UNIVERSITÀ DEGLI STUDI DI NAPOLI "FEDERICO II"
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

MASTER THESIS IN MECHANICAL ENGINEERING

OPTIMIZATION AND INDUSTRIALIZATION OF THE LASER DRILLING PROCESS FOR THE PRODUCTION OF SHAPED HOLES ON AEROSPACE SUPERALLOYS VIA STATISTICAL METHODS

TUTORS:
CH.MO PROF. ING. BIAGIO PALUMBO (DIPARTIMENTO DI INGEGNERIA INDUSTRIALE)
CH.MO PROF. ING. CLAUDIO LEONE (UNIVERSITÀ DEGLI STUDI DELLA CAMPANIA "LUIGI VANVITELLI")

CO-TUTORS:
ING. GAETANO DE CHIARA (AVIO AERO)
ING. FRANCESCO DEL RE (DIPARTIMENTO DI INGEGNERIA INDUSTRIALE)
ING. SILVIO GENNA (UNIVERSITÀ DEGLI STUDI DI ROMA "TOR VERGATA")

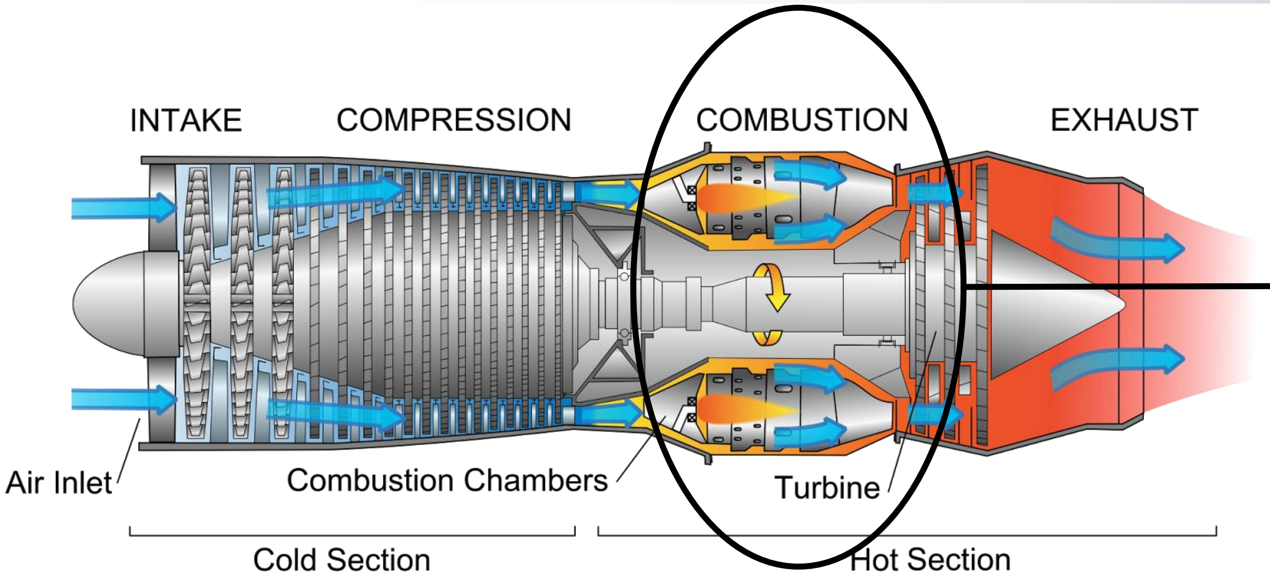
CANDIDATE:
ANTONIO TARTAGLIONE
M64/682

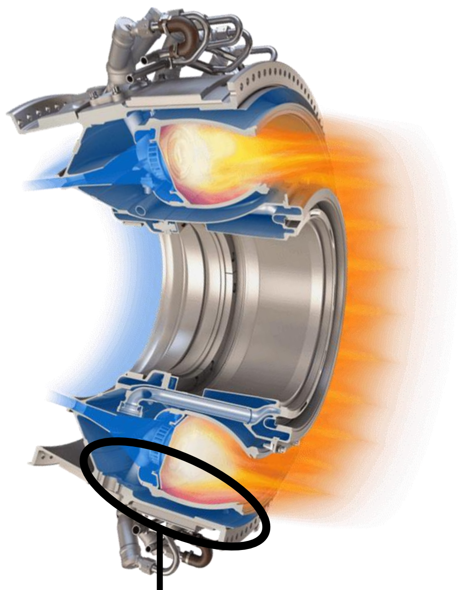
Avio Aero: the company

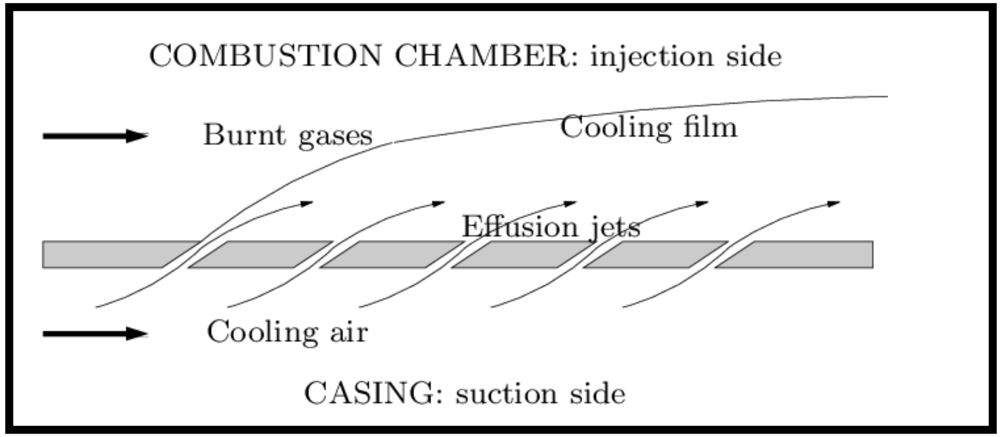
Avio Aero
A GE Aviation Business

A leading aerospace company

The film cooling in the Jet Engine Combustor



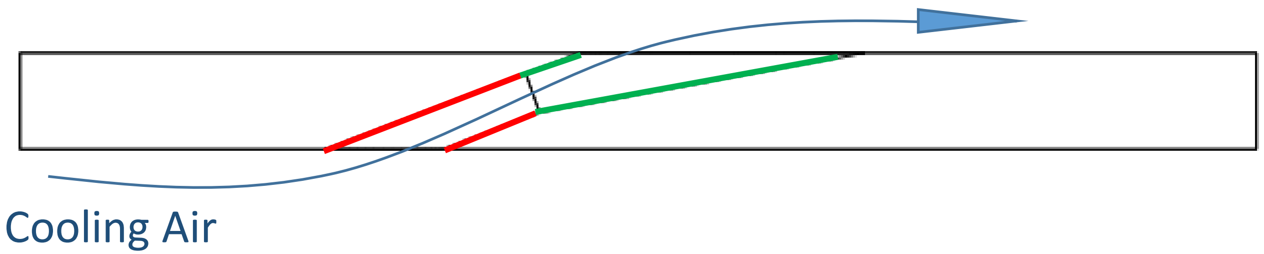


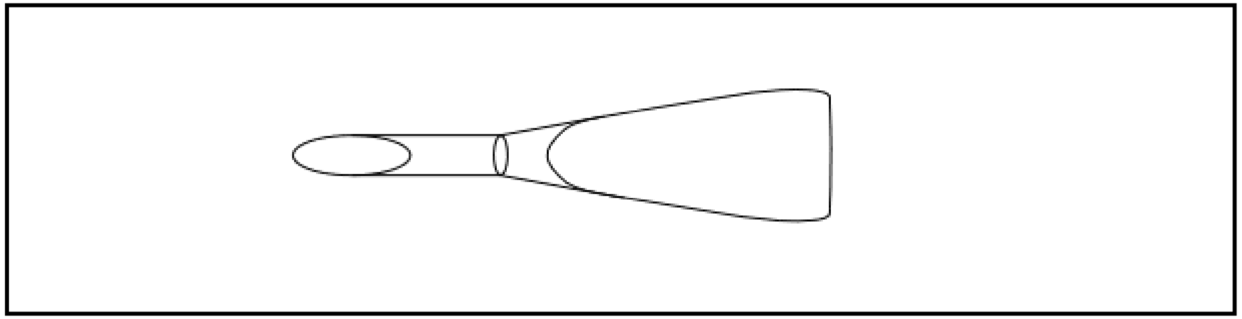


Gases may reach a temperature around 1600 °C.
The material used melt at 1200 °C.

