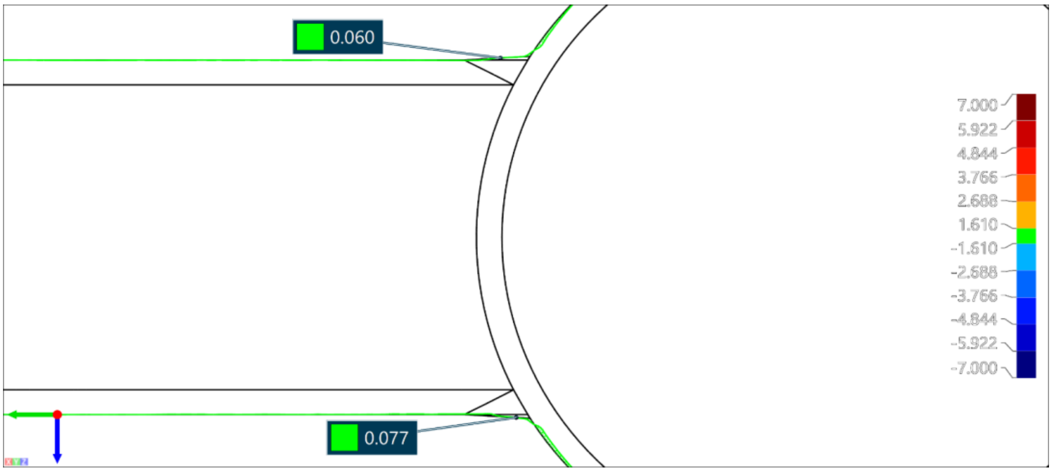
saddle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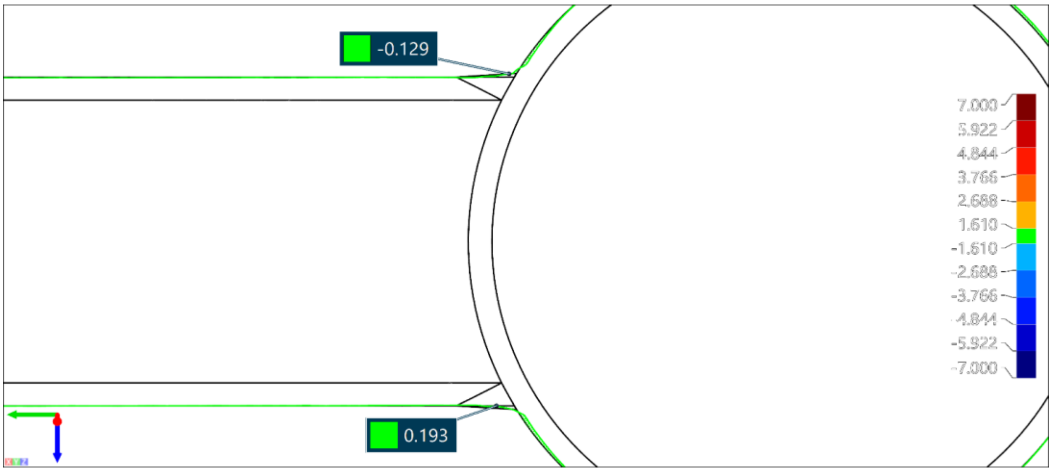
100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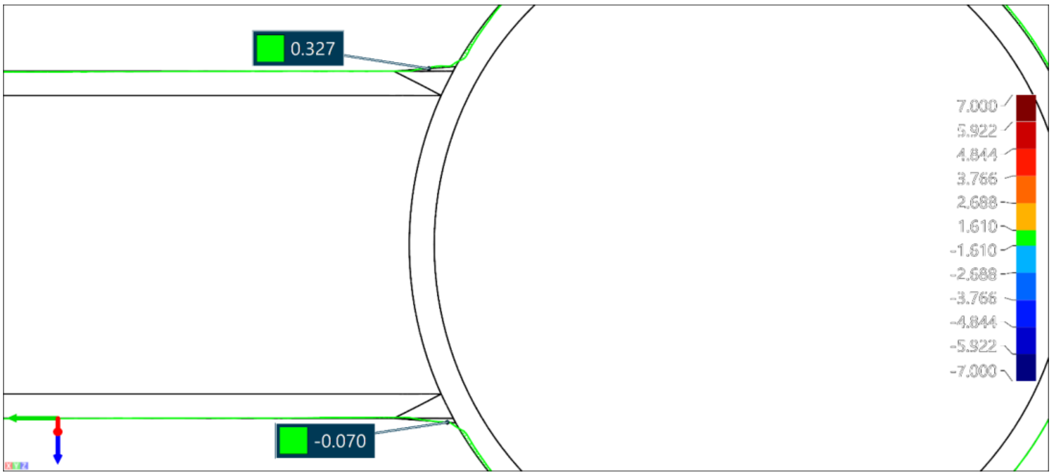
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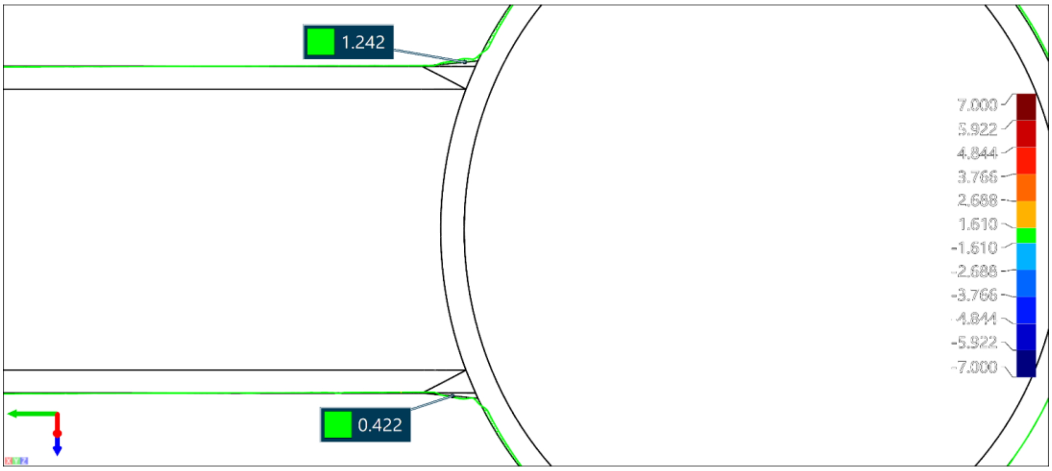
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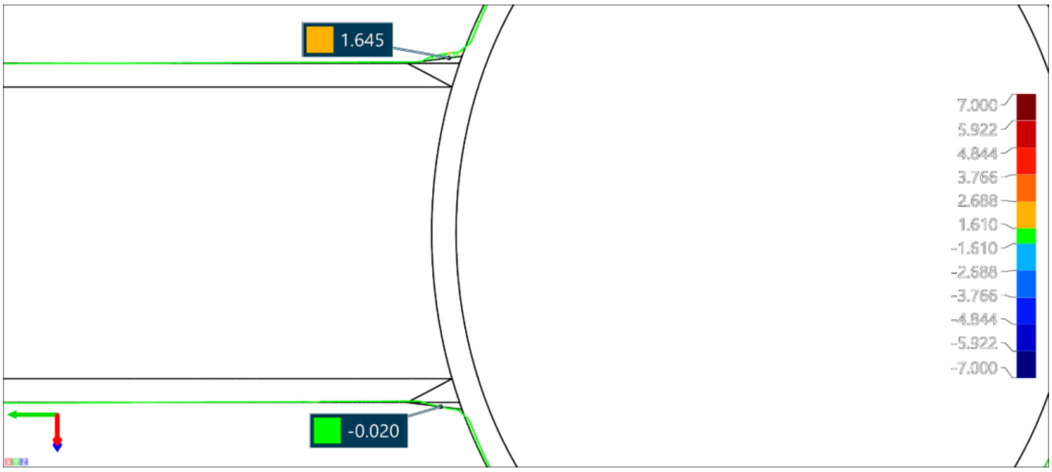
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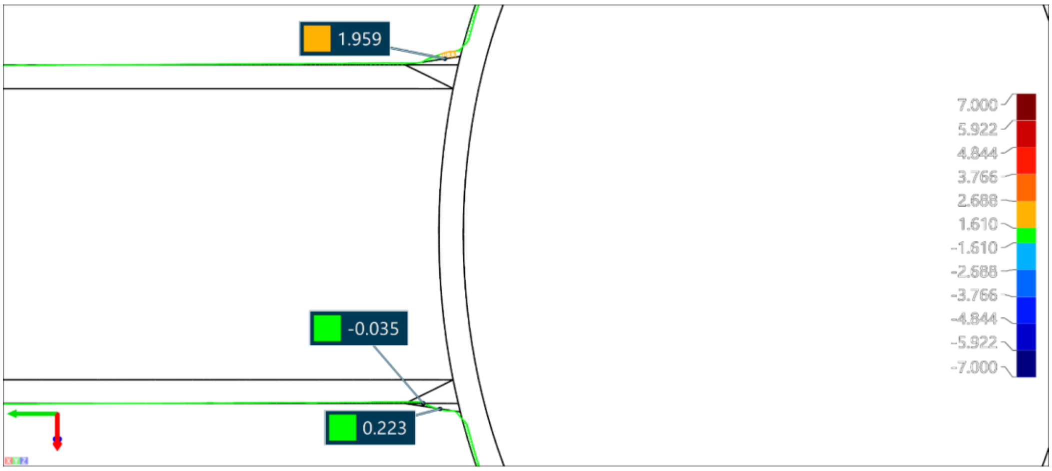
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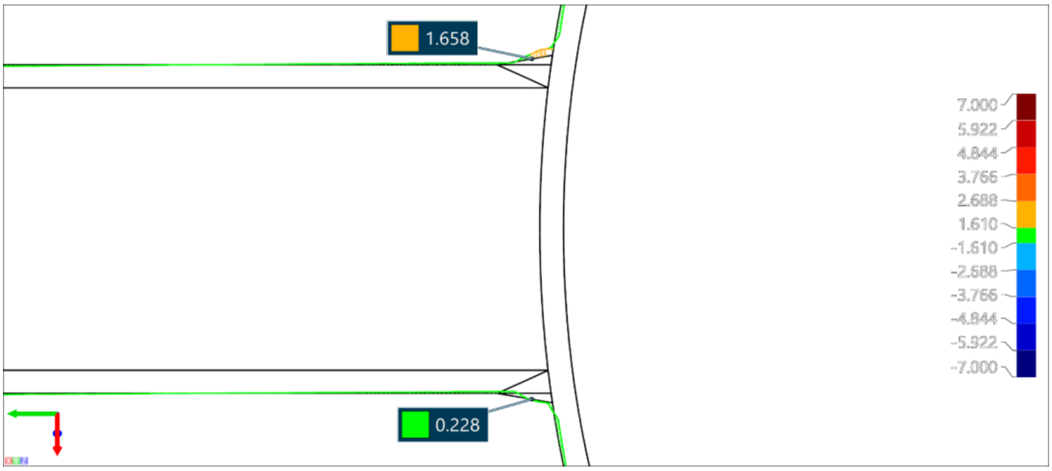
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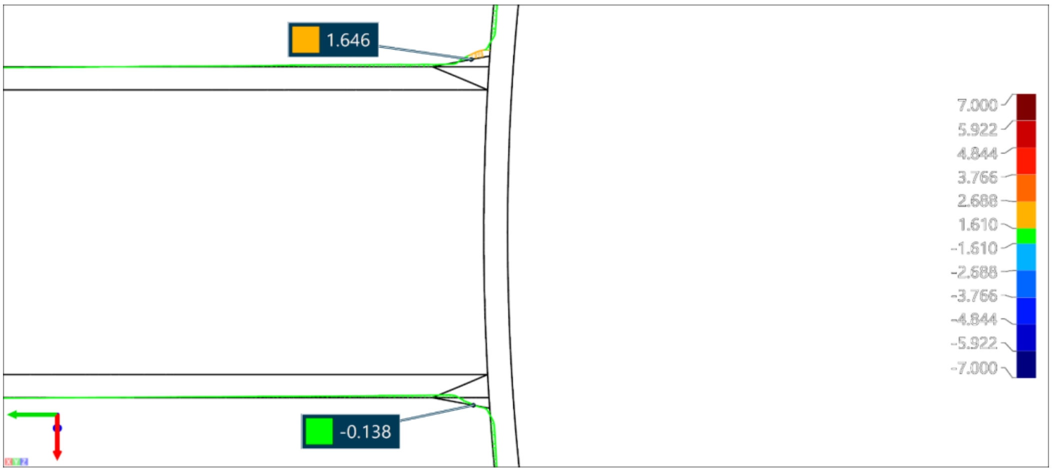
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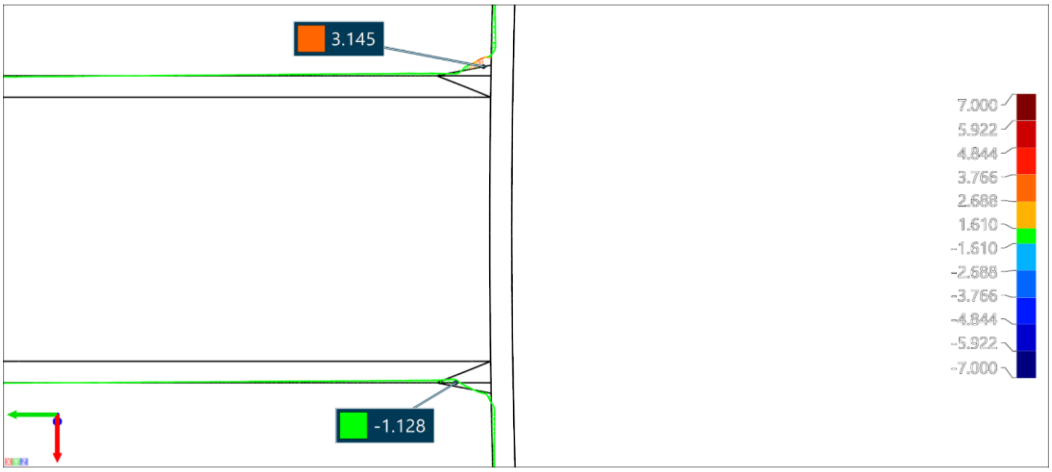
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-7.000

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Report prepared by

Name ____

Date ____

Signature ____

Report reviewed by

Name ____

Date ____

Signature ____

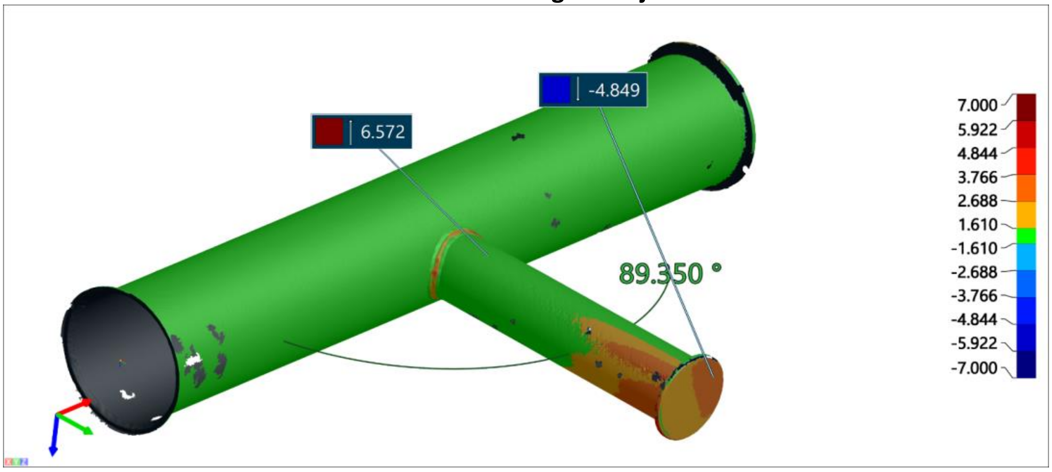
Project information

Organization	UIS
Units	mm

Part information

Part name	S31655-4000-T-06
Operator name	Kris Kolos

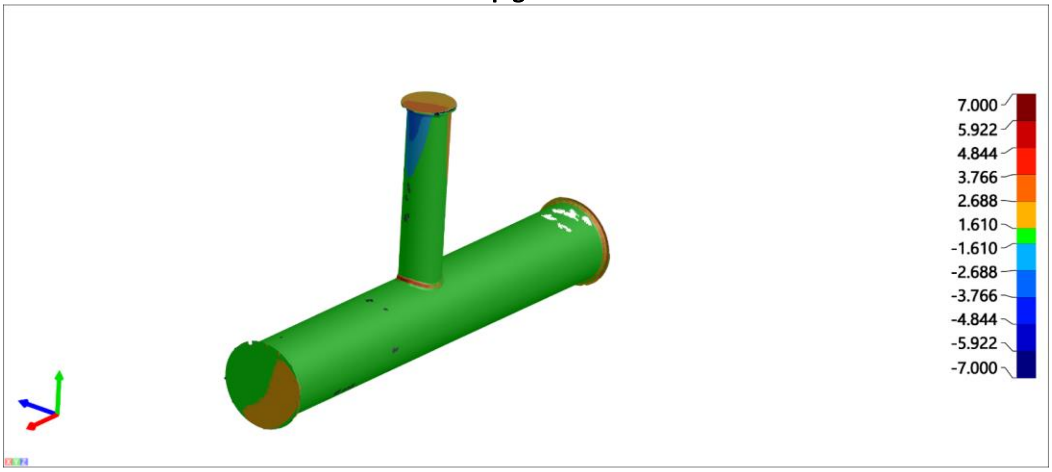
extremes and angle of T joint



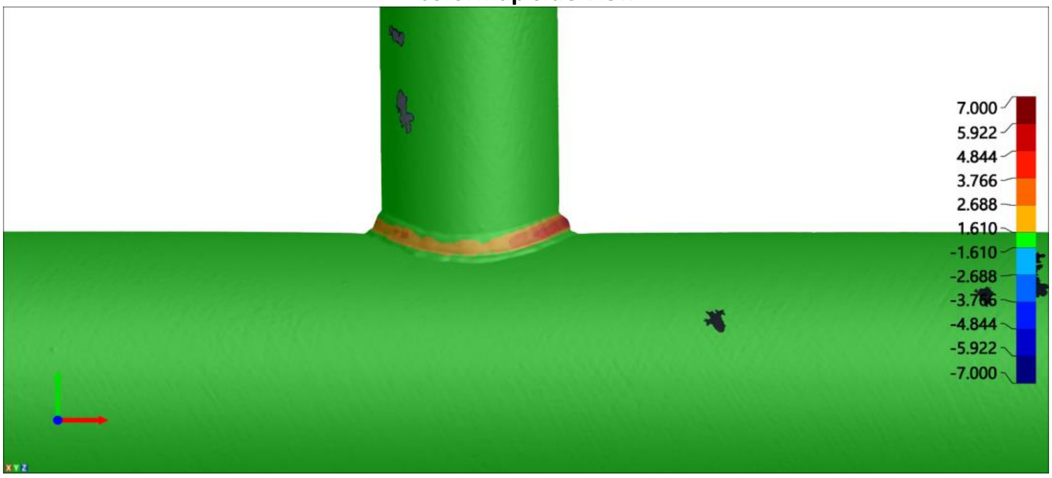
Color map 1 - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-4,849	-4,849	**-3,239**
Max.	1,610	0,000	6,572	6,572	**4,962**
±	3,220	0,000	11,421	11,421	**8,201**
SD	1,000	0,000	0,809	0,809	

colormap general view



colormap side view



Cylinder 1 - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∅	+3.540 -3.540	219,100	219,135	0,035	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		1,955		