The surfaces exposed to the combustion must be adequately cooled to avoid their structural failure.

Film cooling by Shaped Holes





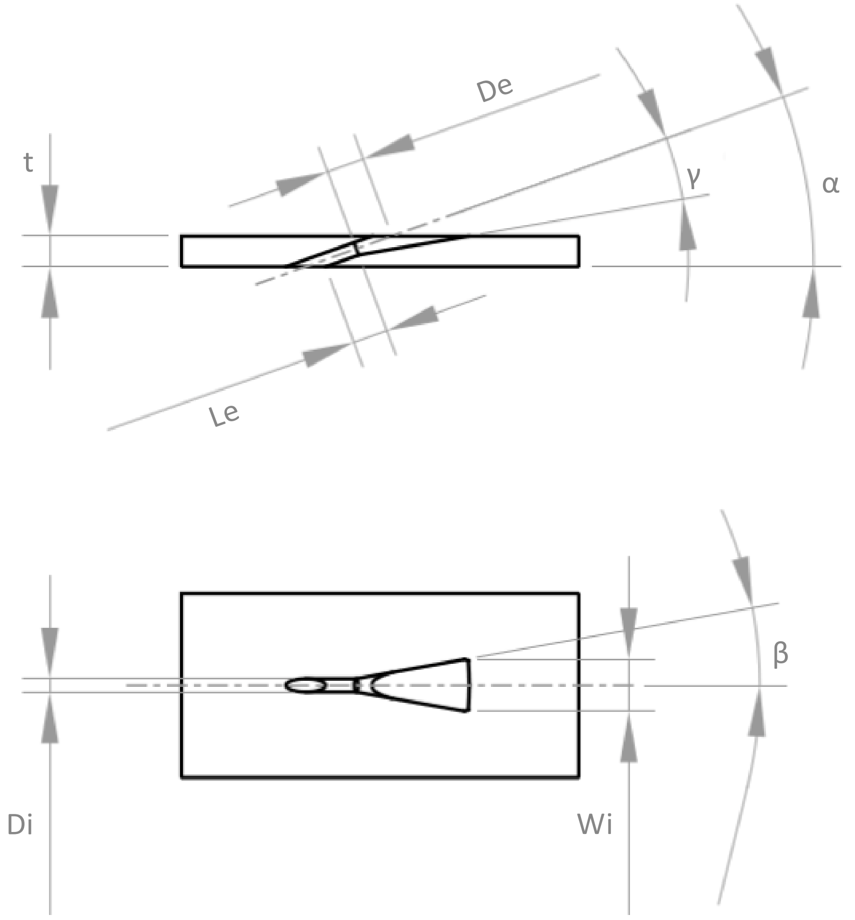
The use of holes with variable section (*shaped holes*) allows to increase the cooling efficiency of the combustion chamber.

The shaped holes are composed by two parts:

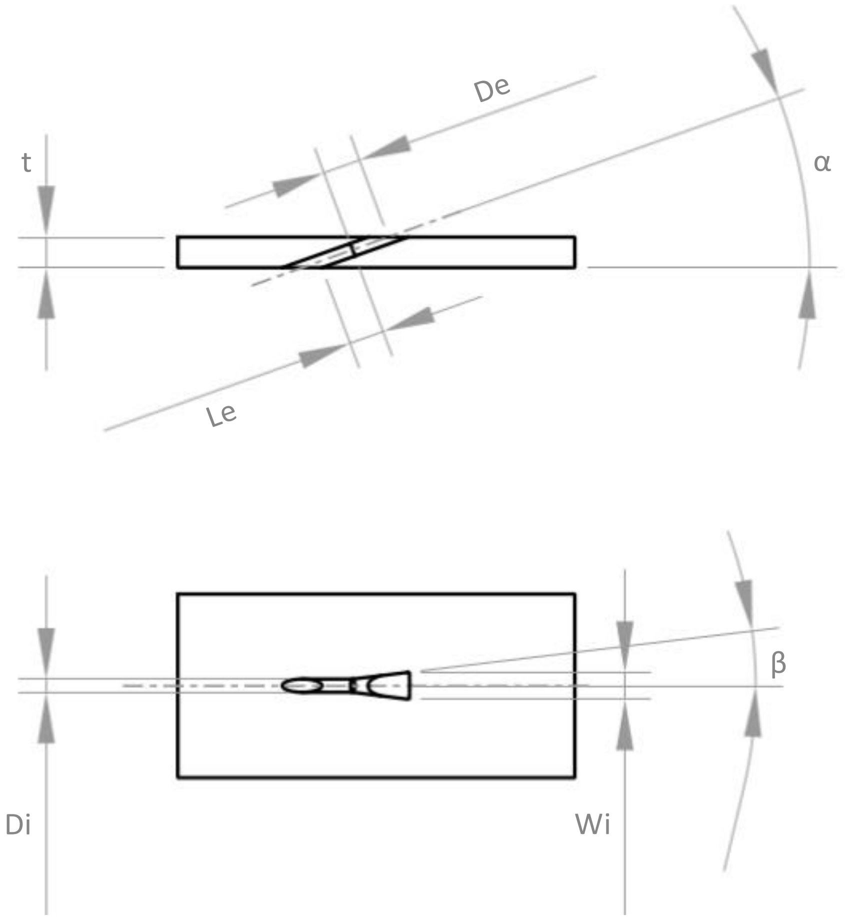
- the metering section refers to the cylindrical part of the hole;
- the diffuser refers to the divergent part of the hole, whose function is to spread a film of air over the parts surface.

Shaped Holes Configurations

Job 1



Job 2



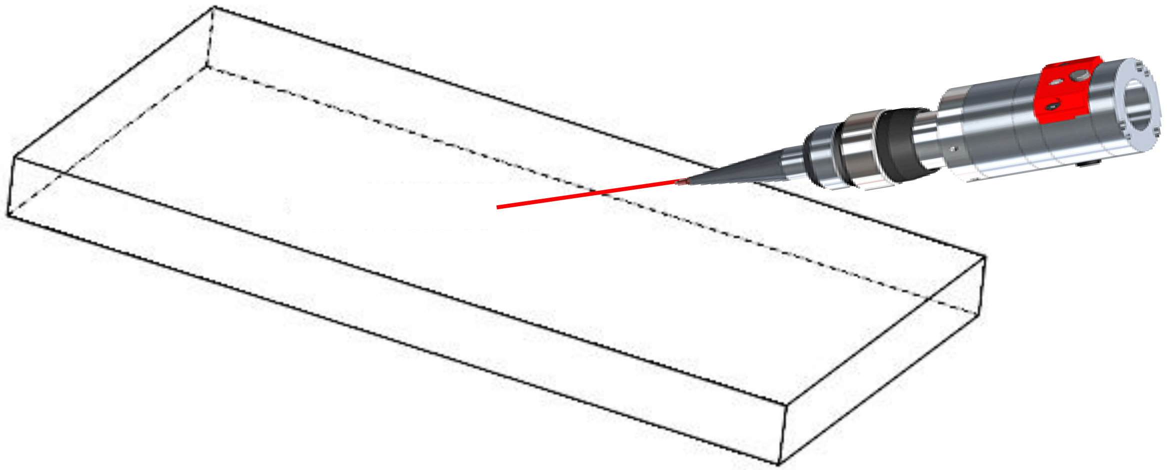
Shaped Hole geometrical features

- Plate tickness – **t**
- Hole axis slope – **α**
- Metering section diameter – **Di**
- Metering section length – **Le**
- Diffuser slope – **γ**
- Diffuser depth – **De**
- Diffuser width – **Wi**
- Diffuser angle – **β**

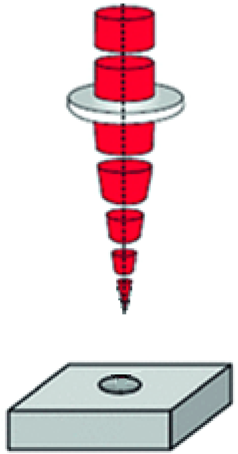
Laser Pulsed Drilling methods

Different drilling methods can be used for the production of Shaped Holes.

To maximize shaped holes quality while minimizing the drilling time per single hole, it was decided to perform:

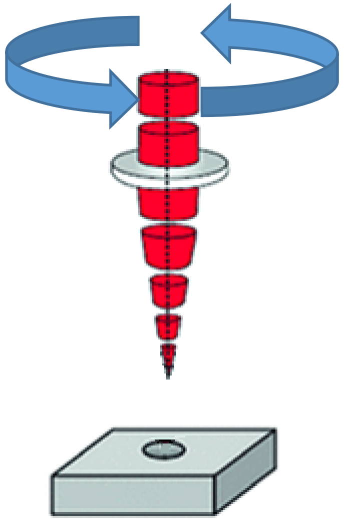


- **Phase I: Percussion Drilling**
- **Phase II: Trepanning**
- **Phase III: Percussion Drilling**



PERCUSSION

FASTER BUT LESS ACCURATE



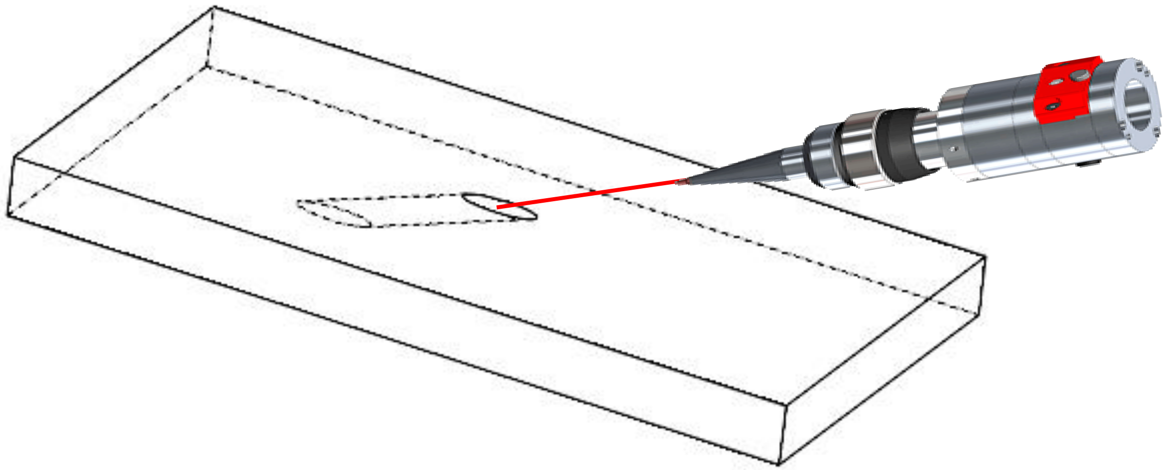
TREPANNING

SLOWER BUT MORE ACCURATE

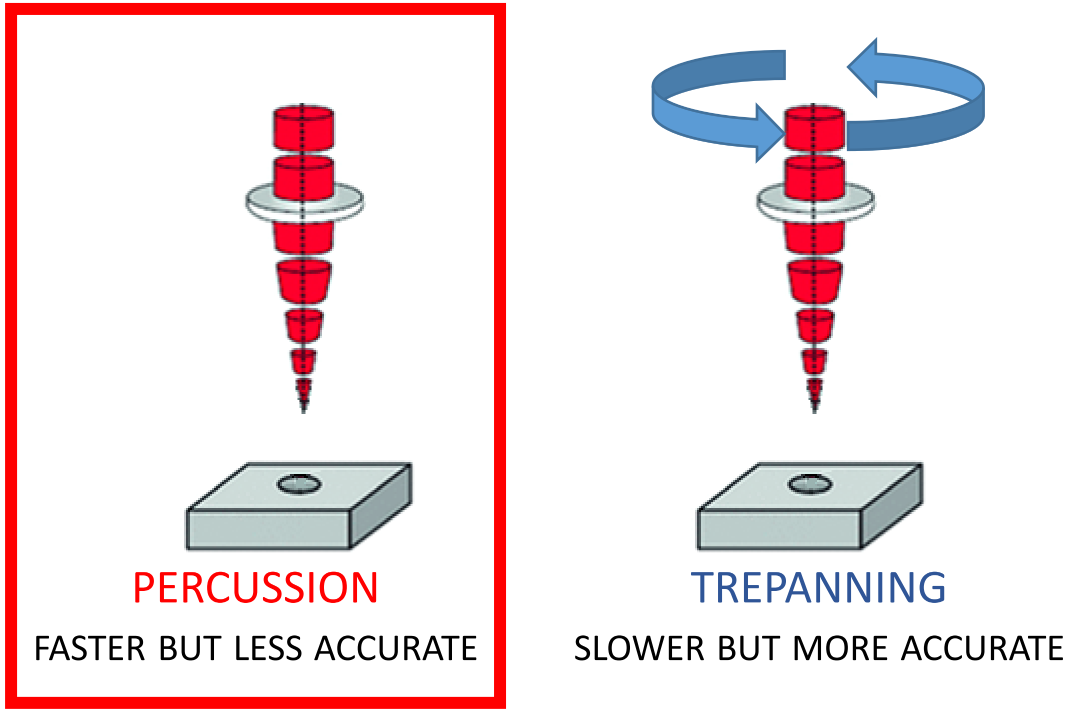
Laser Pulsed Drilling methods

Different drilling methods can be used for the production of Shaped Holes.