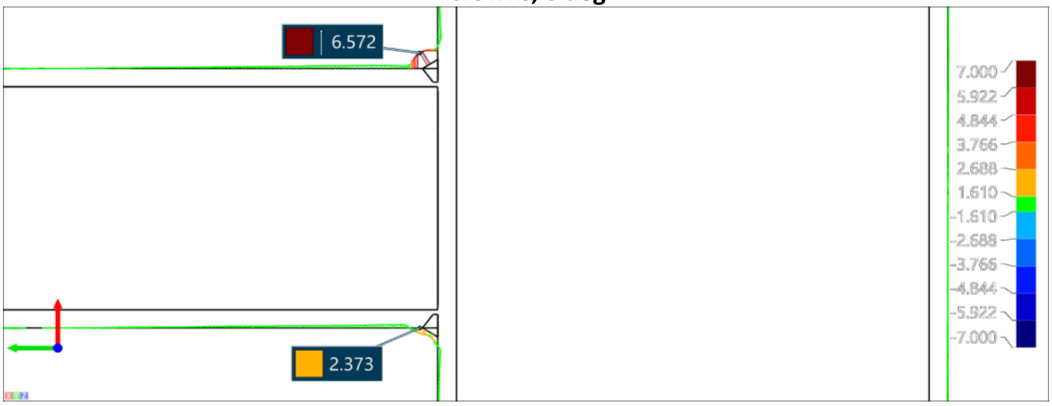
Cylinder 2 - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∅	+1.610 -1.610	114,300	115,193	0,893	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		2,039		

Angle [°] - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,350	-0,650	**-0,317**
∠XZ	+0.333 -0.333	0,000	0,367	0,367	**0,034**
∠YZ	+0.333 -0.333	0,000	2,683	2,683	**2,350**

crowns, 0 deg



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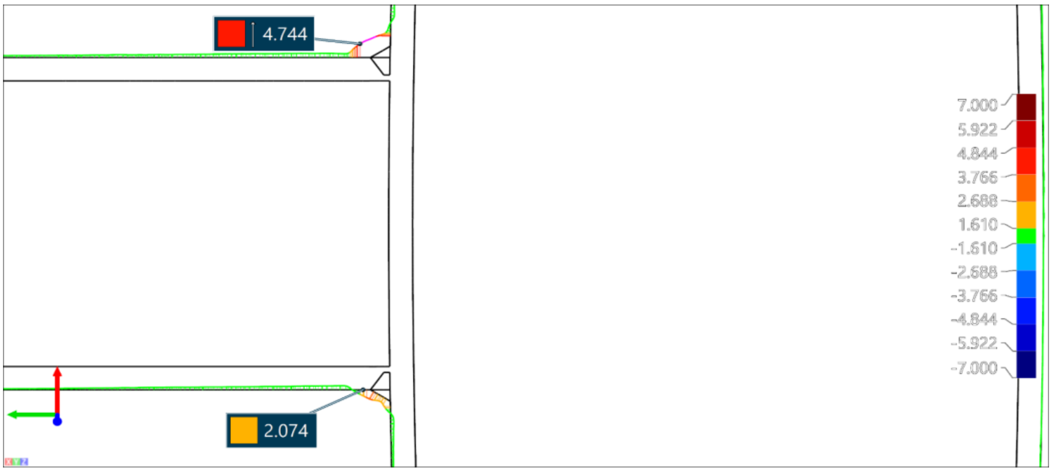

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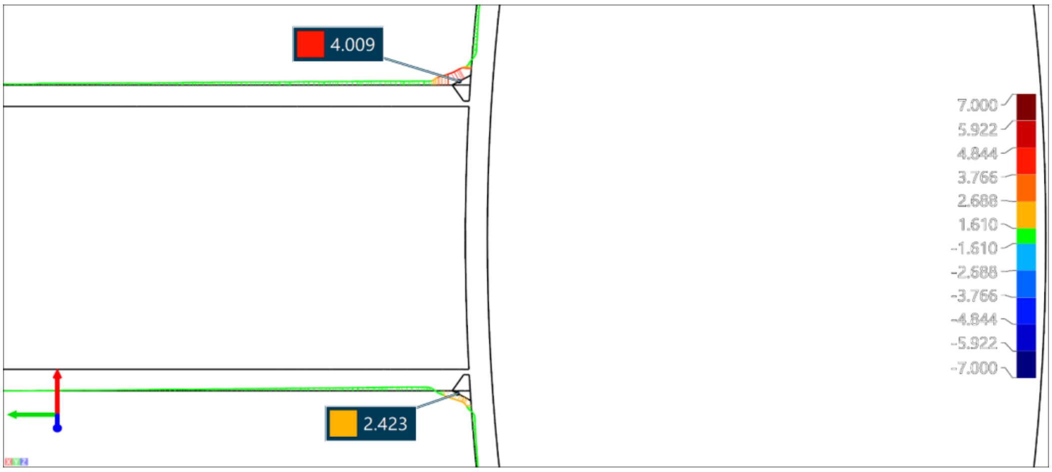

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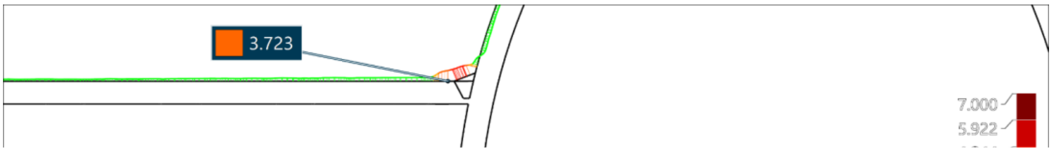

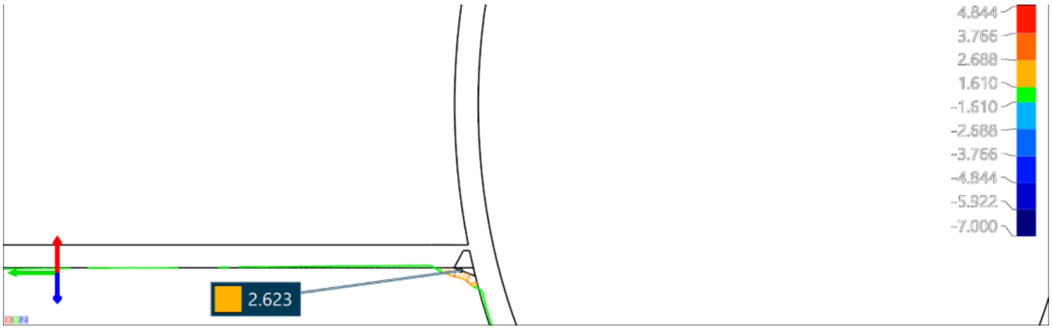
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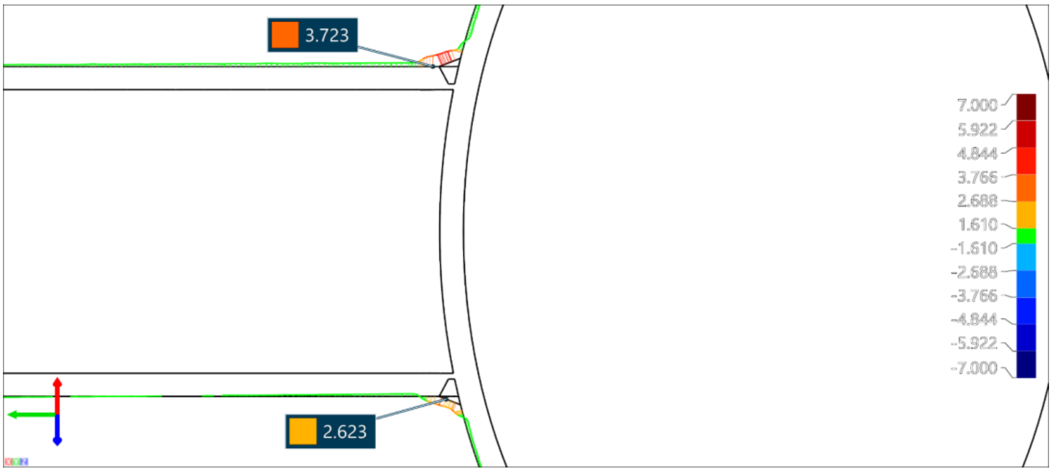
40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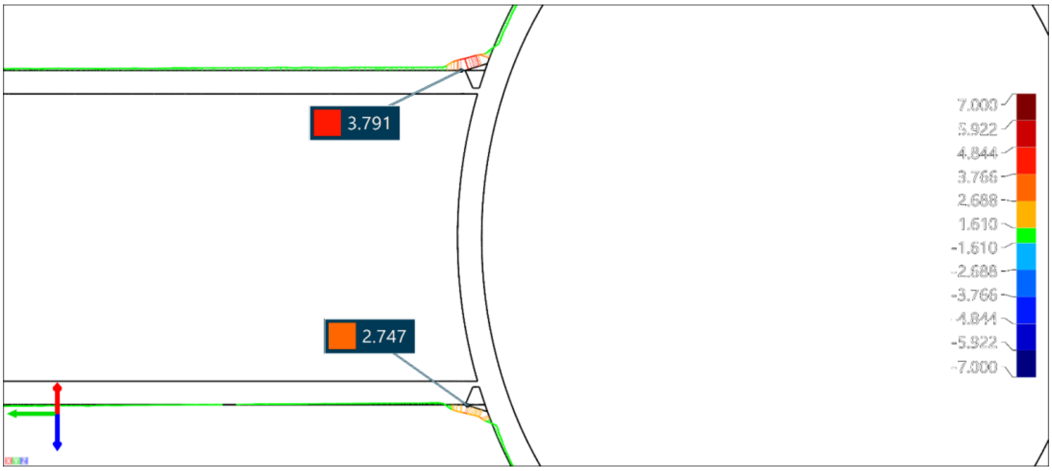
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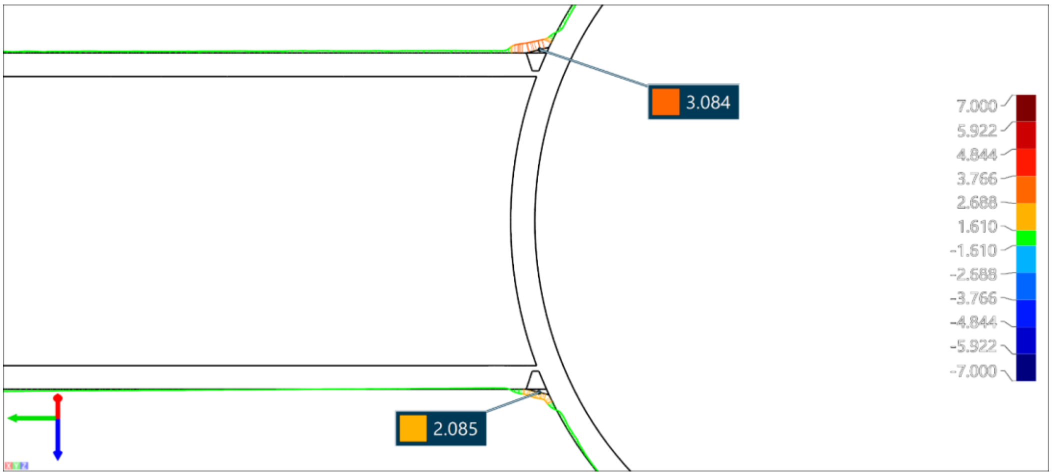
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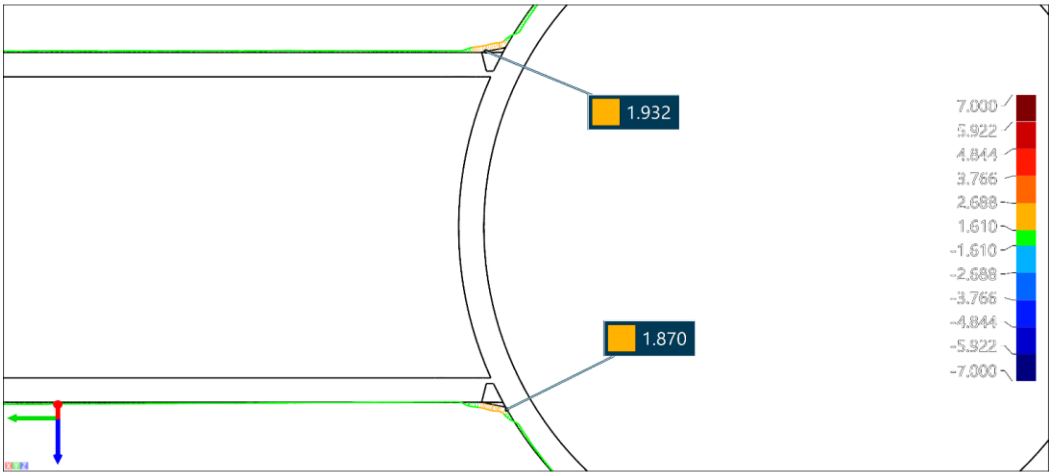
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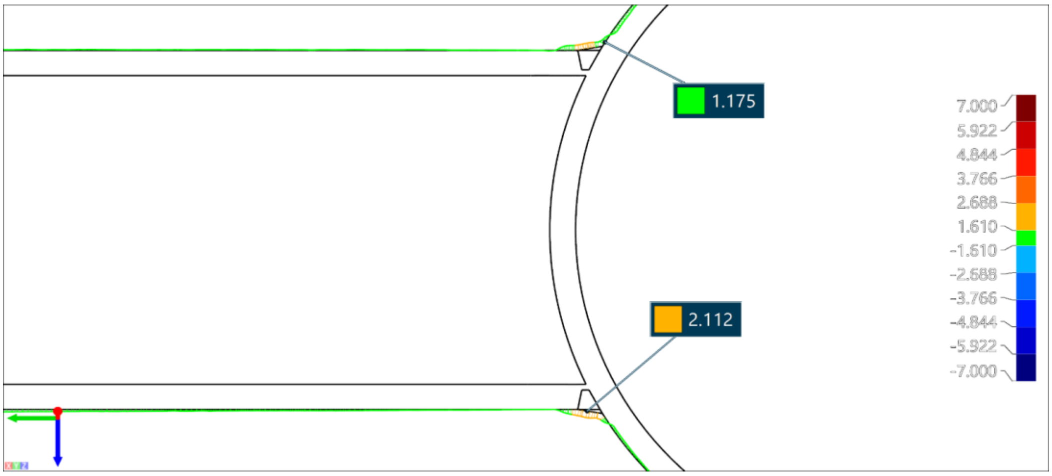
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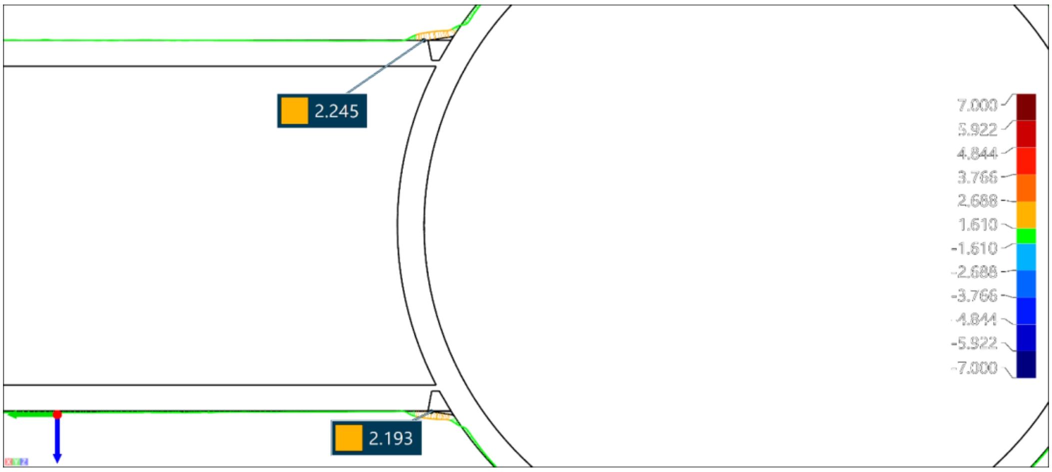
-7.000

saddle



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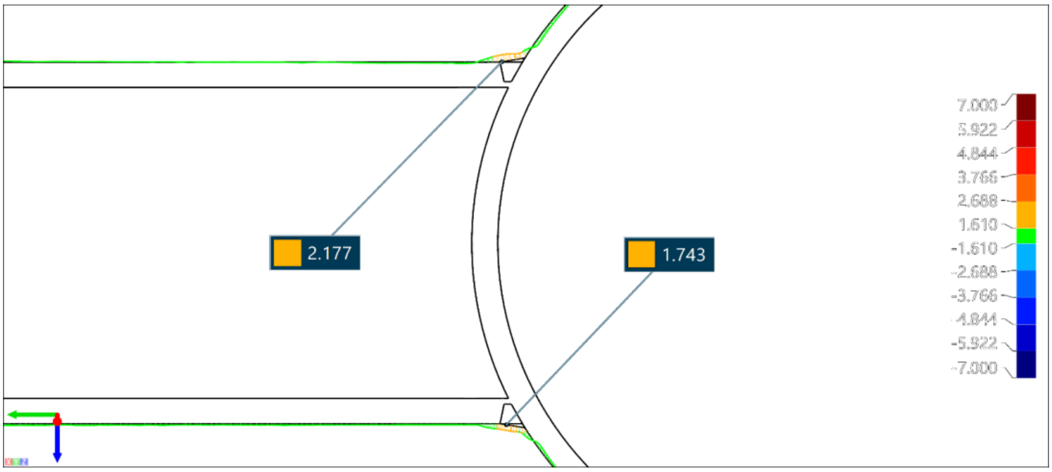