To maximize shaped holes quality while minimizing the drilling time per single hole, it was decided to perform:



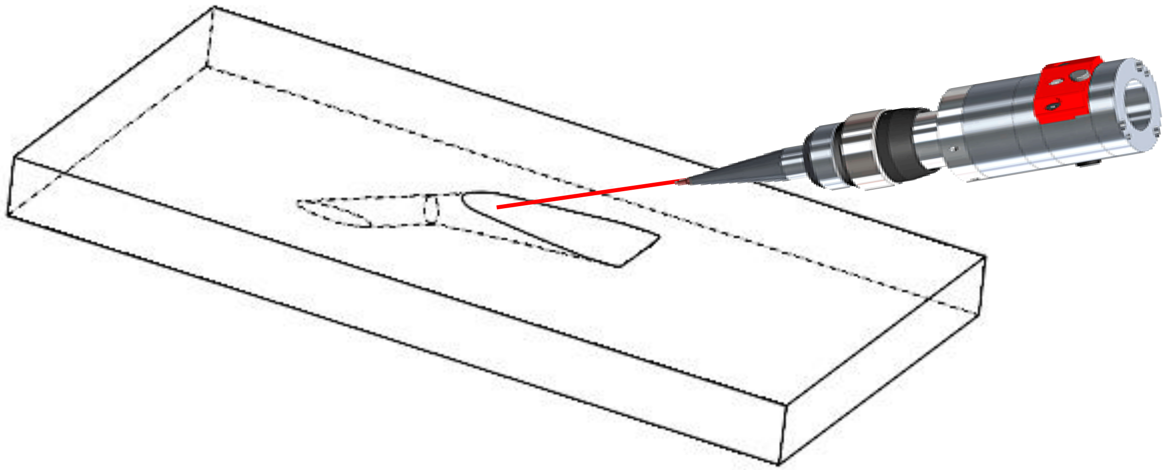
- **Phase I:** **Percussion Drilling**
- **Phase II:** **Trepanning**
- **Phase III:** **Percussion Drilling**



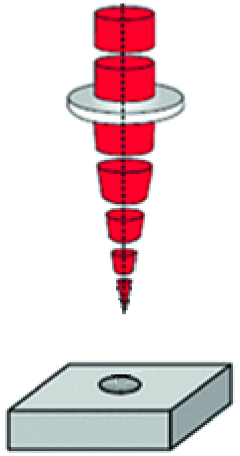
Laser Pulsed Drilling methods

Different drilling methods can be used for the production of Shaped Holes.

To maximize shaped holes quality while minimizing the drilling time per single hole, it was decided to perform:

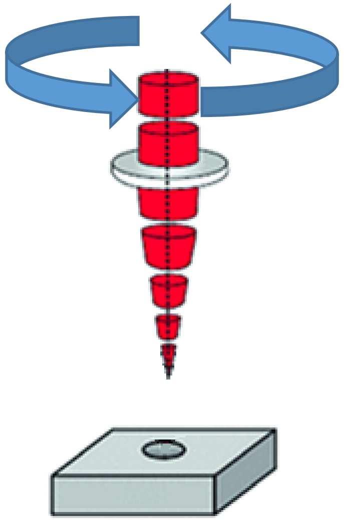


- **Phase I: Percussion Drilling**
- **Phase II: Trepanning**
- **Phase III: Percussion Drilling**



PERCUSSION

FASTER BUT LESS ACCURATE



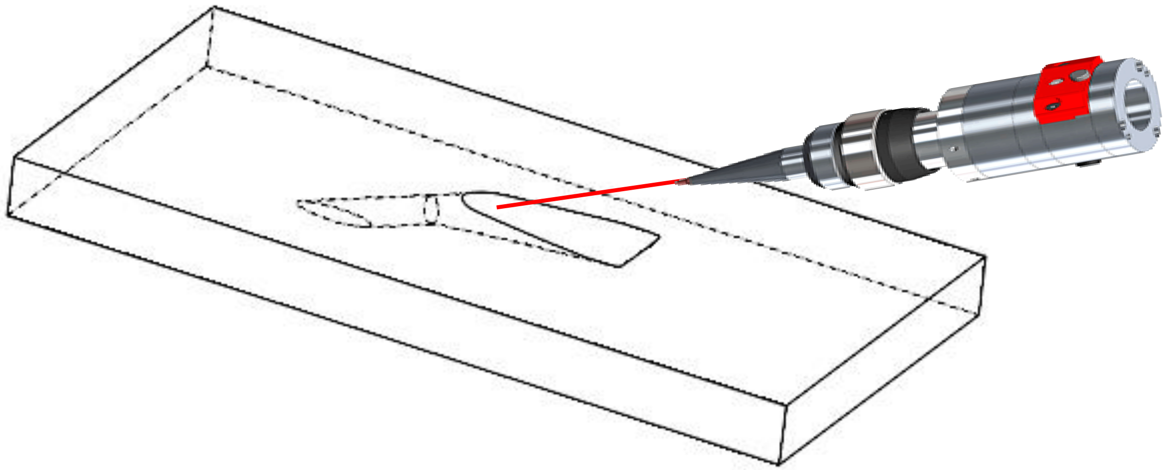
TREPANNING

SLOWER BUT MORE ACCURATE

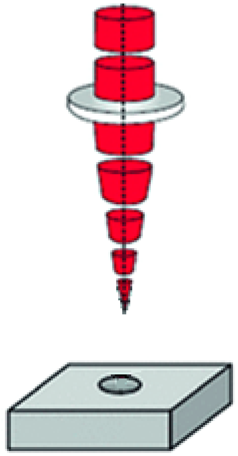
Laser Pulsed Drilling methods

Different drilling methods can be used for the production of Shaped Holes.

To maximize shaped holes quality while minimizing the drilling time per single hole, it was decided to perform:

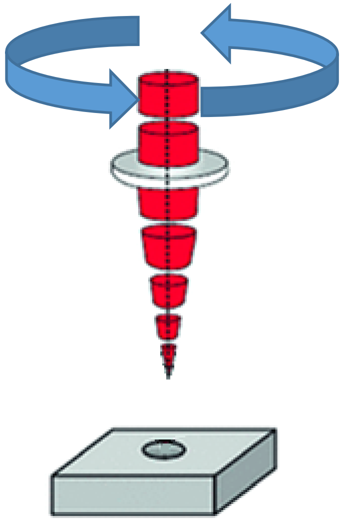


- **Phase I: Percussion Drilling**
- **Phase II: Trepanning**
- **Phase III: Percussion Drilling**



PERCUSSION

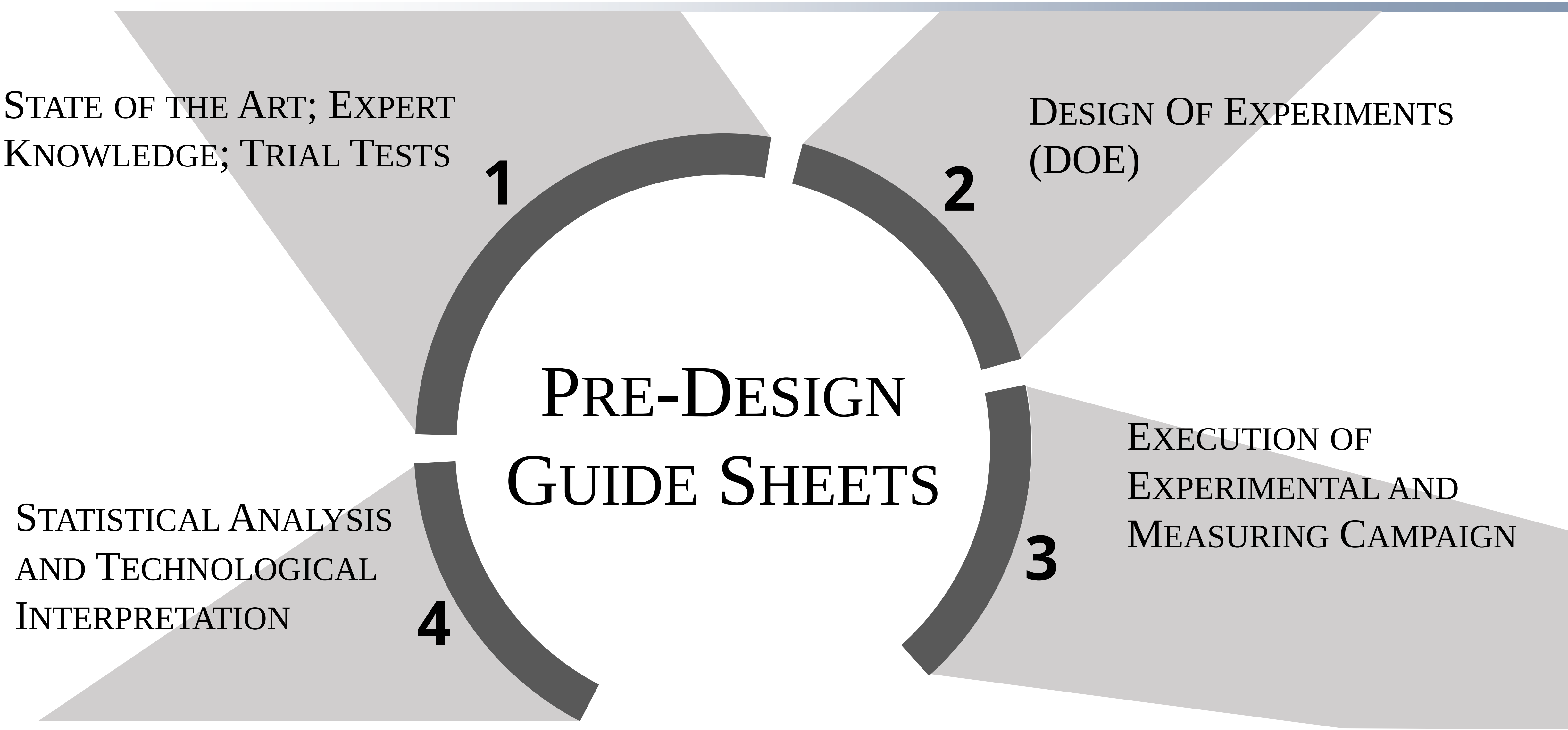
FASTER BUT LESS ACCURATE



TREPANNING

SLOWER BUT MORE ACCURATE

Systematic approach to planning for a Designed Industrial Experiment



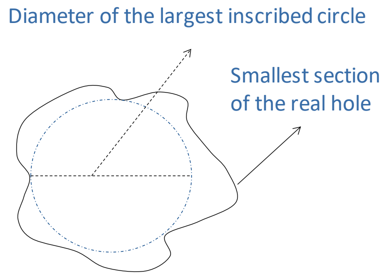
Experimental Equipment – Laser System

LASERDYNE 606D (1200/12000 LS)

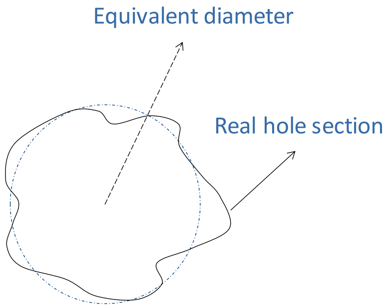
- **Work area**
  X 600 mm – Y 600 mm – Z 600 mm
  BeamDirector®: C 900 deg – D 300 deg
- **Axis speed**
  X, Y, Z: 50 m/min
  BeamDirector®: 90 RPM
- **Laser source**
  Fiber QCW **1200/12000** W pulsed fiber laser
- **System 94P Interface**
- **Special features**
  - **PSC** → **Part Surface Control**
  - **OFC** → **Optical Focus Control**
- **Assist Gas**
  O_2, N_2

Measuring Equipment

PIN GAUGE

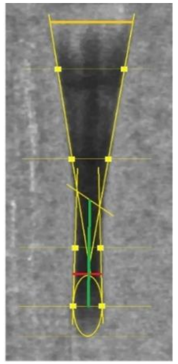


PNEUMATIC GAUGE



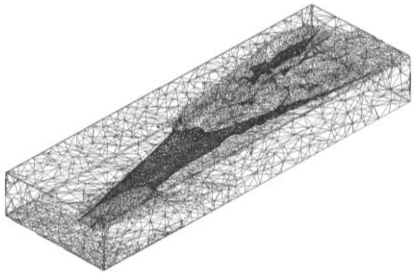
DIGITAL MICROSCOPE

X-RAY ANALYSIS



Shaped Hole

X-RAY TOMOGRAPHY ANALYSIS



Avio Aero A GE Aviation Business

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

History of the project

2016	2017	2018	2019	2019/2020
***D. Siviero* [a]**	***V. Amato* [b], *A. Panetta* [c]**	***B. Tonin* [d], *A. Di Napoli* [c]**	***S. Ambrosio* [d], *I. Bellotta* [c]**	***A. Tartaglione* [d]**
Statistical approach in aerospace industry innovation. A case study: the shaped holes drilling process	*Experimental study for shaped holes manufacturing by fiber laser technology for aerospace applications*	*Experimental study for shaped holes manufacturing by fiber laser technology for aerospace superalloys: statistical approach and technological interpretation*	*Design and optimization of laser drilling process for the production of shaped holes on aerospace superalloy via statistical approach*	*Optimization and industrialization of the laser drilling process for the production of shaped holes on aerospace superalloys via statistical methods*

Analysis and optimization of laser drilling process and control of the shaped holes via advanced statistical methods

Research contract between GE Avio and the Department of Industrial Engineering (DII) of University of Naples Federico II, in partnership with the Department of Engineering of University of Campania Luigi Vanvitelli and the University of Rome Tor Vergata.

(a) Università degli Studi di Napoli Federico II – Corso di Laurea Magistrale in Ingegneria Aerospaziale
(b) Università degli Studi di Napoli Federico II – Corso di Laurea Magistrale in Ingegneria Gestionale
(c) Università degli Studi della Campania Luigi Vanvitelli – Corso di Laurea Magistrale in Ingegneria Meccanica
(d) Università degli Studi di Napoli Federico II – Corso di Laurea Magistrale in Ingegneria Meccanica per la Progettazione e la Produzione – MEAP (Manufacturing Engineer Advanced Program)

History of the project

Experimental Trial I

First approach on drilling process by laser percussion drilling

Experimental Activity II (EA II)

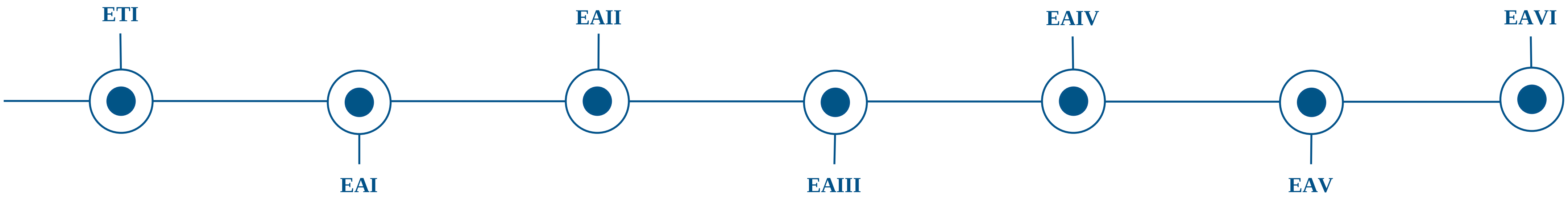
First experimental study on Phase I with 1200/12000 LS

Experimental Activity IV (EA IV)

- Second experimental study on Phase I with 1200/12000 LS
- Selection of best treatment to perform Phase I and Phase III by percussion

Experimental Activity VI (EA VI)

- Improvement of the previously achieved results
- Evaluation of cooling efficiency corresponding to the holes produced through flow tests with PSP technique
- Laser drilling on real test case



Experimental Activity I (EA I)

- Experimental study on Phase I with 900/9000 LS
- Statistical comparison of measuring methods

Experimental Activity III (EA III)