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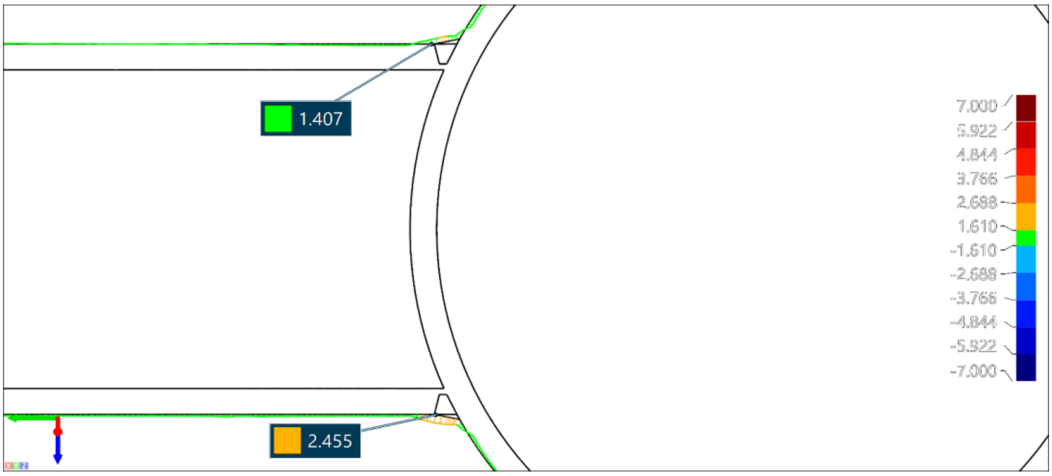

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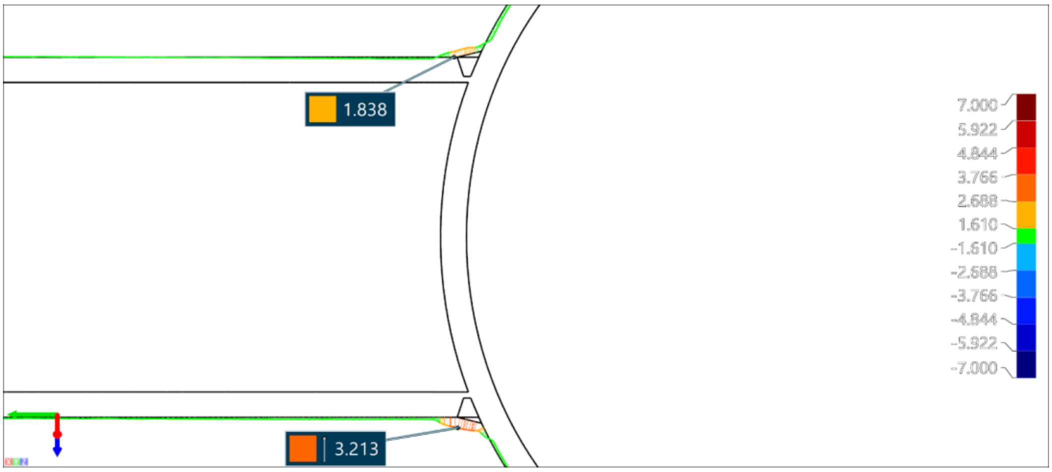

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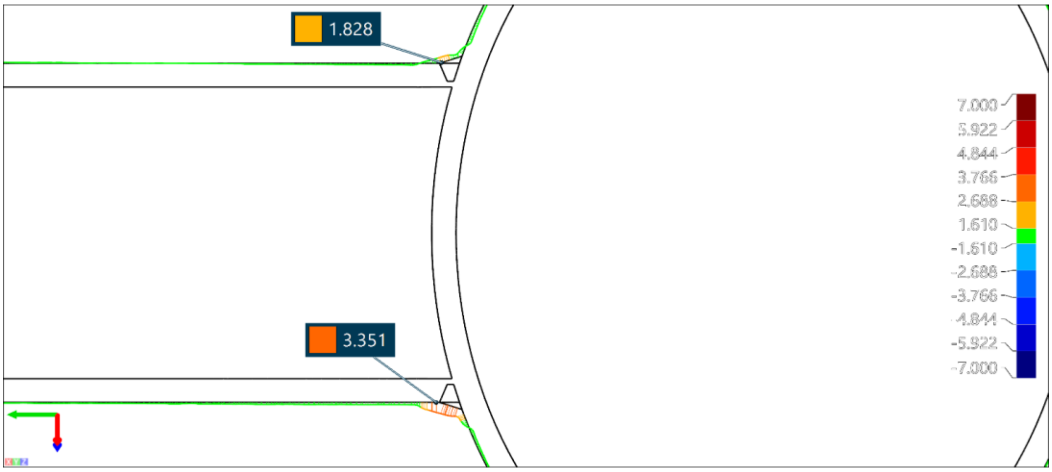
1.610
-1.610
-2.688
-3.766
-4.844
-5.922
-7.000

130



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-2.688
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-4.844
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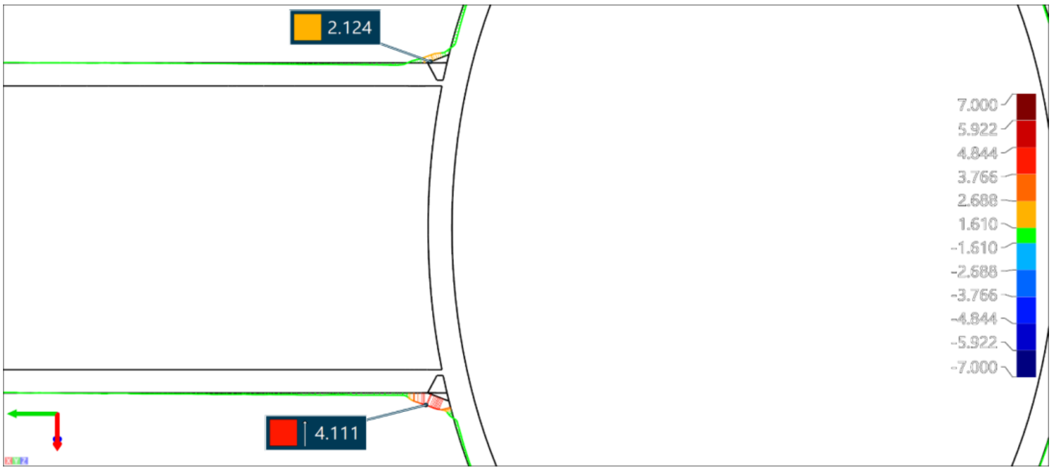
140



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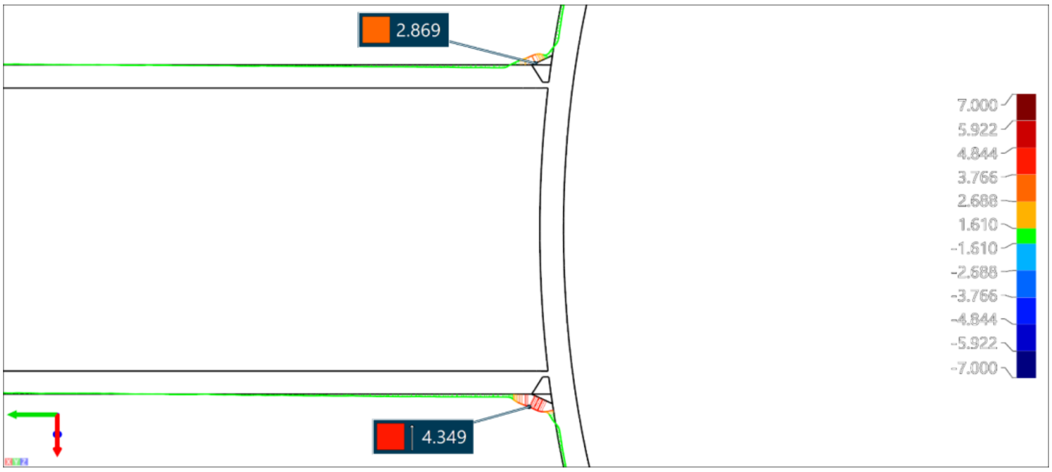

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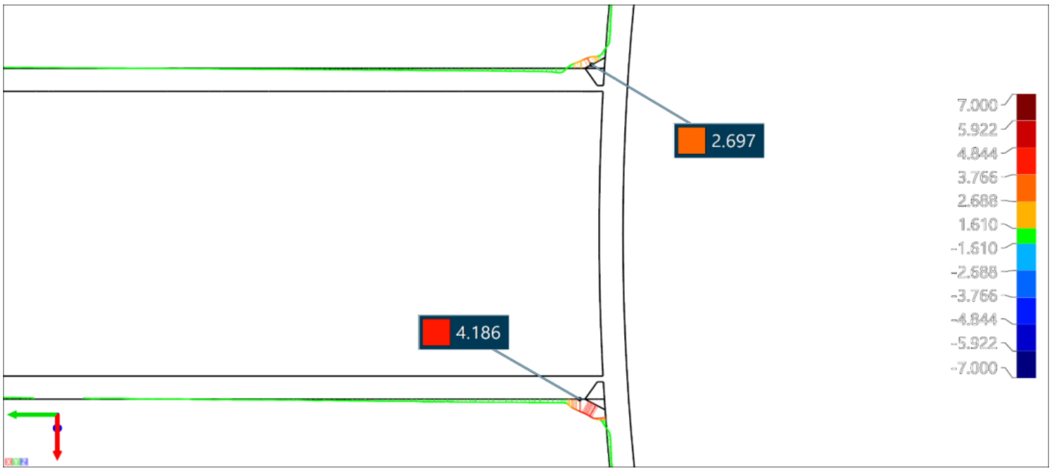
-3.766
-4.844
-5.922
-7.000

160



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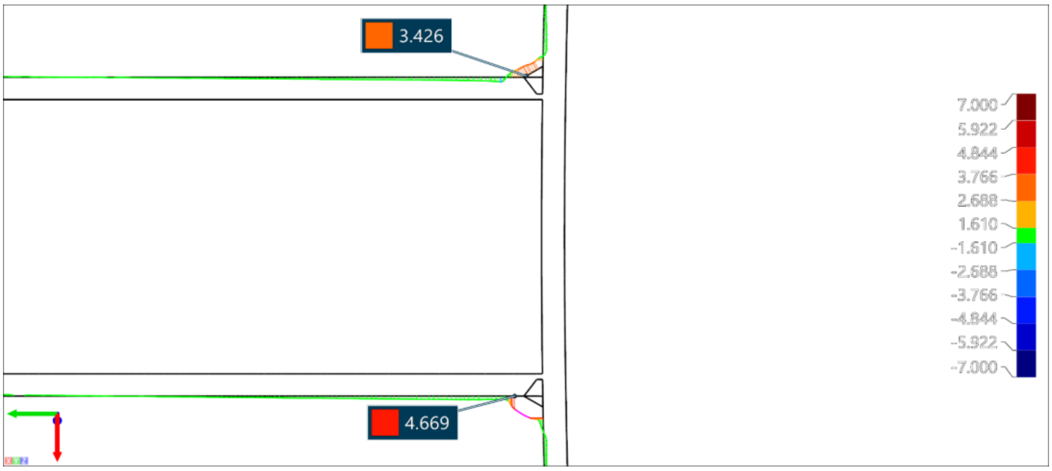
170



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2.688
1.610
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-2.688
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-4.844
-5.922
-7.000

MMC

Project information

Organization	UIS
Units	mm

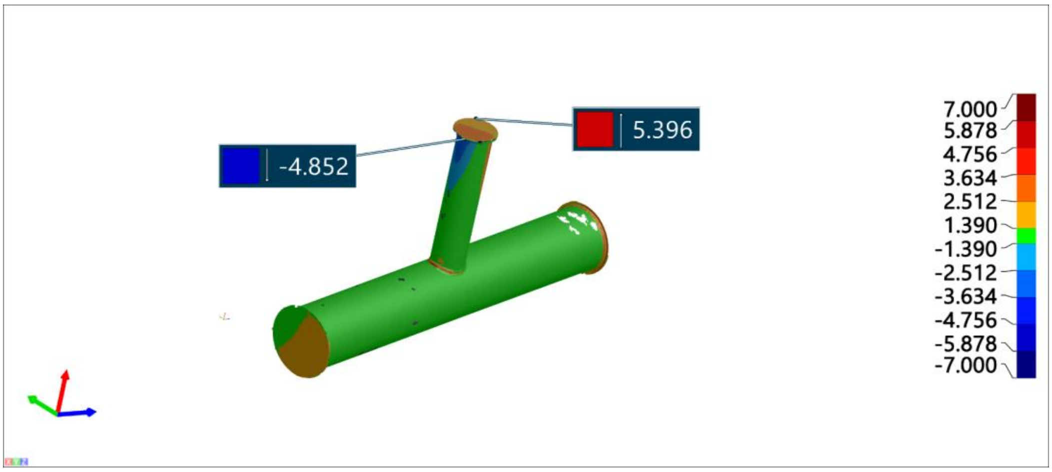
Part information

Part name	S31655-4000-T-06
Operator name	Kris Kolos

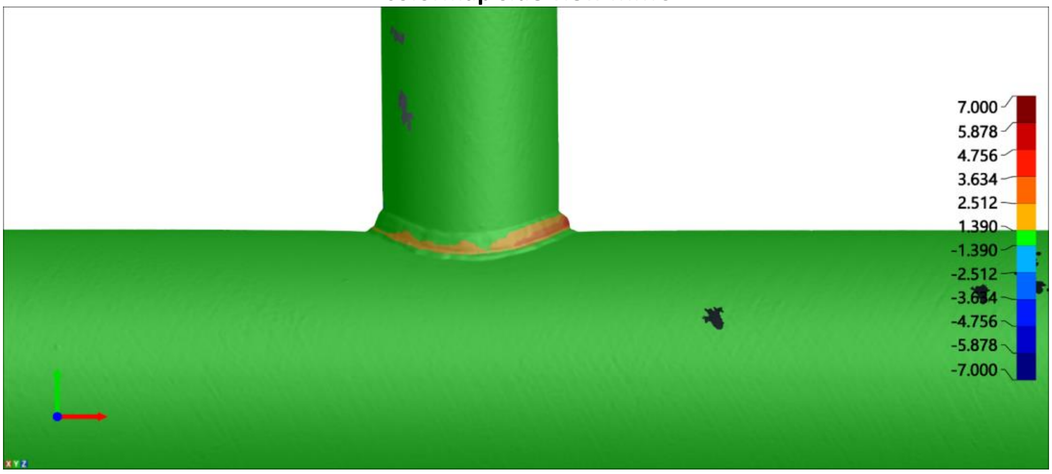
Color map 1 - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-4,852	-4,852	**-3,242**
Max.	1,610	0,000	5,396	5,396	**3,786**
±	3,220	0,000	10,248	10,248	**7,028**
SD	1,000	0,000	0,808	0,808	

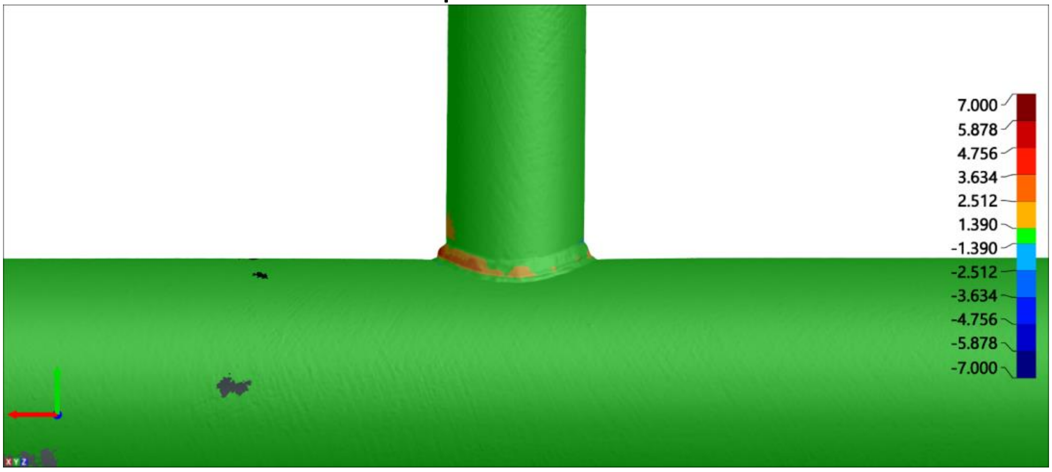
extremes at MMC



colormap side view MMC



colormap other side view MMC



Cylinder 1 - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∅	+3.540 -3.540	219,100	219,135	0,035	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4,380	4,380		1,955		

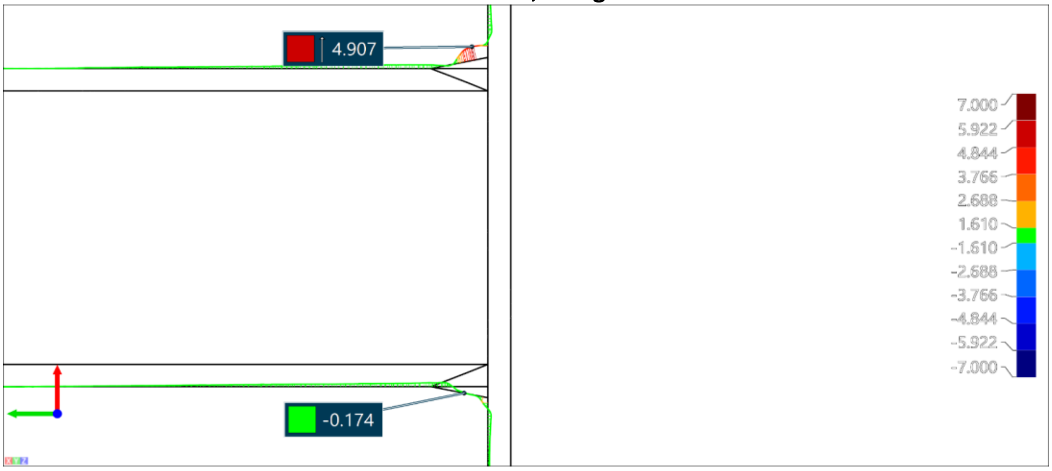
Cylinder 2 - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∅	+1.610 -1.610	114,300	115,193	0,893	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2,290	2,290		2,039		

Angle [°] - Scan5

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,350	-0,650	**-0,317**
∠XZ	+0.333 -0.333	0,000	0,366	0,366	**0,033**
∠YZ	+0.333 -0.333	0,000	2,682	2,682	**2,349**

crowns, 0 deg



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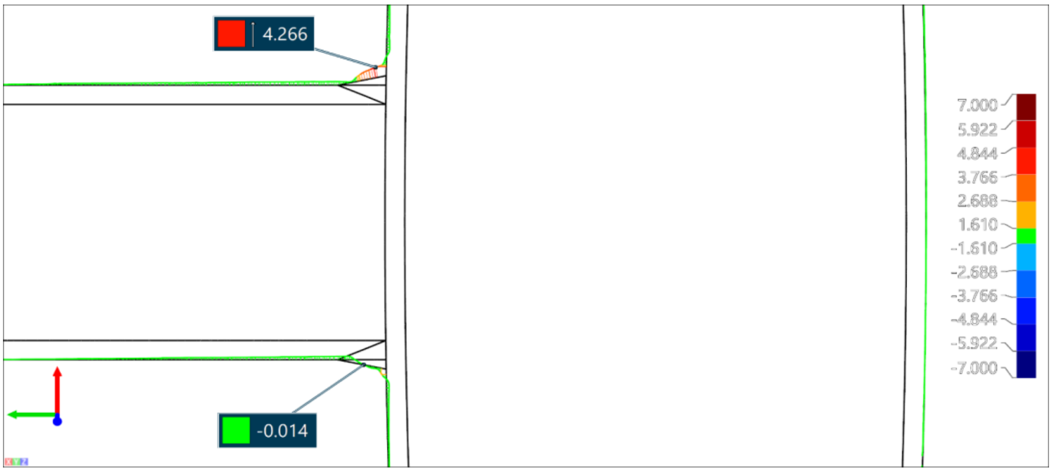