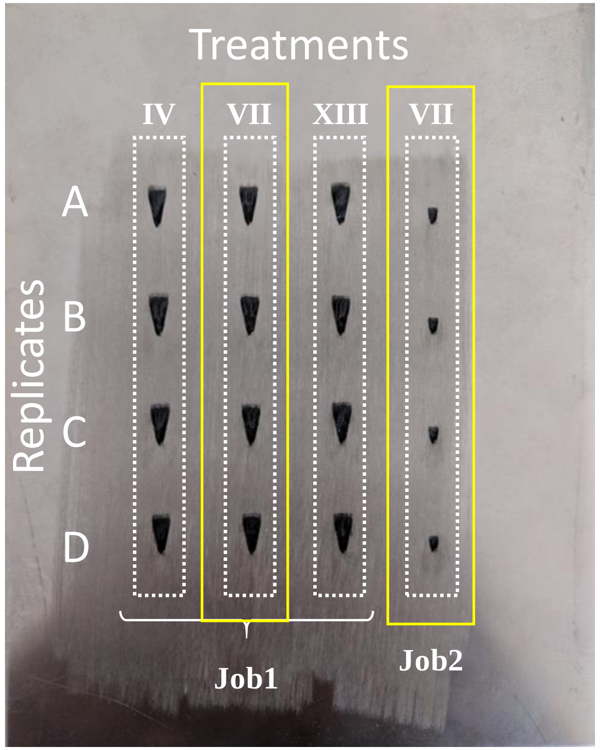
Comparison of results obtained by 900/9000 LS and 1200/12000 LS

Experimental Activity V (EA V)

- Experimental study on Phase II with 1200/12000 LS
- Selection of best treatment to perform Phase II by trepanning

Shaped Holes for X-Ray Tomography

The validation of geometrical and metallurgical characteristics of the produced shaped holes required the execution of **X-Ray Tomography for 3D evaluation**.



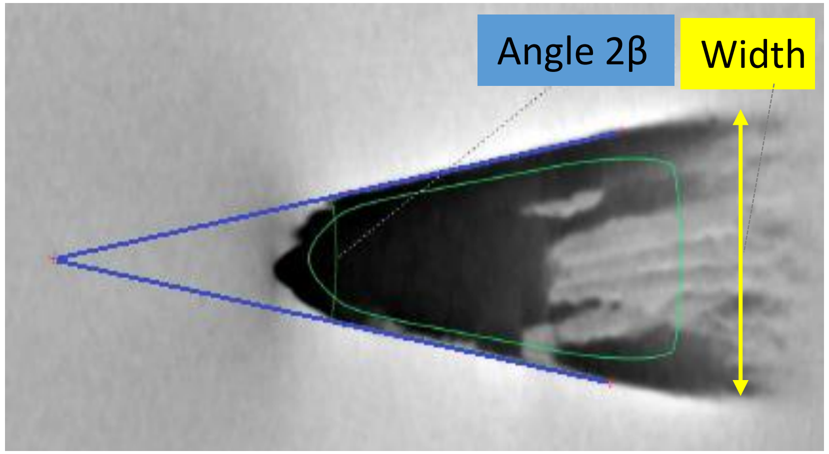
In previous thesis work, four sets of shaped holes were produced with the laser parameters assets (*treatments*) that had returned compliant results in terms of both geometrical and metallurgical characteristics, to be scanned by X-Ray Tomography.

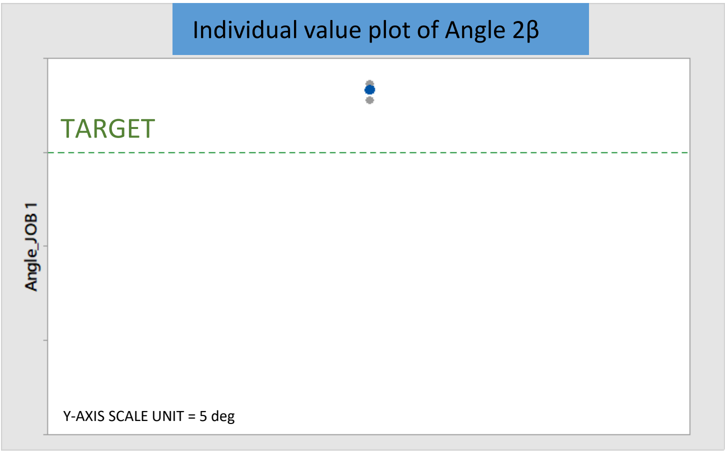
Treatment VII had returned the best results for both Job 1 and Job 2.

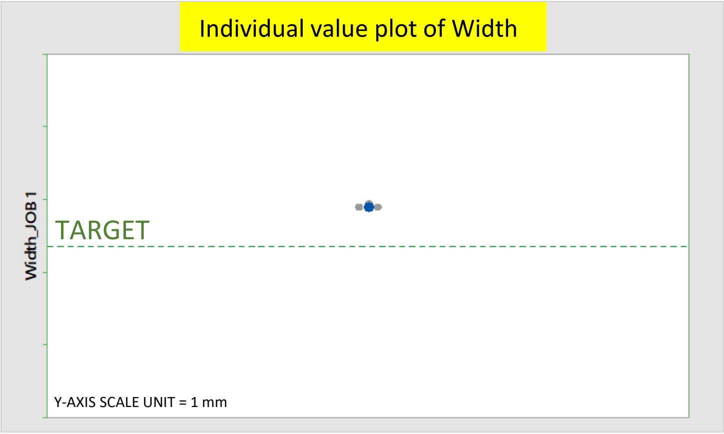
As the necessary equipment is not available at the company, this activity was commissioned to an **external certified laboratory**.

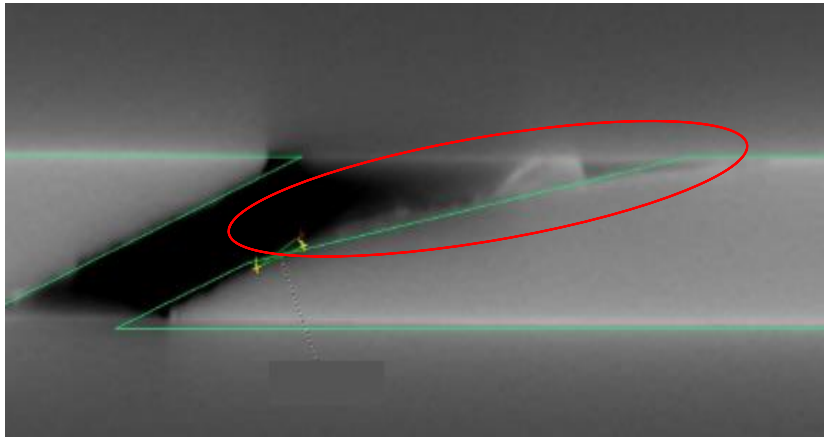
X-Ray Tomography results: Diffuser width, angle 2β and angle γ

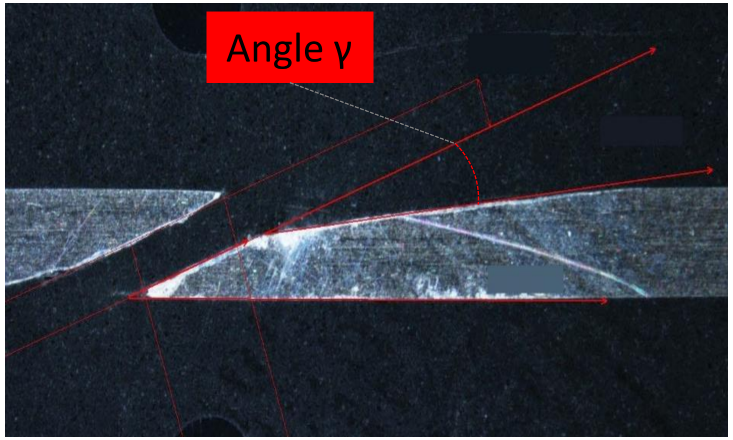
Tomographic analysis highlighted a slightly wider diffuser for both Job1 and Job2 (results are reported for Job1 only).

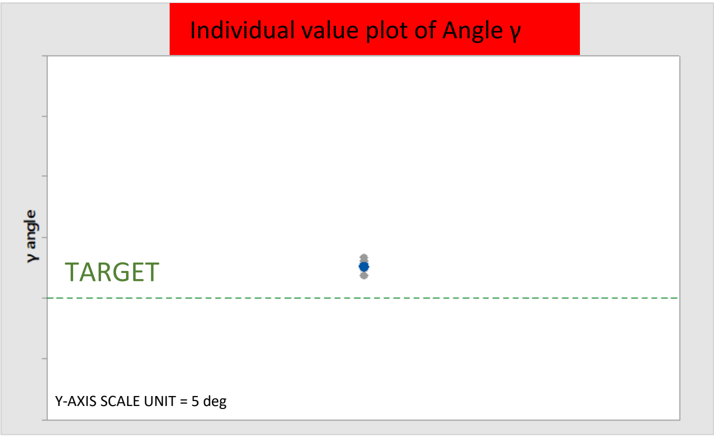








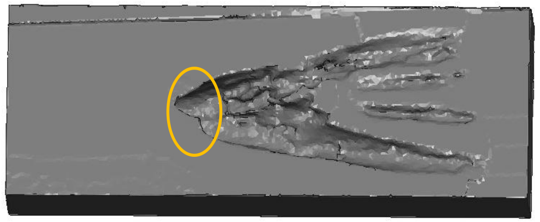


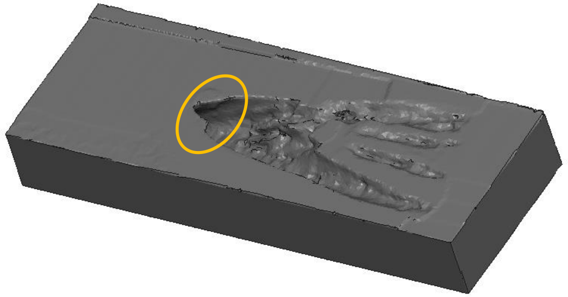


X-Ray Tomography results: diffuser defects

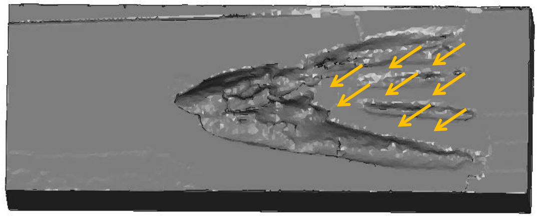
Beyond the information obtained on geometric characteristics, the added value of tomographic analysis refers to some critical issues pointed out about the quality of shaped holes with Job 1 geometry:

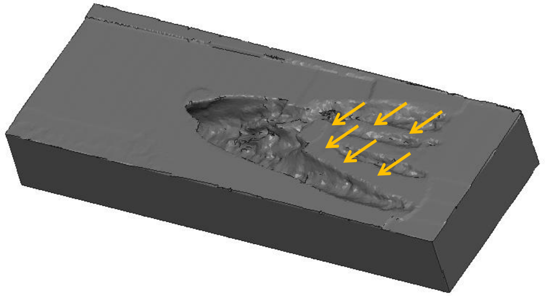
- **asymmetrical shape** of the diffuser





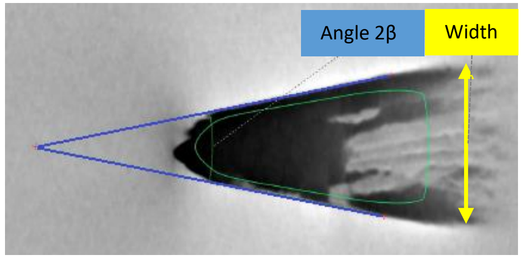
- mixture of **oxide** and **recast layer** in the diffuser



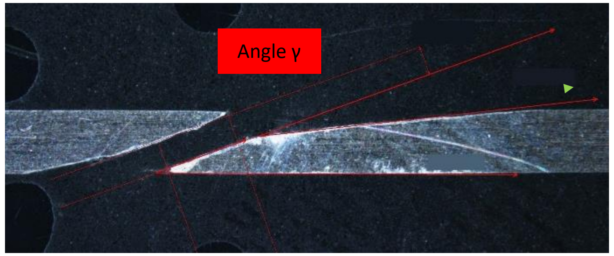


Optimization of diffuser size and quality

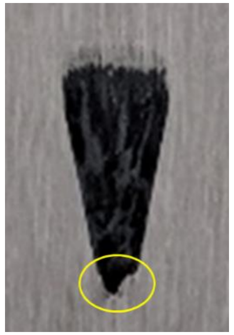
Three sets of experiments were designed and executed to improve the diffuser size and quality and to meet the assigned requirements:



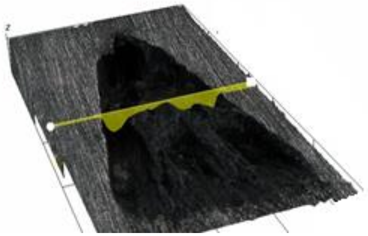
Diffuser width and angle larger than nominal value