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1.610
-1.610
-2.688
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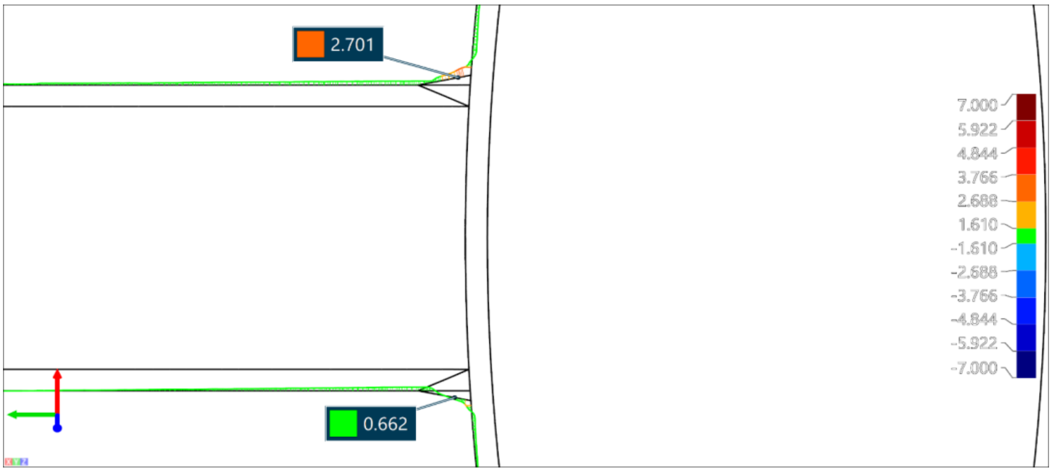
-4.844
-5.922
-7.000

20



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1.610
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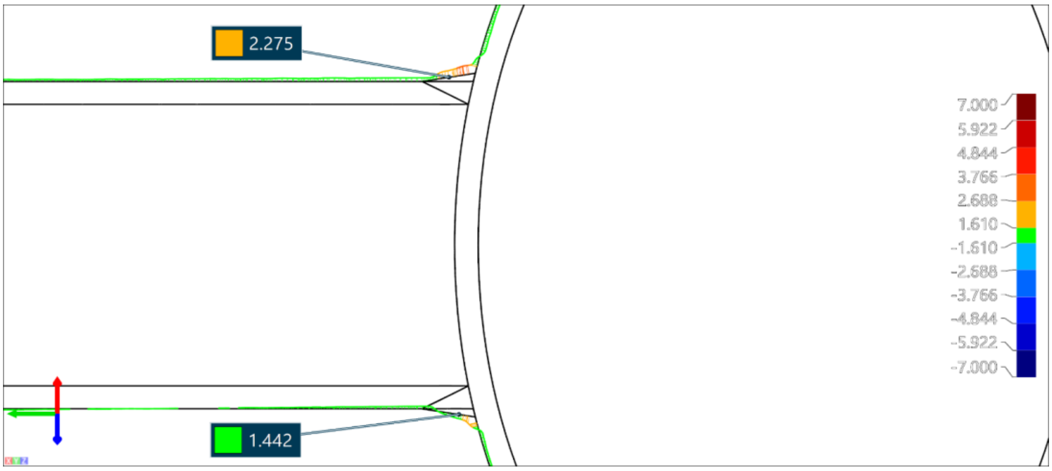
-5.922
-7.000

30



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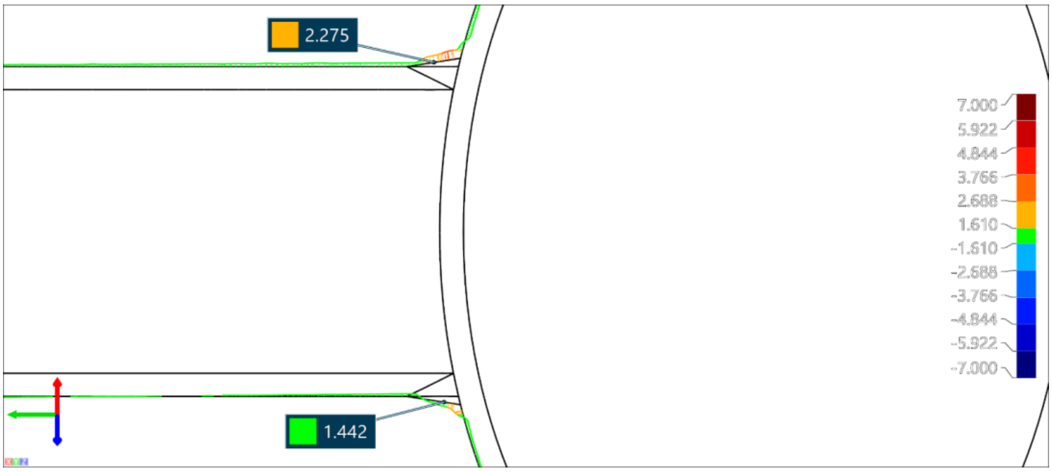
-7.000

40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1.610
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-5.922
-7.000

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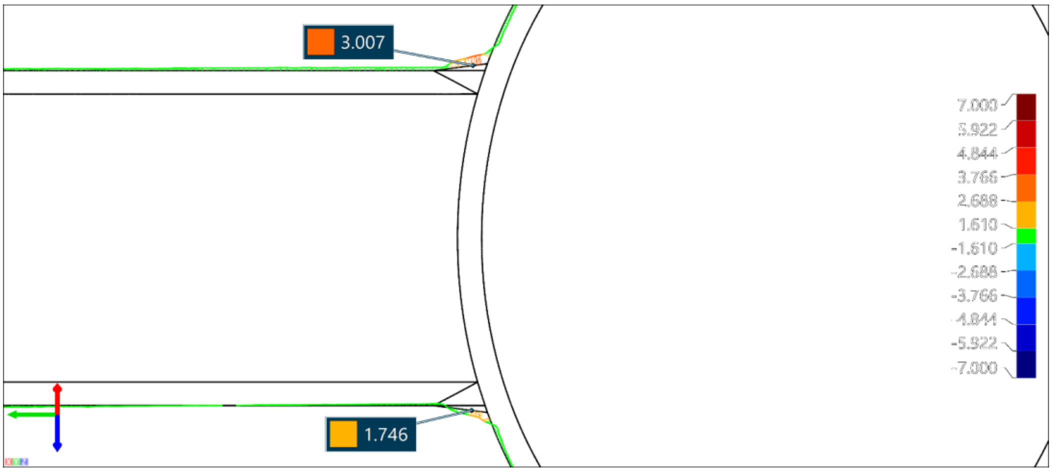
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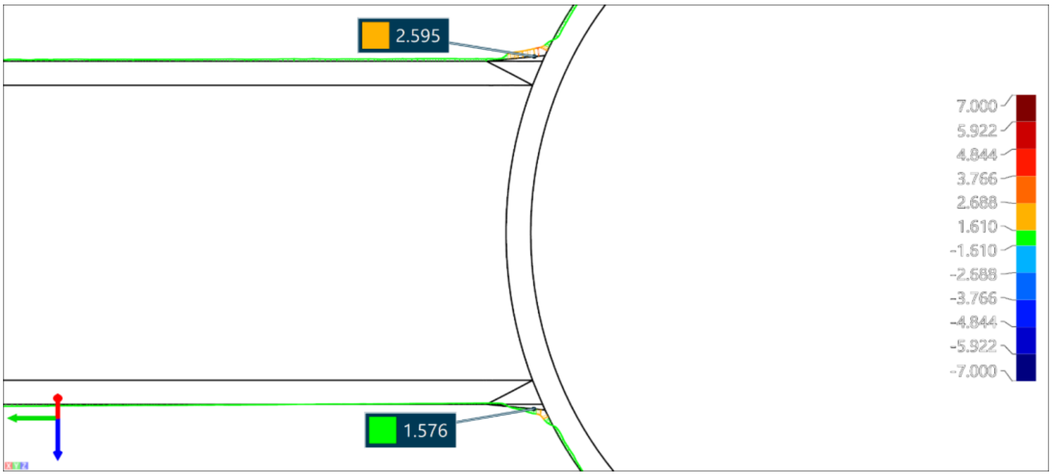
-5.922
-7.000

60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-2.688
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-4.844
-5.922
-7.000

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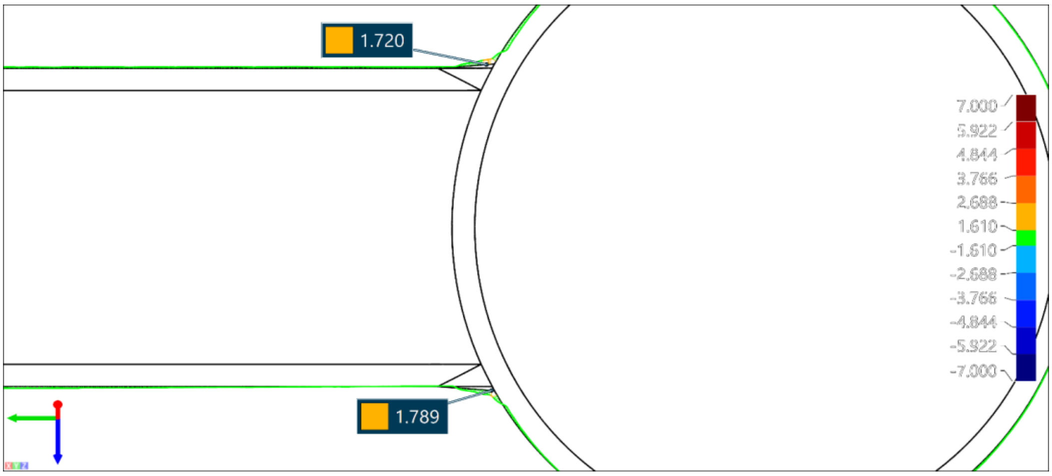
70



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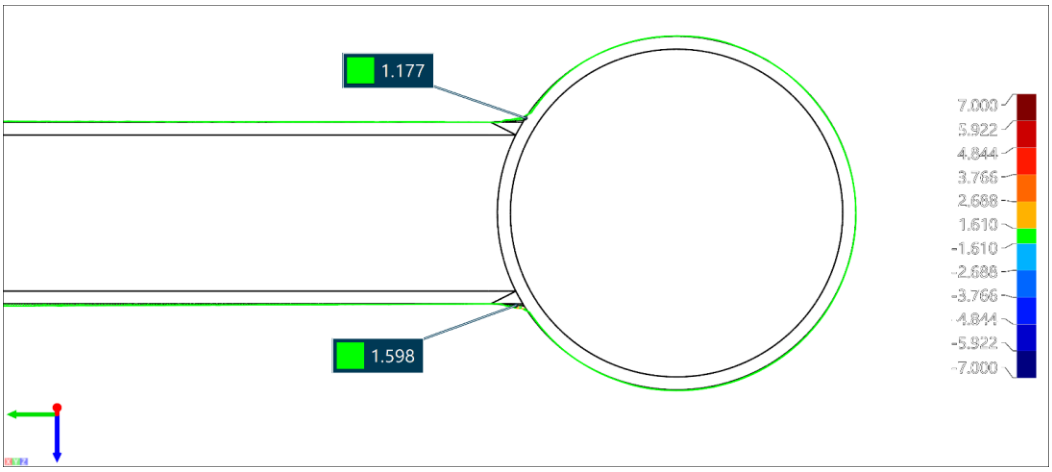
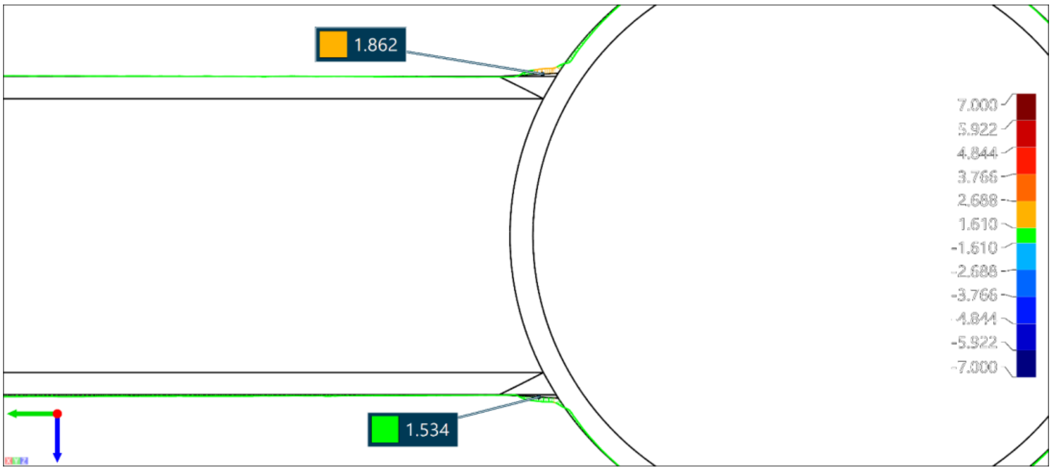


saddle



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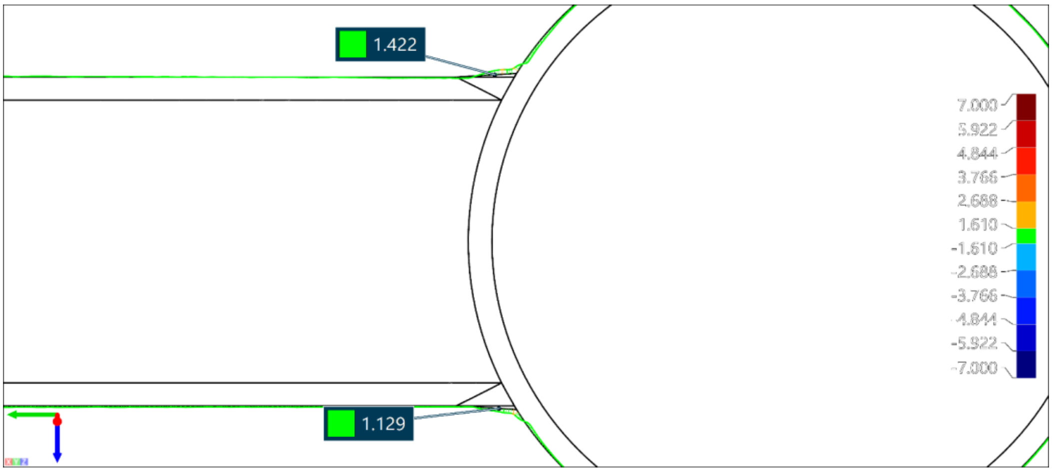
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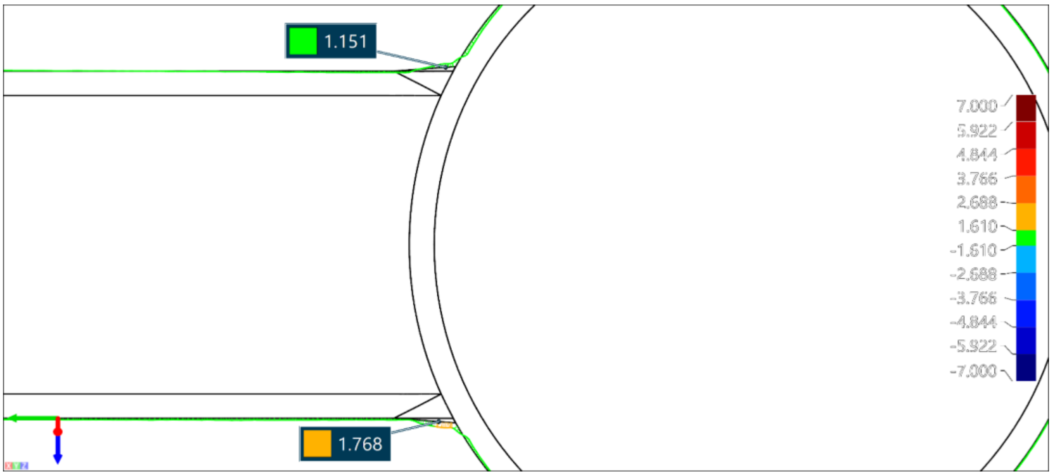
110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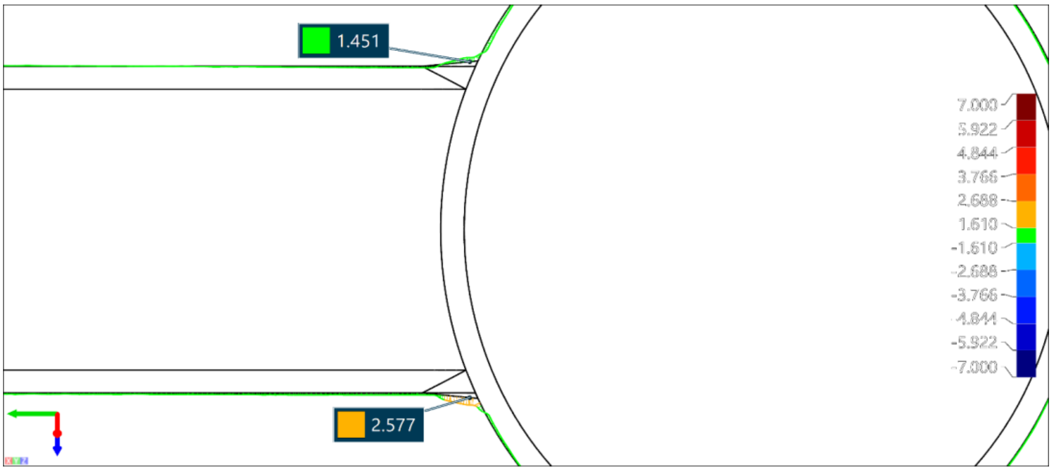
120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-2.688
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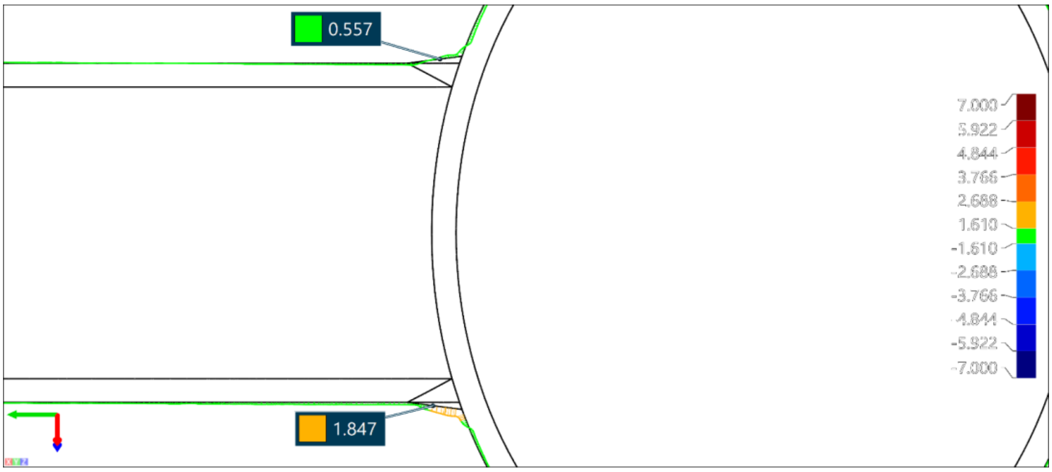
-5.922
-7.000

130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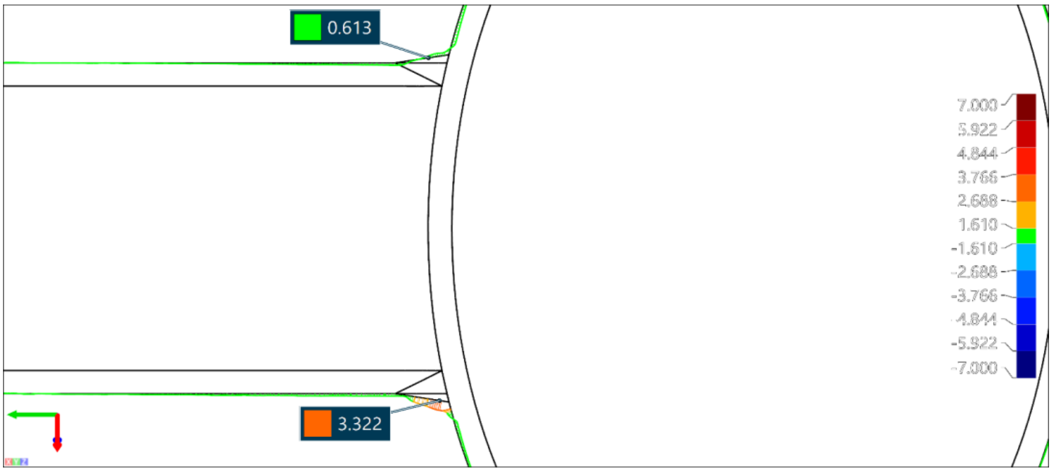
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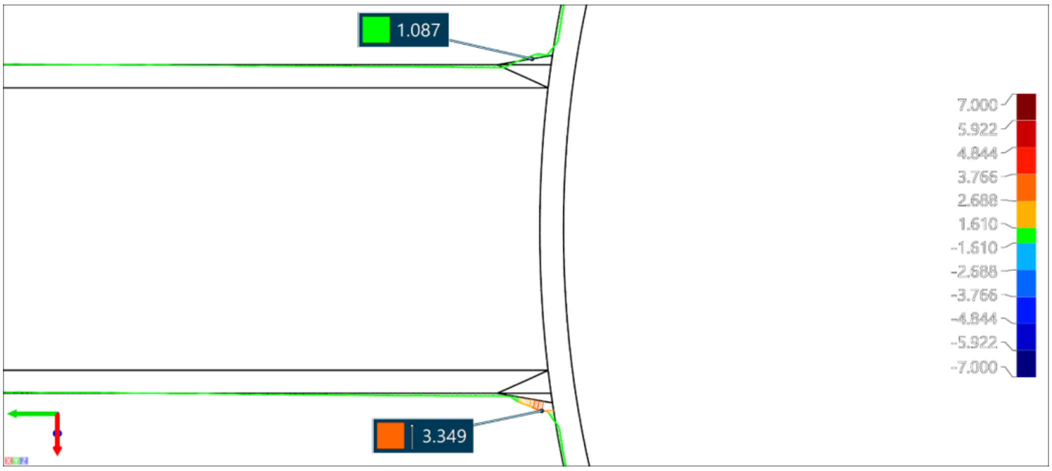
150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-2.688
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-5.922
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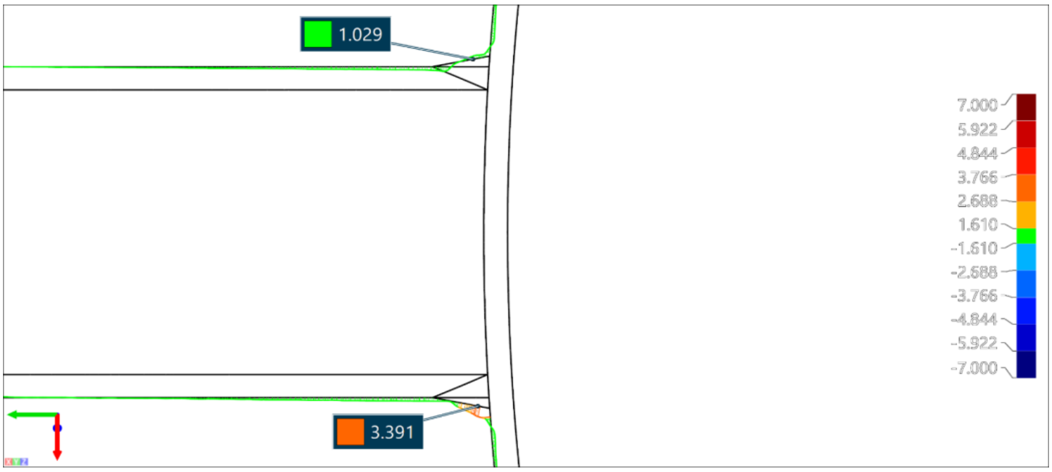
160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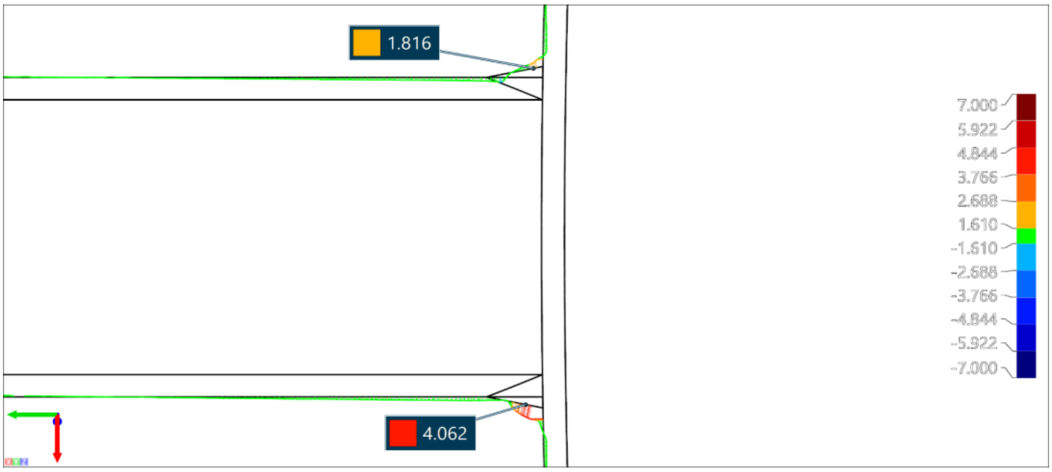
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-2.588
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-5.922
-7.000

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Report prepared by

Name ____

Date ____

Signature ____

Report reviewed by

Name ____

Date ____

Signature ____

LMC

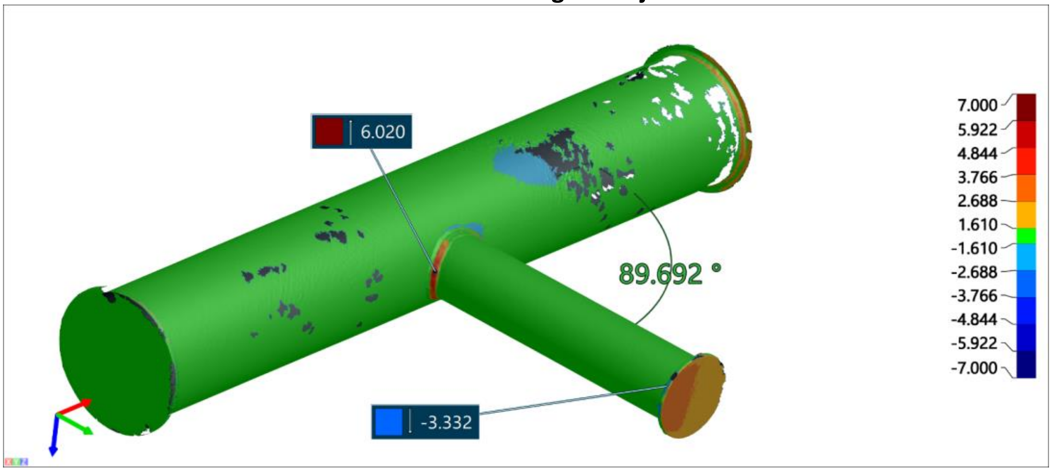
Project information

Organization	UIS
Units	mm

Part information

Part name	S31655-4000-T-07
Operator name	Kris Kolos

extremes and angle of T joint



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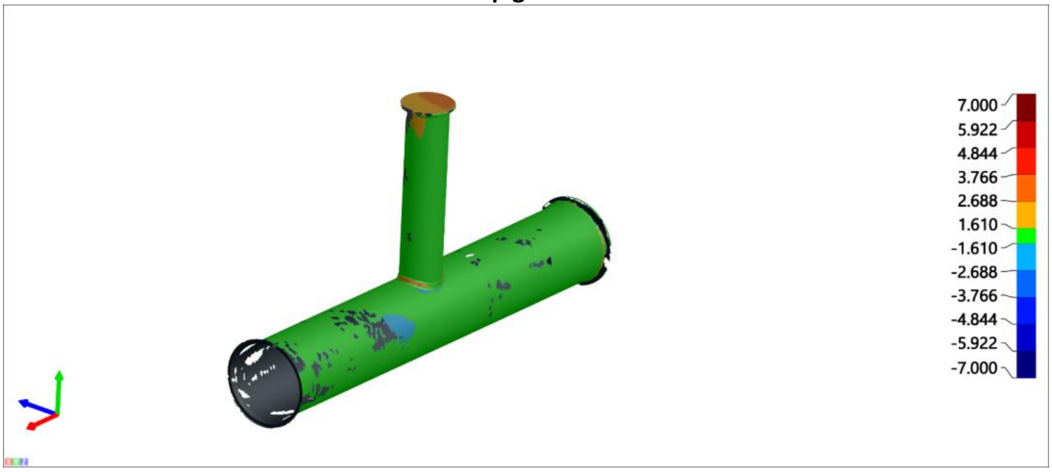
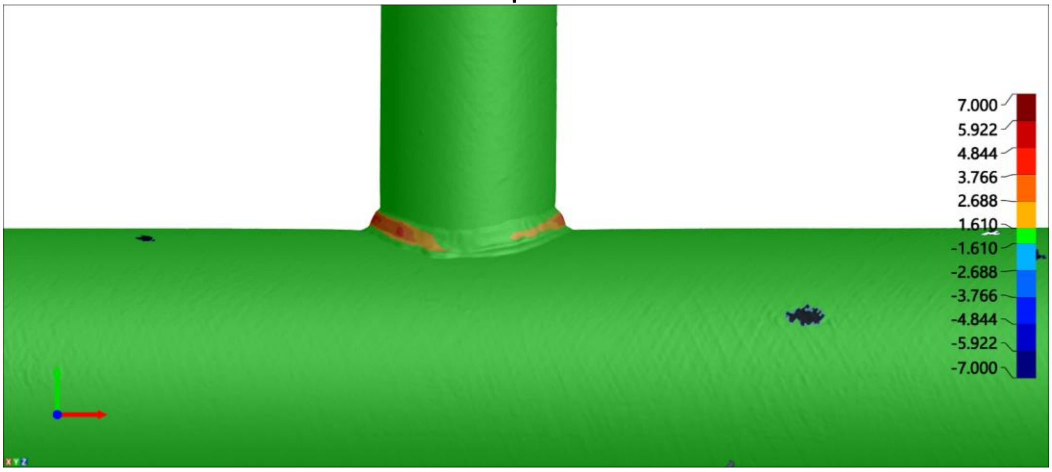
Color map 1 - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-3,332	-3,332	**-1,722**
Max.	1,610	0,000	6,020	6,020	**4,410**
±	3,220	0,000	9,352	9,352	**6,132**
SD	1,000	0,000	0,654	0,654	

colormap general view



colormap side view



Cylinder 1 - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,247	0,147	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		3,366		

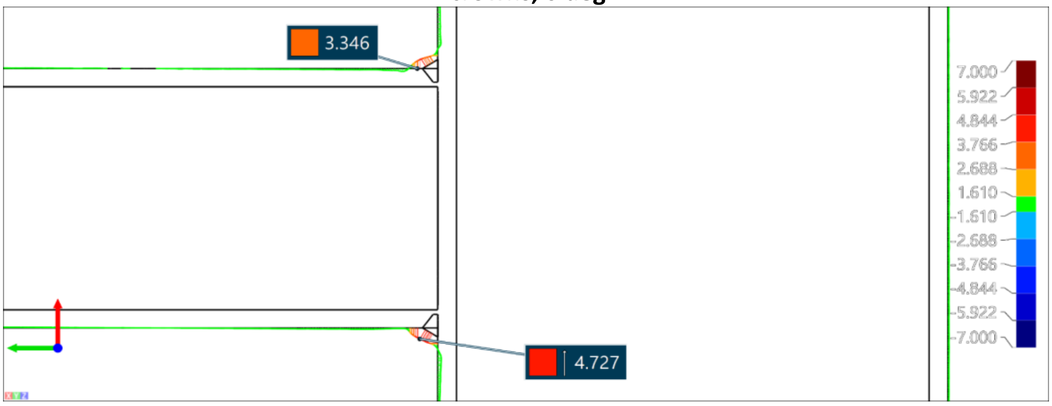
Cylinder 2 - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,574	0,274	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		7,919		**5,629**

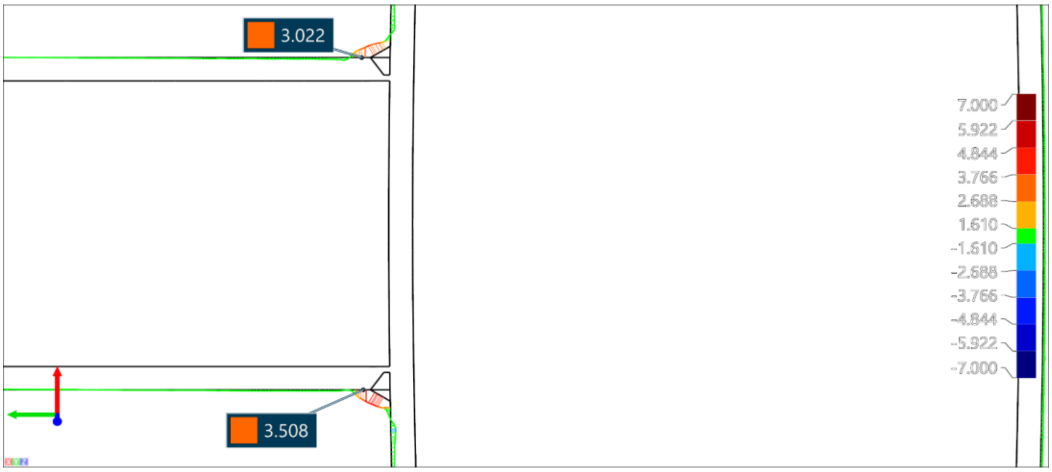
Angle [°] - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,692	-0,308	
∠XZ	+0.333 -0.333	0,000	13,880	13,880	13,547
∠YZ	+0.333 -0.333	0,000	6,235	6,235	5,902

crowns, 0 deg



10



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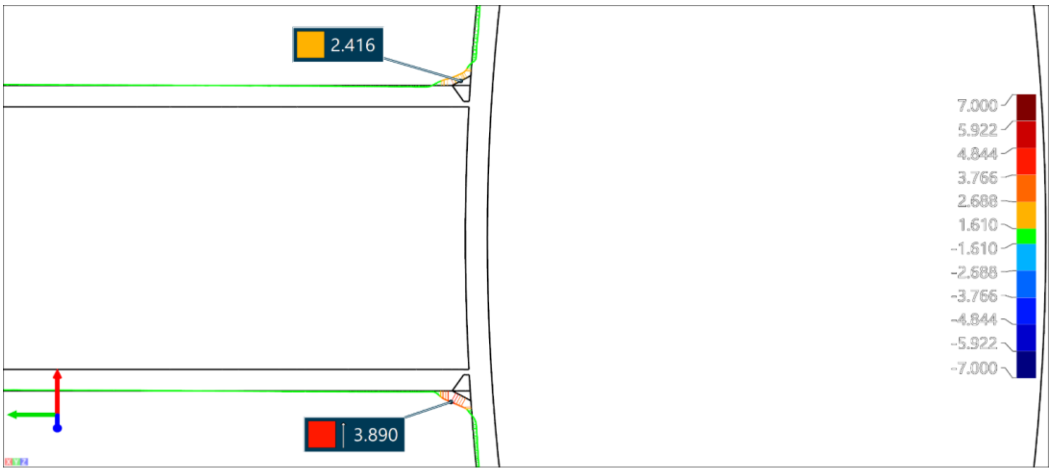

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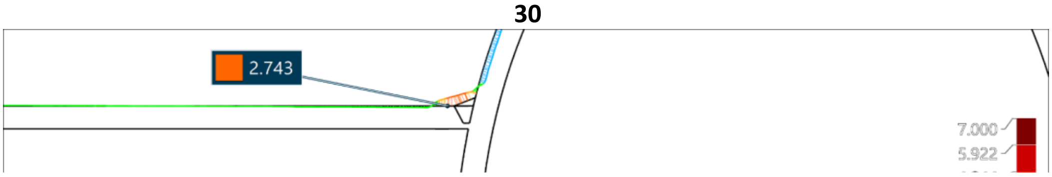

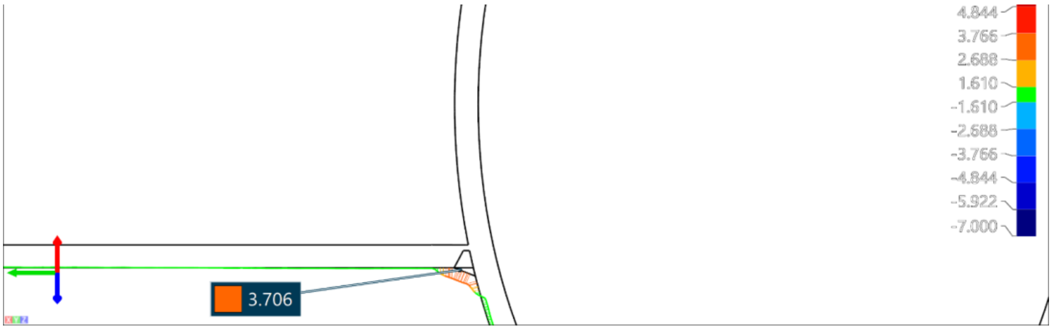
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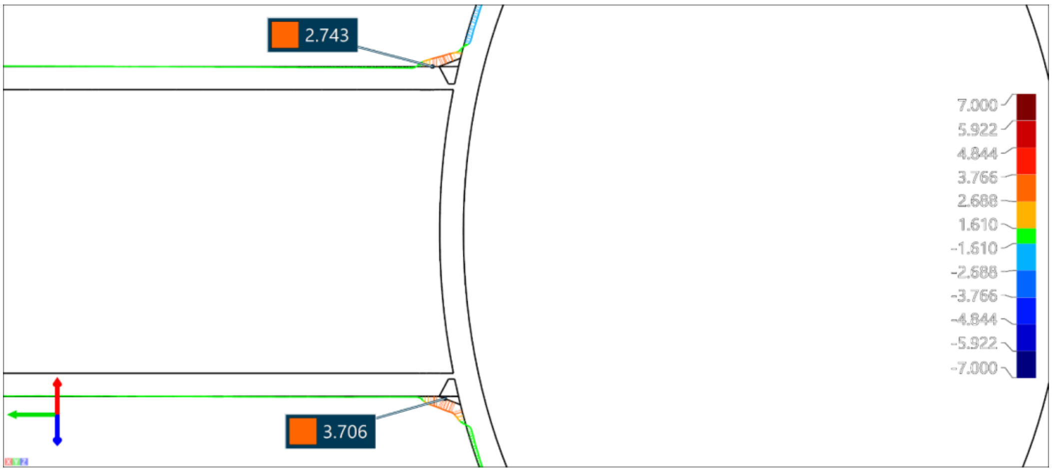
40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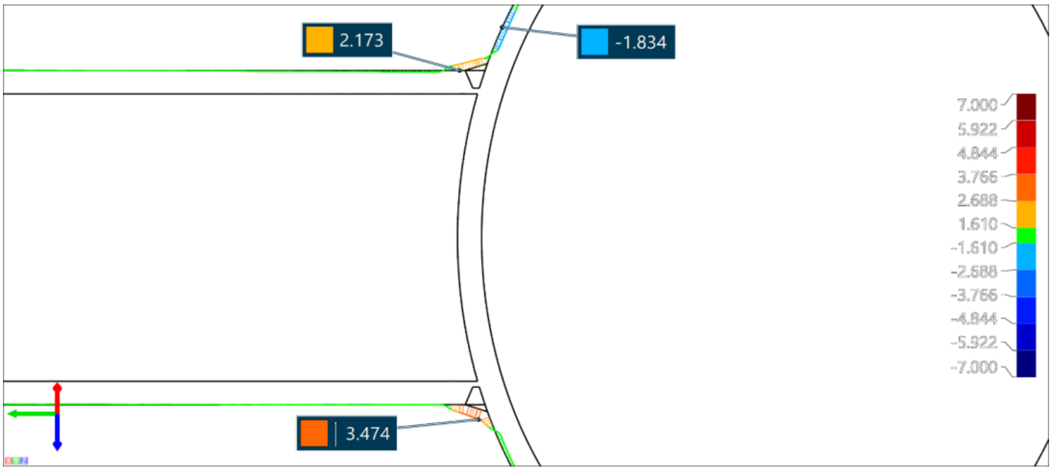
50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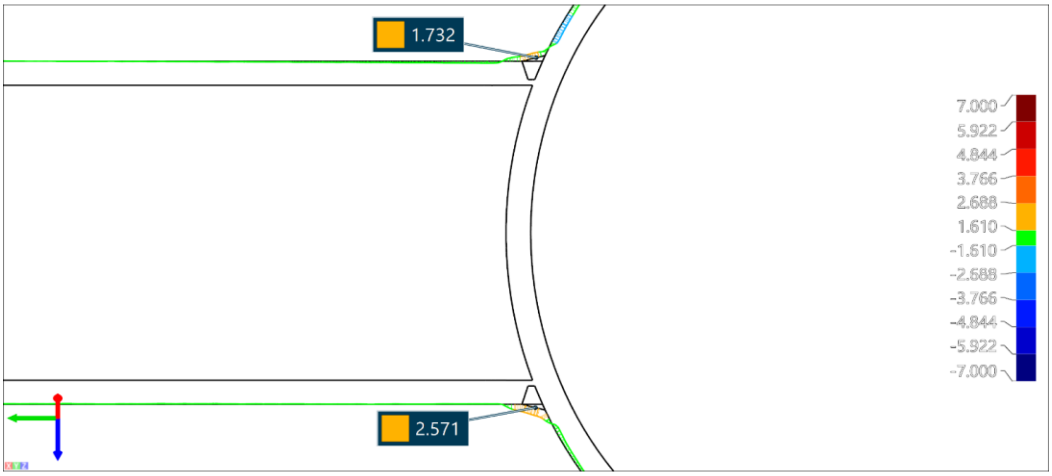
60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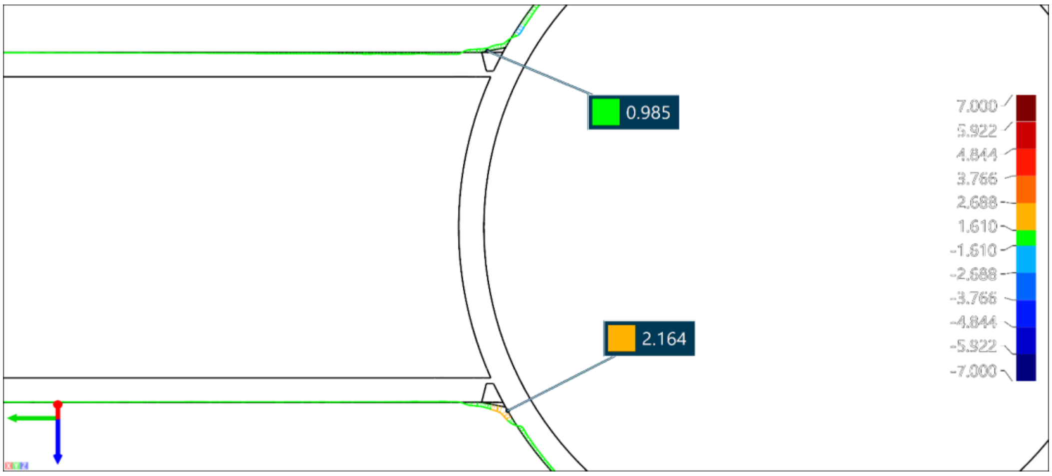
70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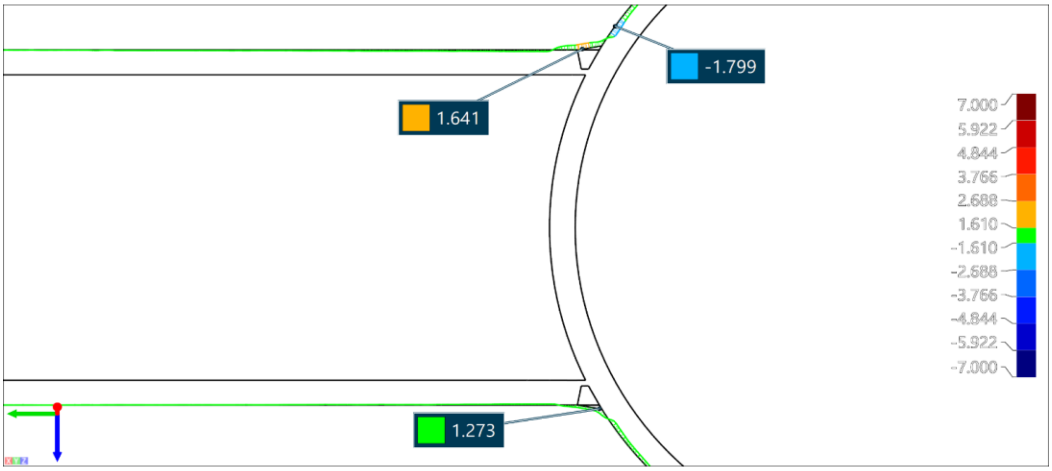
80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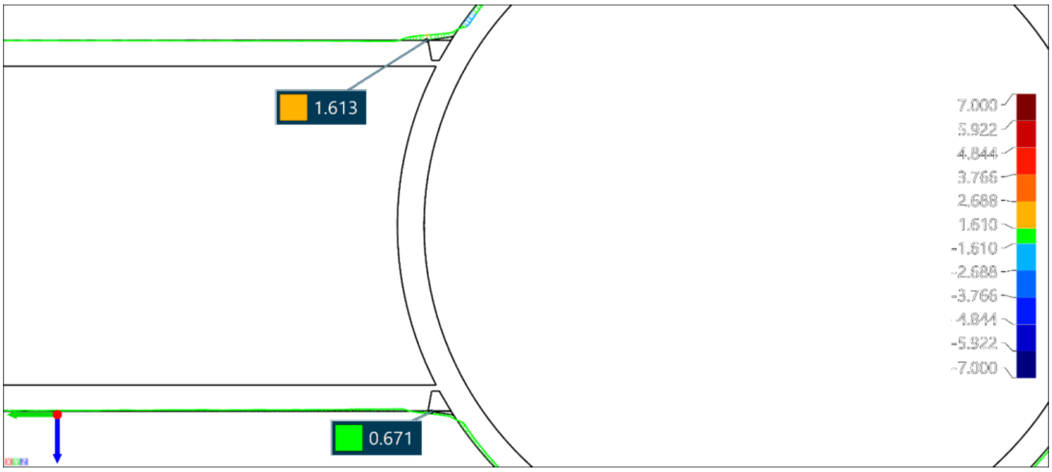
saddle



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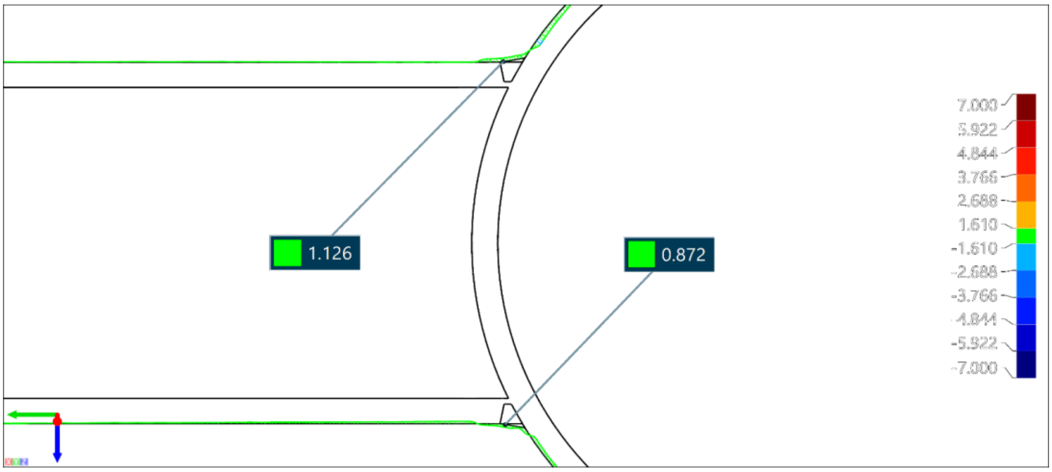

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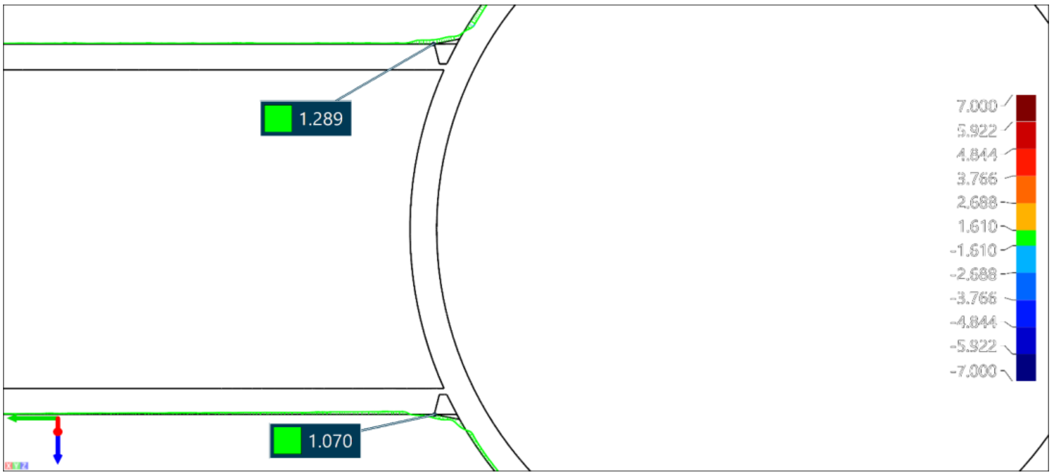

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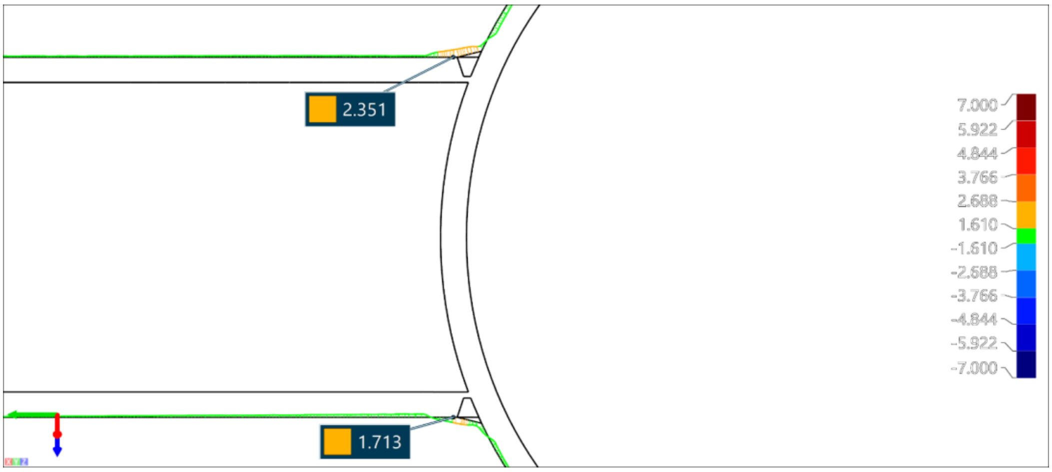

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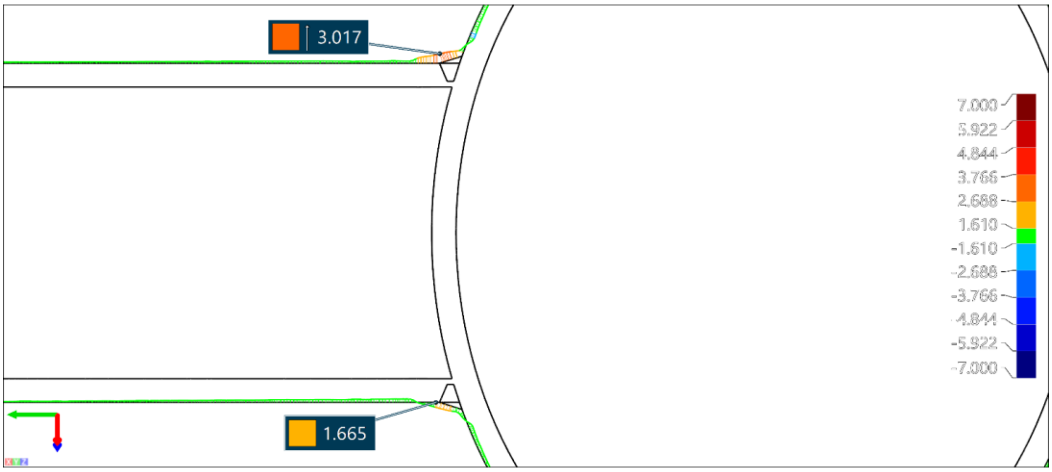

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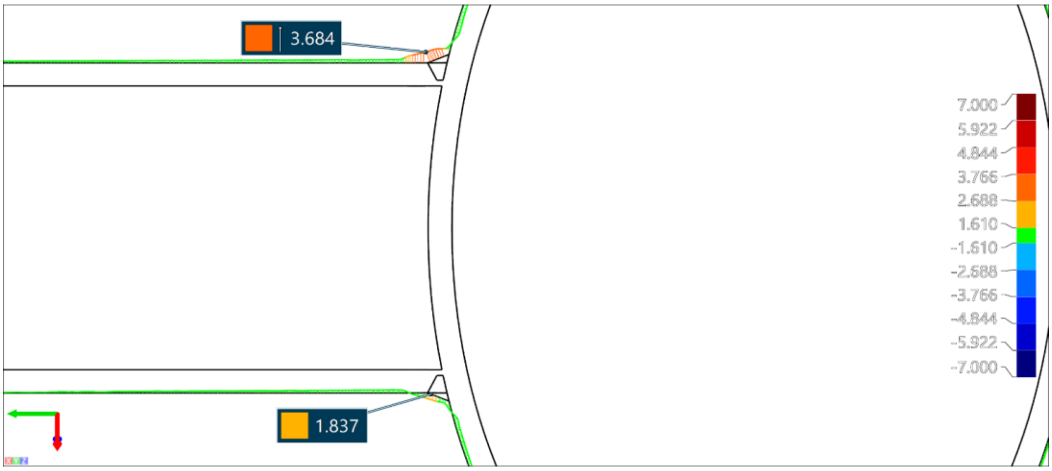

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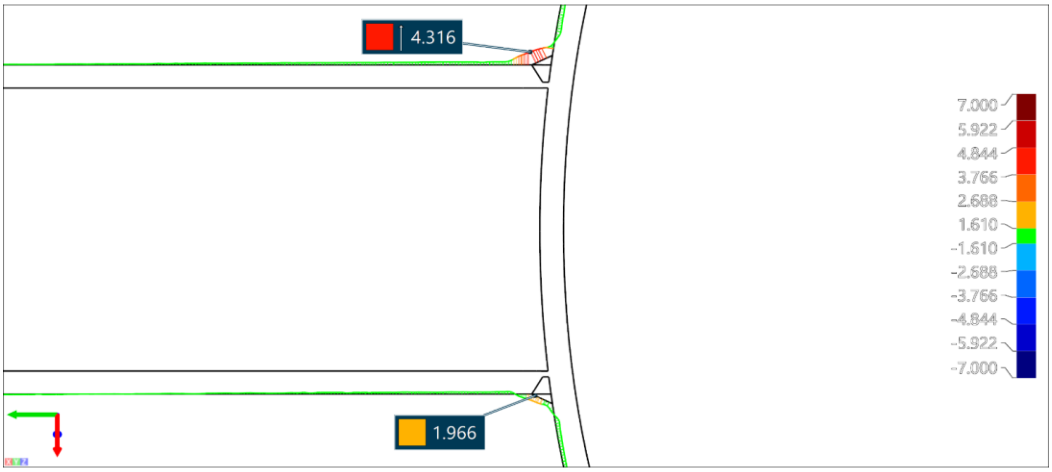
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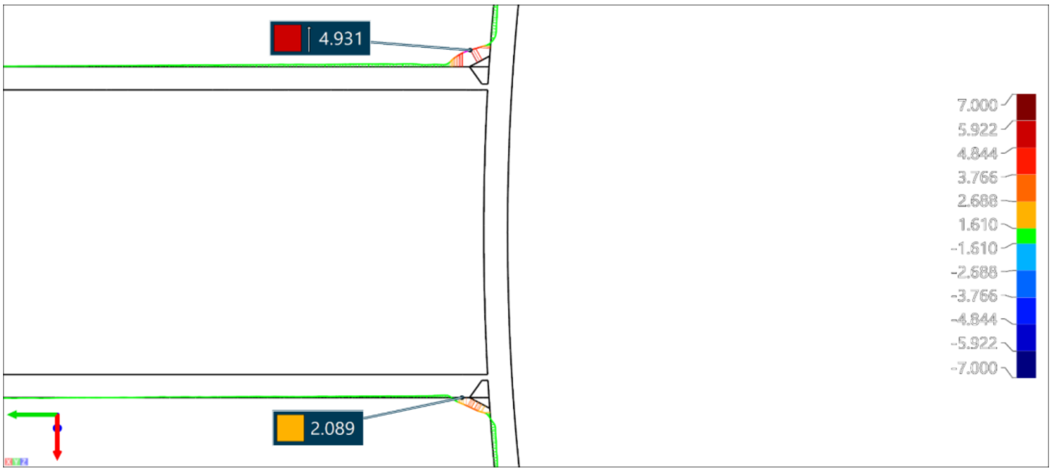
160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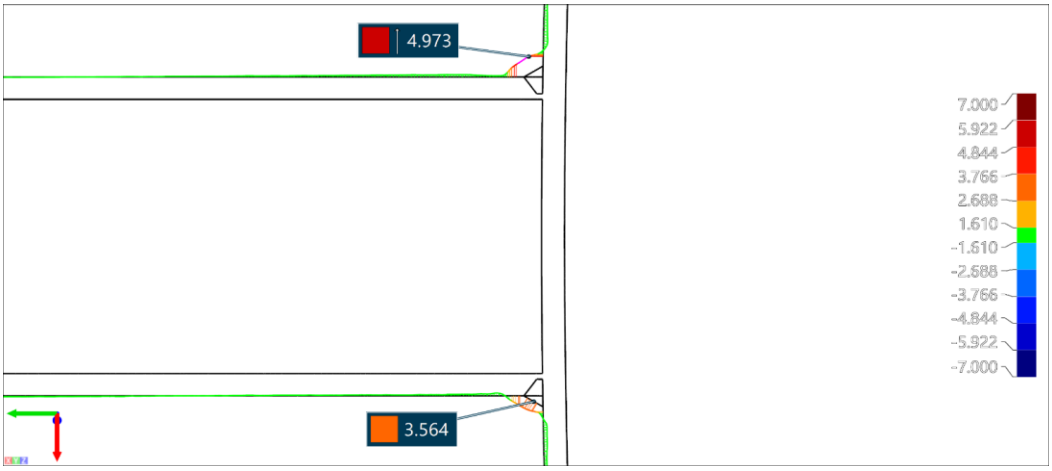
170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-2.688
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-4.844
-5.922
-7.000

MMC

Project information

Organization	UIS
Units	mm

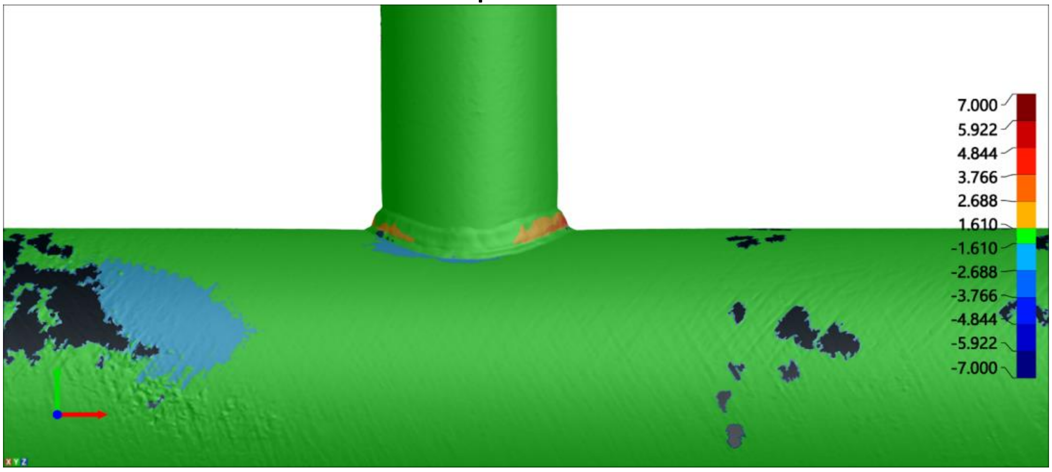
Part information

Part name	S31655-4000-T-07
Operator name	Kris Kolos

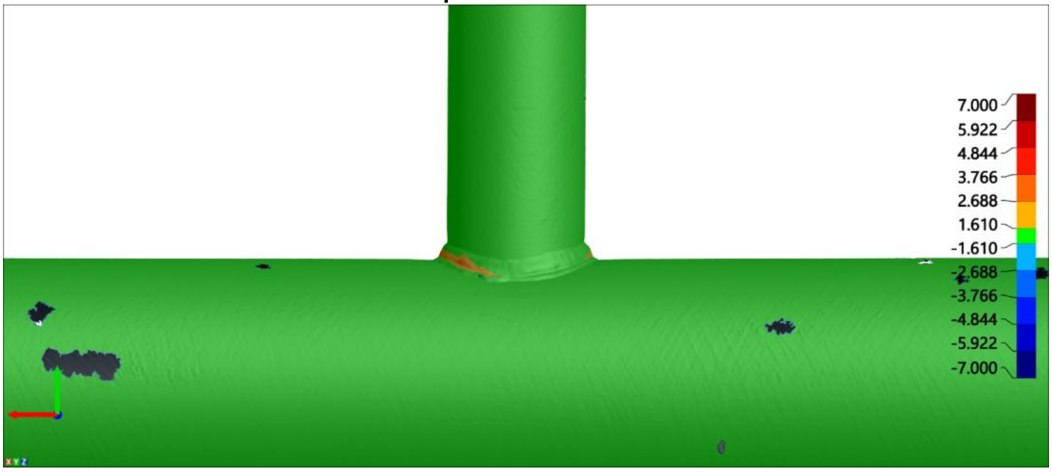
Color map 1 - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Min.	-1,610	0,000	-3,335	-3,335	**-1,725**
Max.	1,610	0,000	5,189	5,189	**3,579**
±	3,220	0,000	8,523	8,523	**5,303**
SD	1,000	0,000	0,643	0,643	

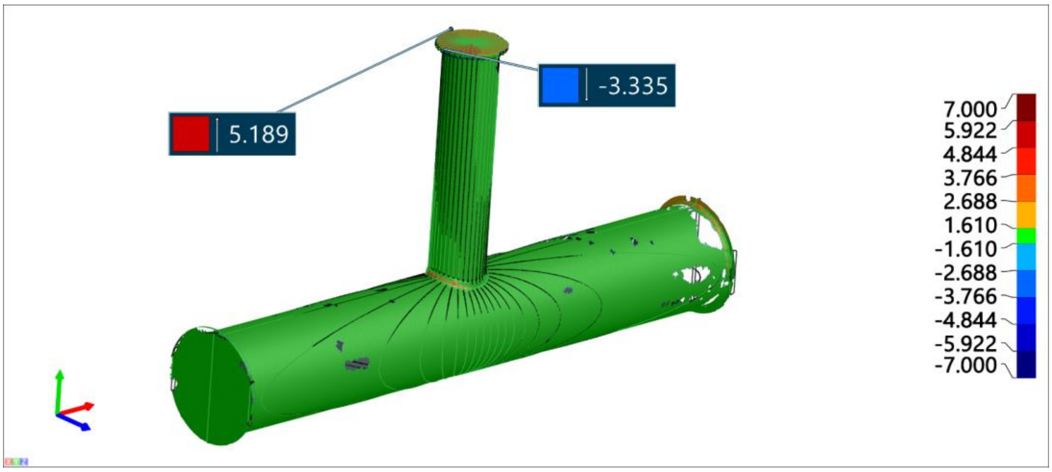
colormap side view MMC



colormap other side view MMC



extremes at MMC



Cylinder 1 - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+3.540 -3.540	219,100	219,247	0,147	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 4.380	4,380		3,366		

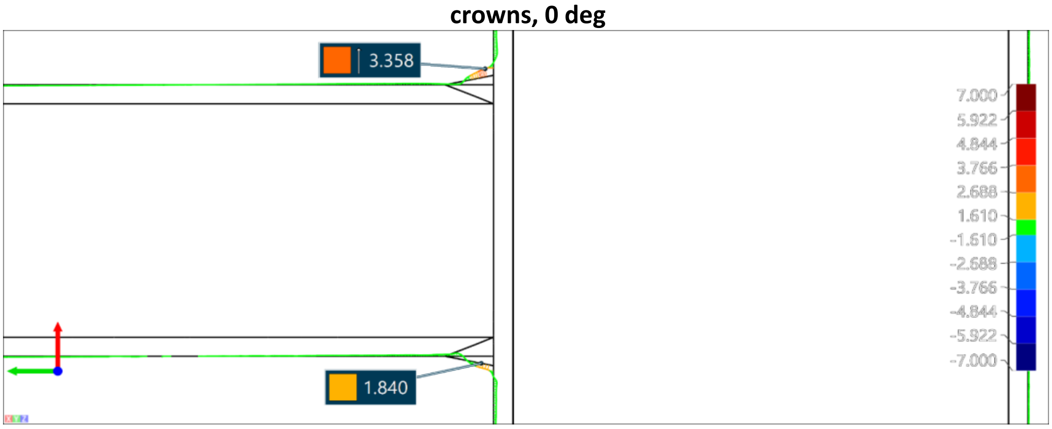
Cylinder 2 - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
Ø	+1.610 -1.610	114,300	114,574	0,274	
GD&T	**Tolerance**	**Nominal values**	**Measured values**	**Deviations**	**Out of tol.**
⌭ 2.290	2,290		7,919		**5,629**

Angle [°] - Scan7

Dimensions	Tolerance	Nominal values	Measured values	Deviations	Out of tol.
∠XY	+0.333 -0.333	90,000	89,692	-0,308	
∠XZ	+0.333 -0.333	0,000	13,888	13,888	**13,555**
∠YZ	+0.333 -0.333	0,000	6,228	6,228	**5,895**

crowns, 0 deg



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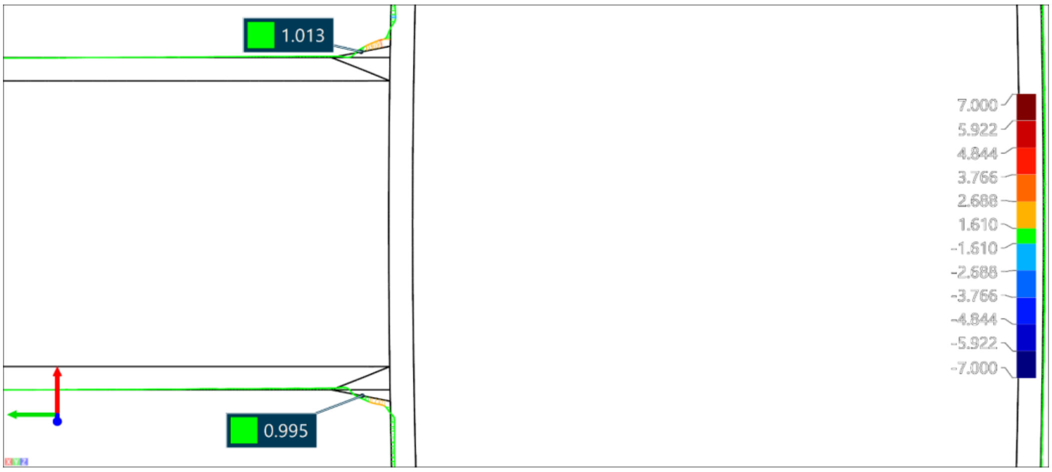

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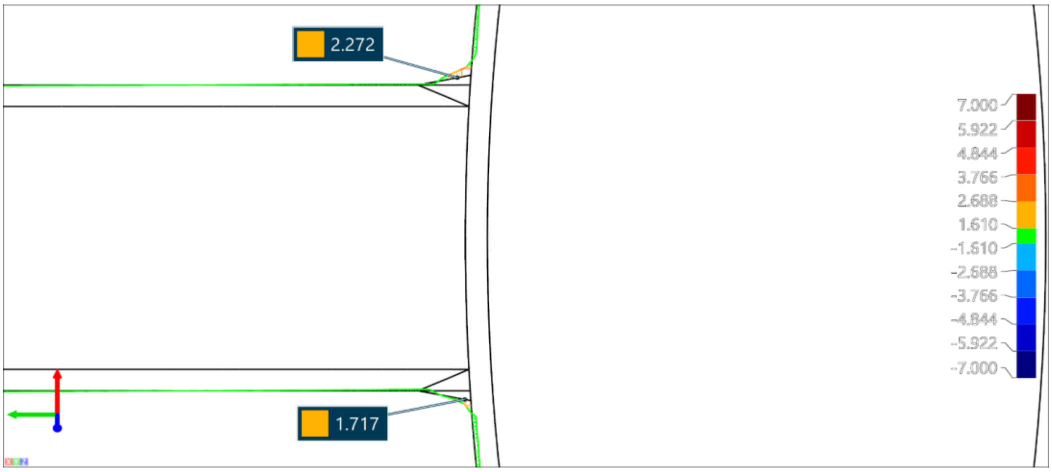
20



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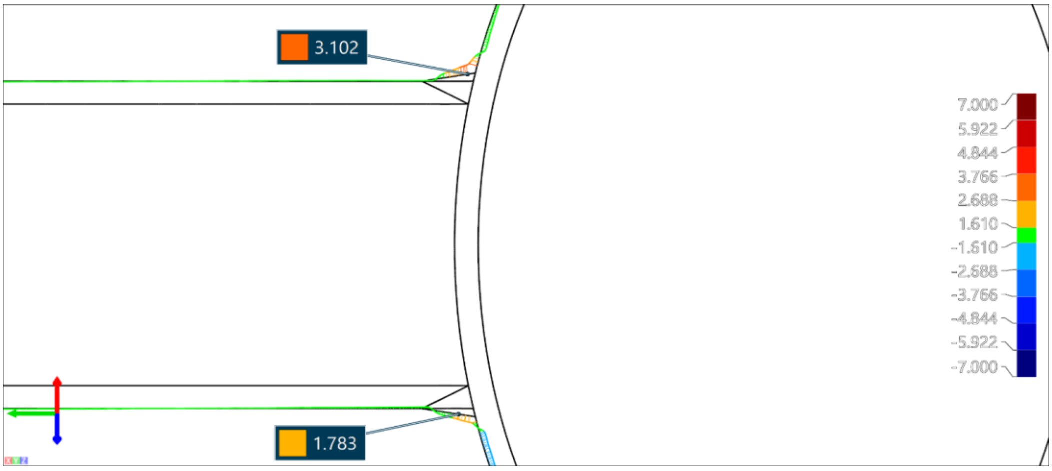

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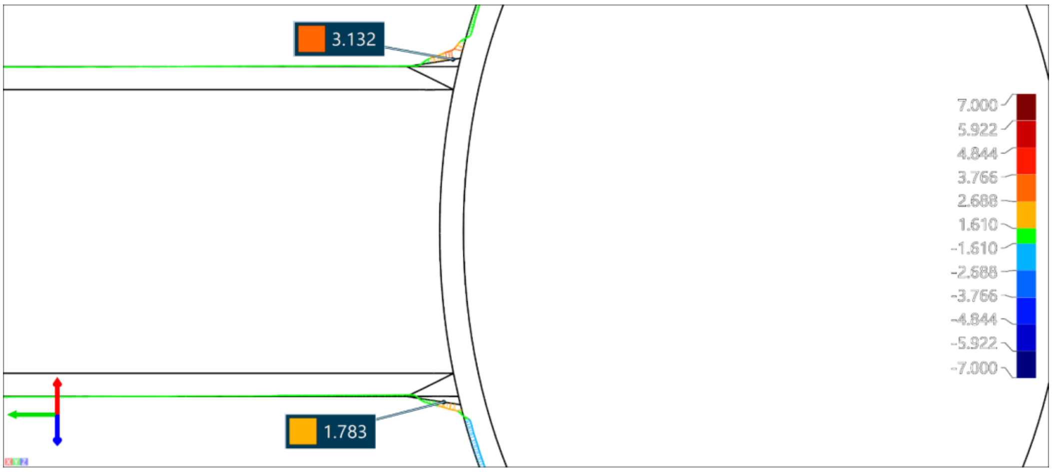
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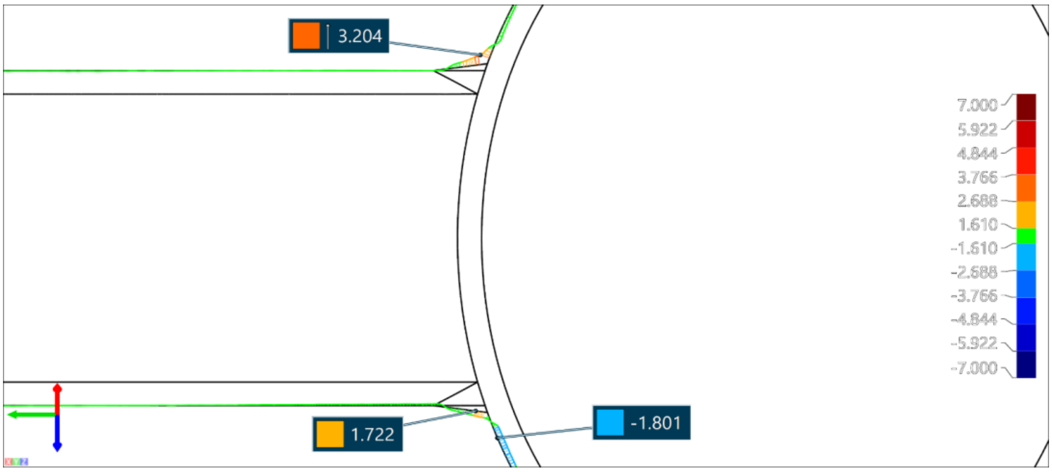
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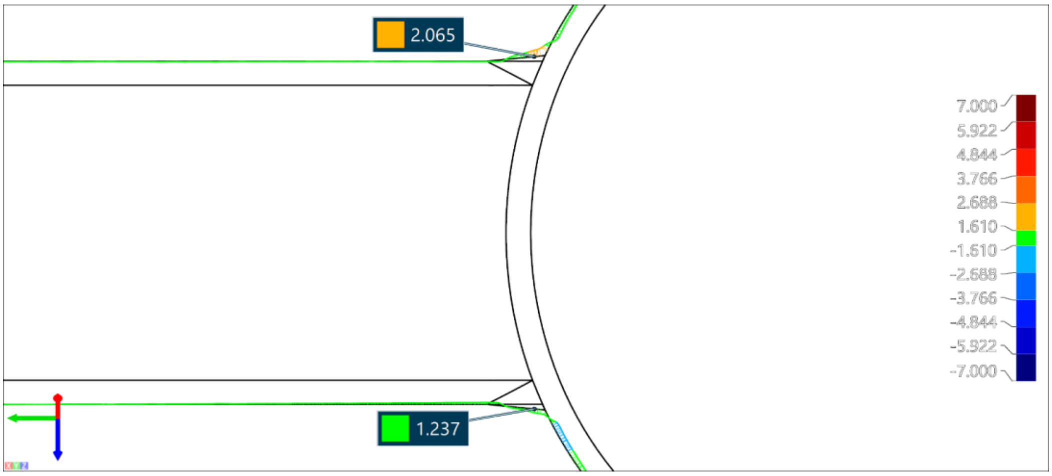
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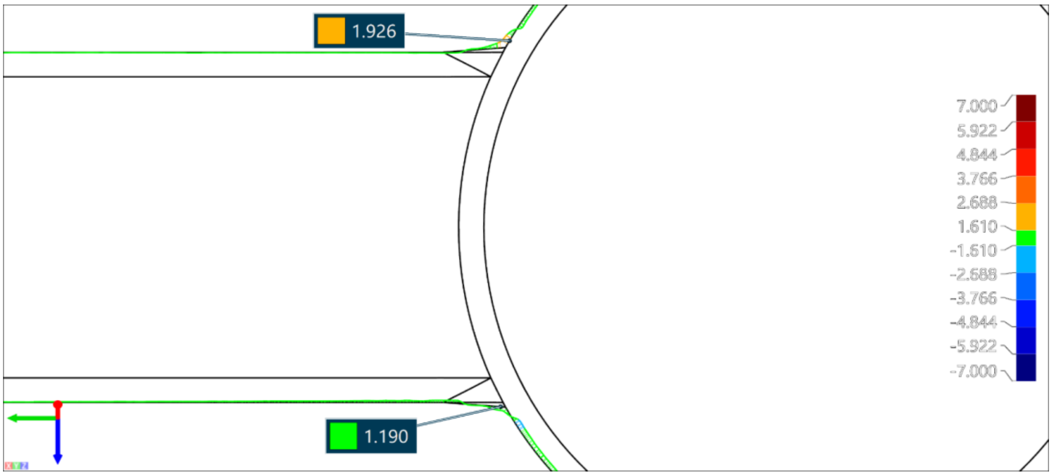
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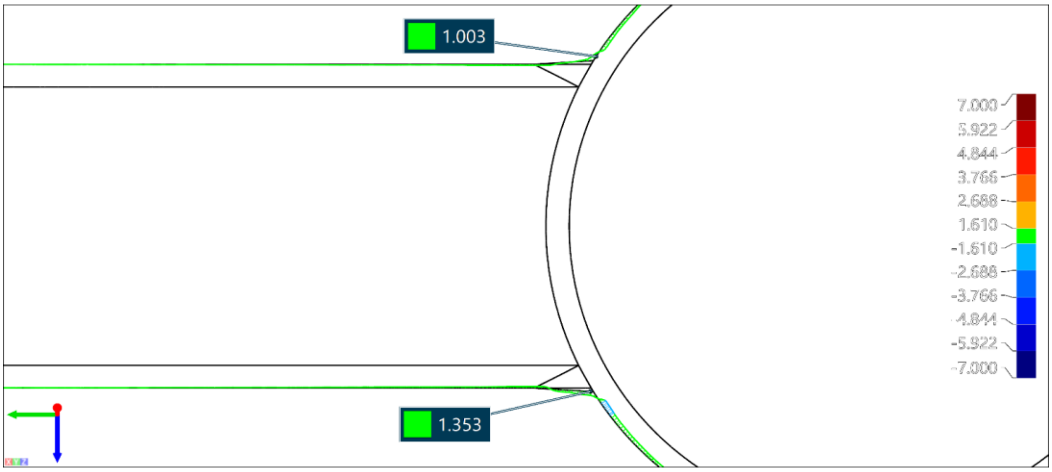
80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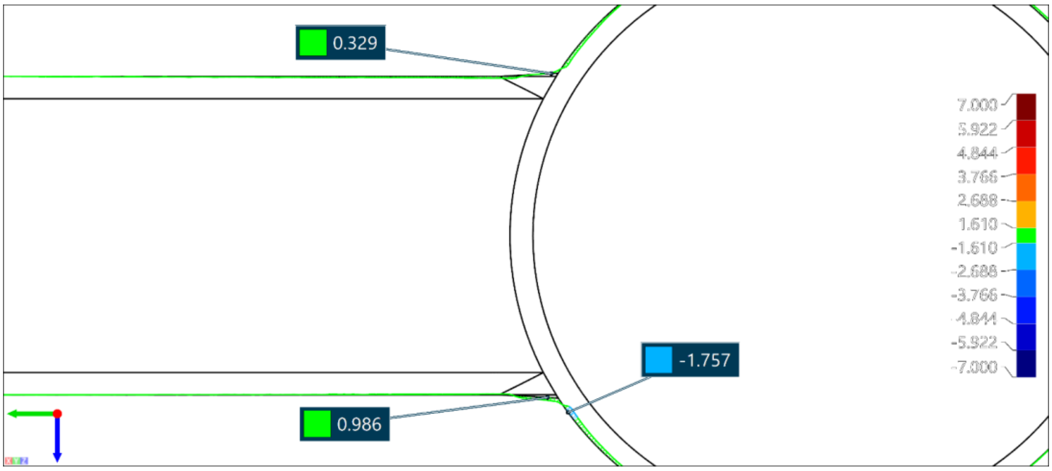
saddle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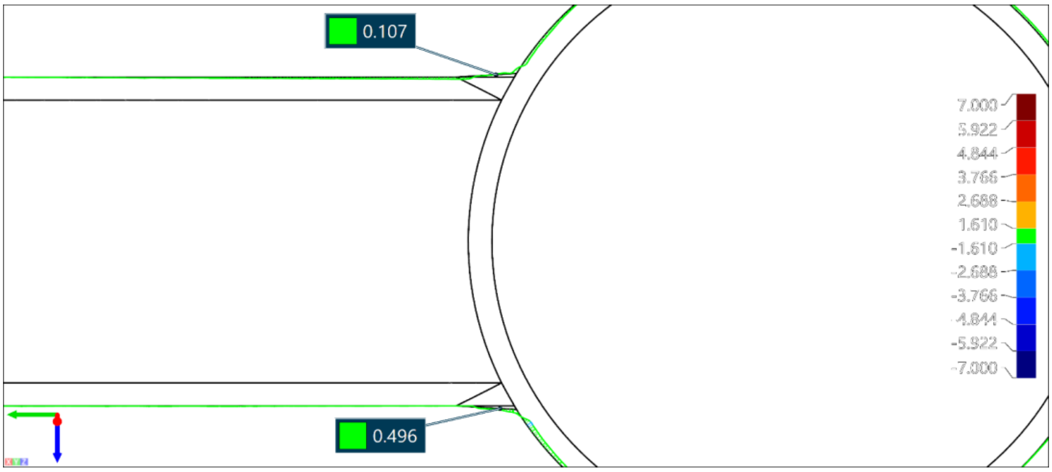
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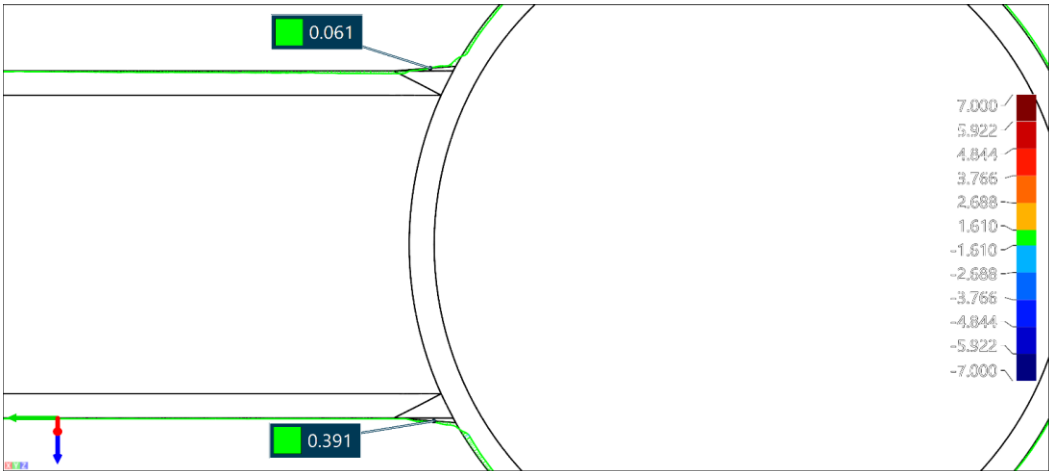
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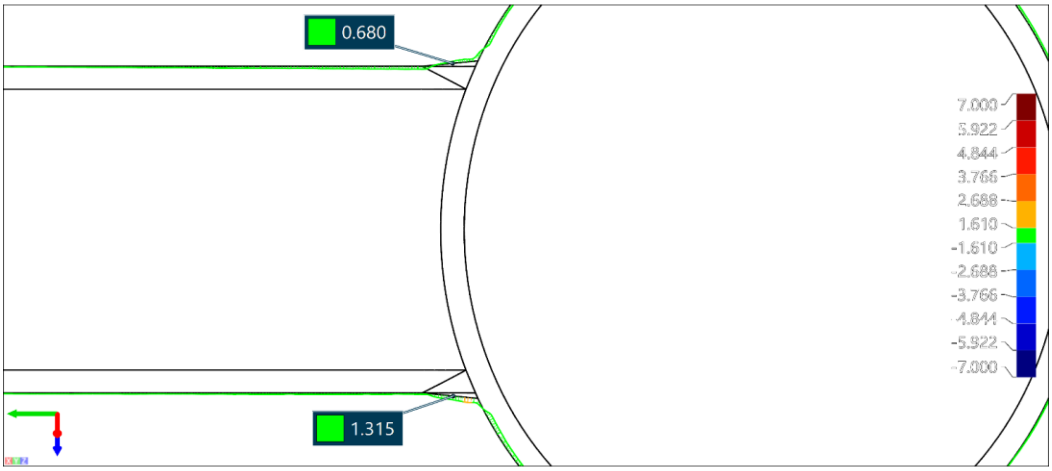
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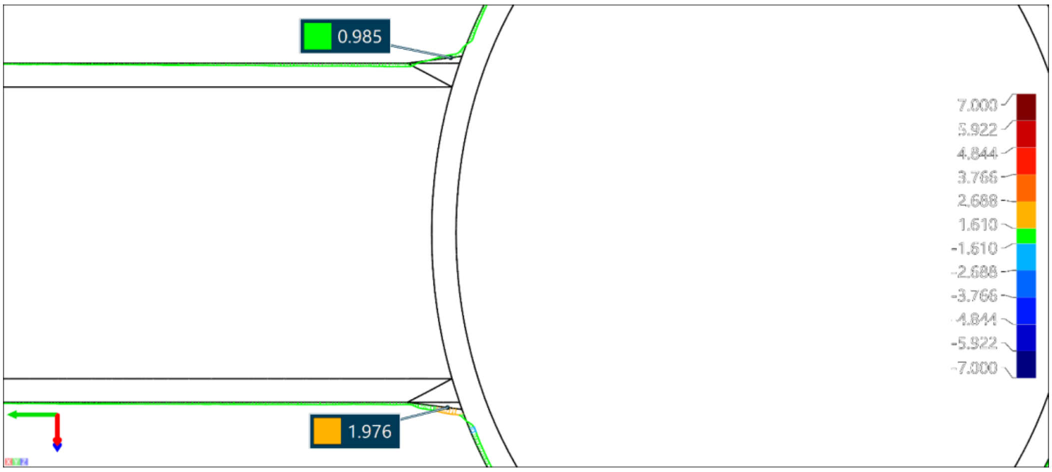
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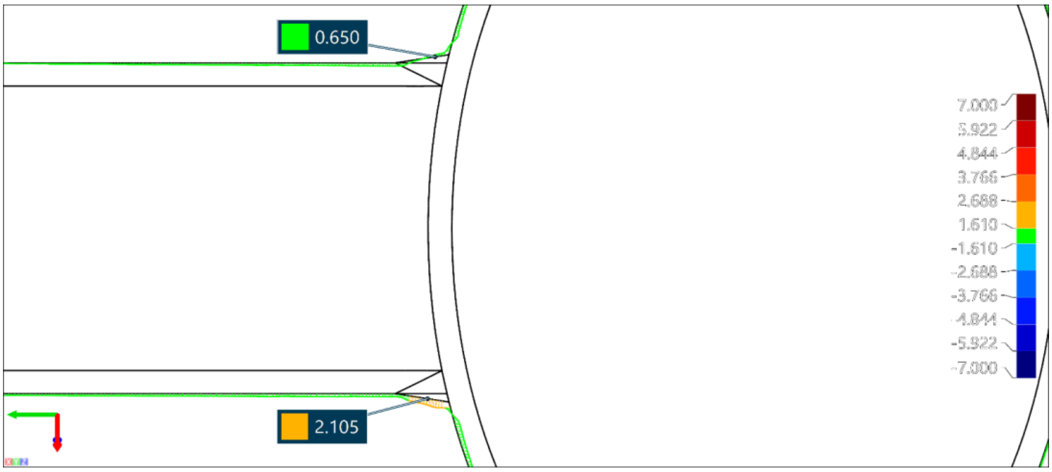
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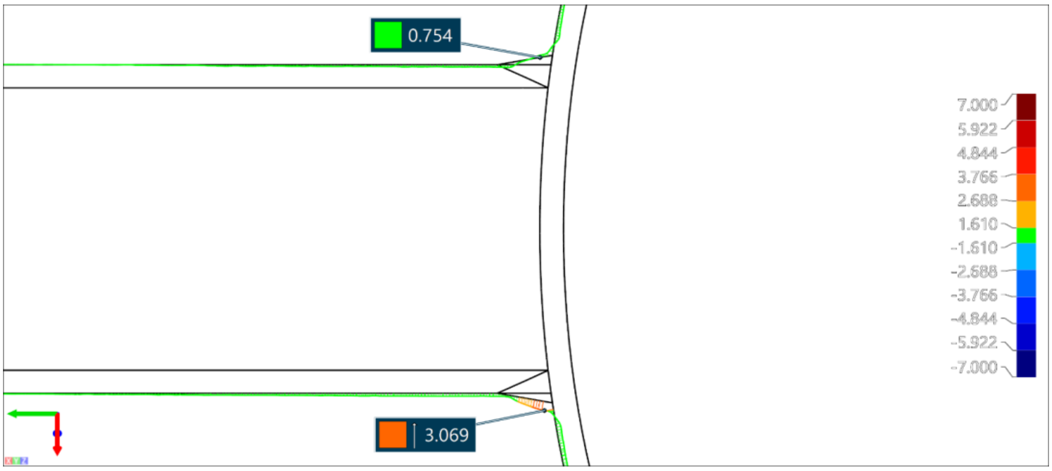
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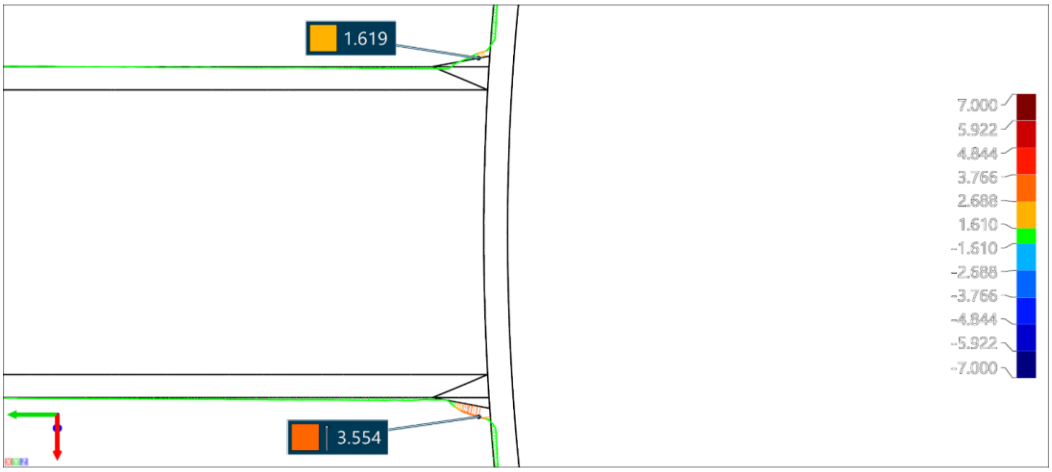

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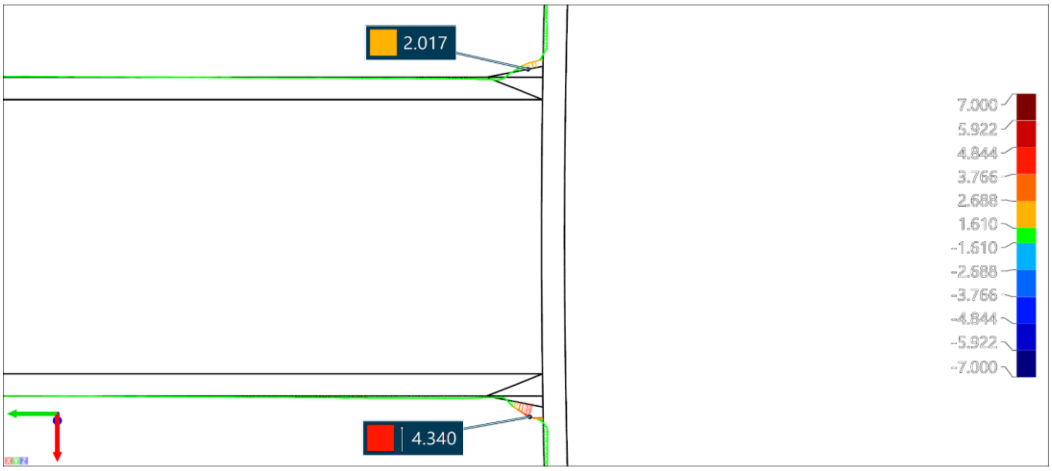

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Name ____

Date ____

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