Diffuser slope larger than nominal value



Asymmetry

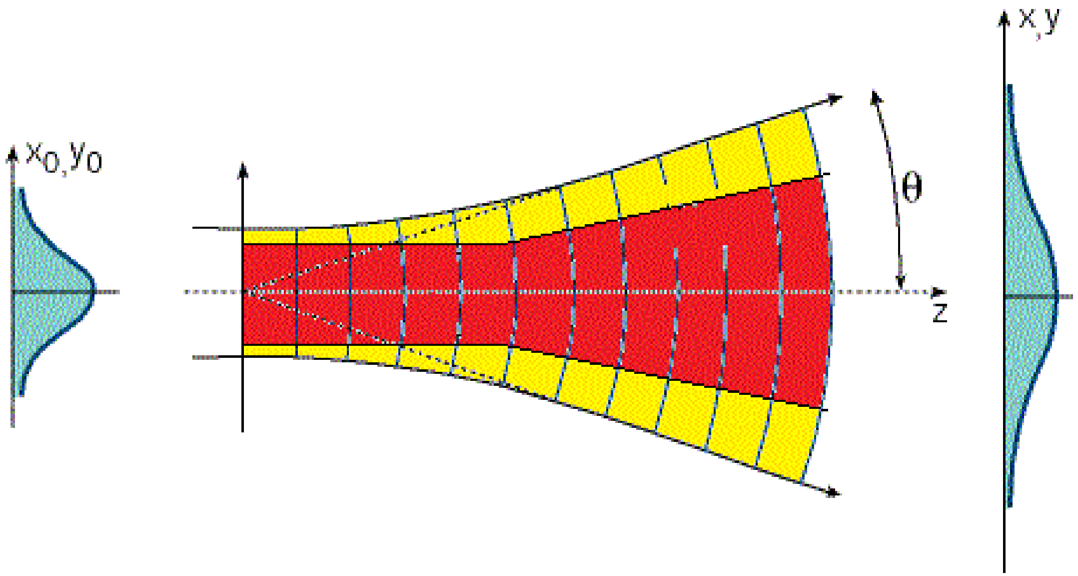


Recast layer

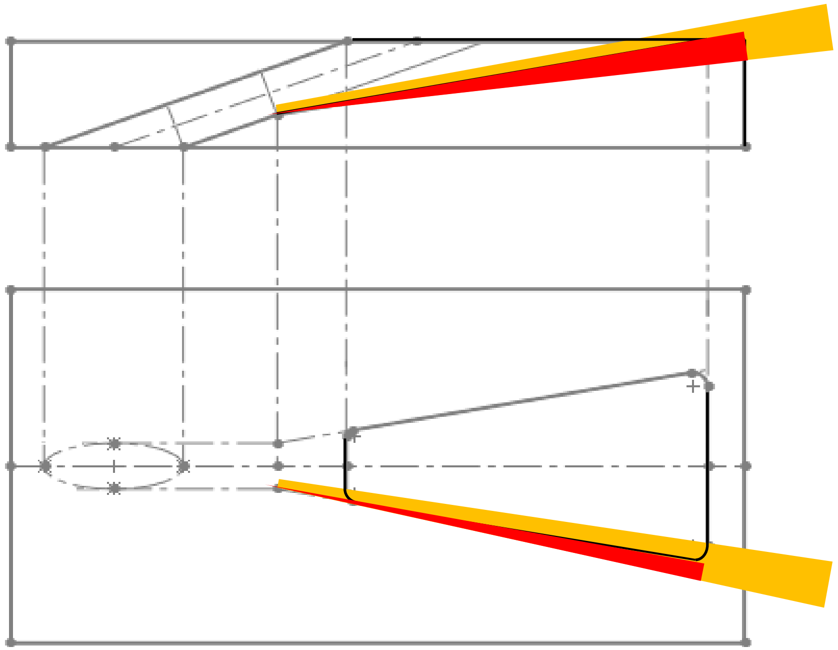
Proposed solution: **beam angle compensation**

Proposed solution: **variation of laser beam pathway**

SH optimization: Beam angle compensation



Based on the results of the X-Ray tomography and the theoretical considerations about the laser beam characteristics, an angle compensation was introduced: the laser beam movement was modified in order to achieve the geometrical targets. It allowed to **reduce by 23% the drilling time** per single hole.



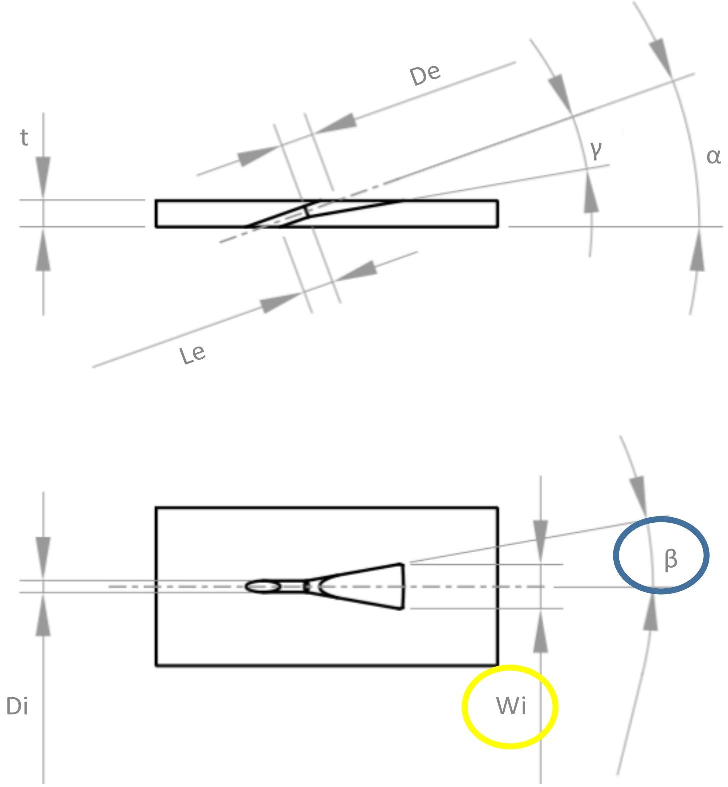
Diffuser slope

Diffuser width and angle

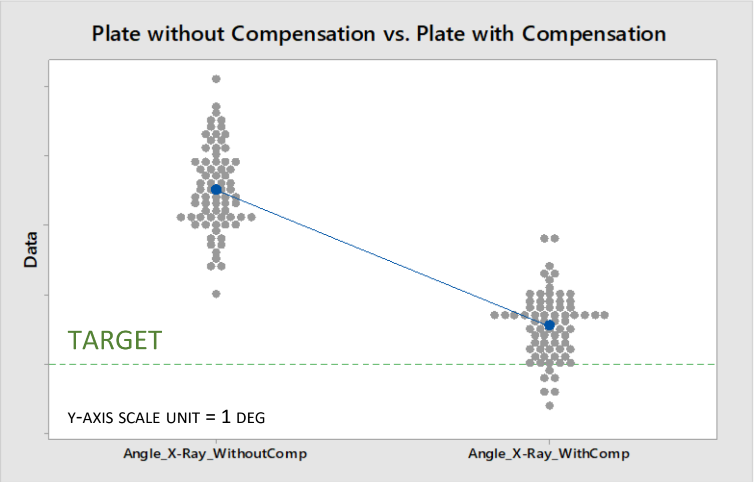
- The beam has an hyperboloid shape.
- The irradiance has a Gaussian profile, so the effectiveness of the laser drops far from the axis.

Results of the angle compensation: Angle 2β and Width by X-Ray

Job 1

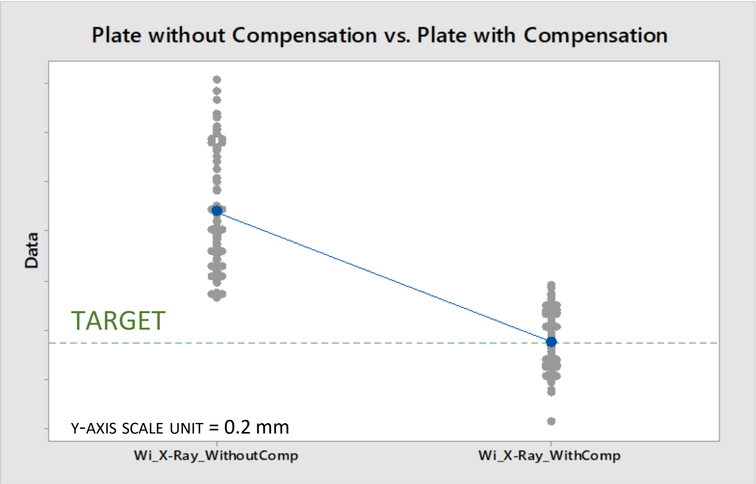


Without Angle Compensation	With Angle Compensation
	



- Different variances (p-value = 0.000)
- Different means (p-value = 0.000)

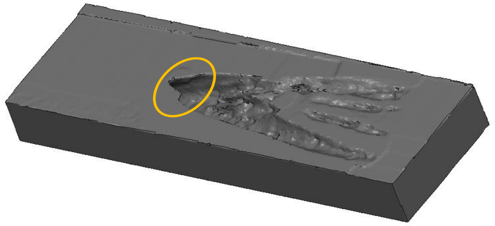
Without Angle Compensation	With Angle Compensation
	



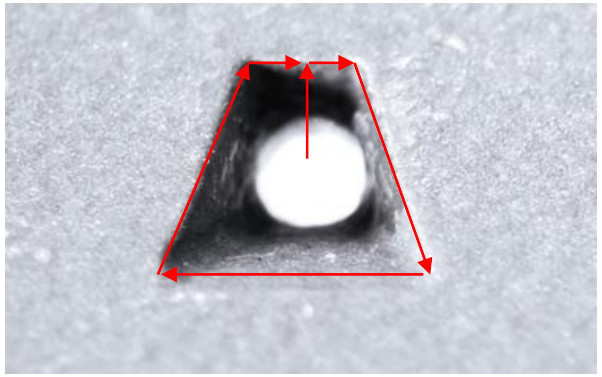
- Different variances (p-value = 0.038)
- Different means (p-value = 0.000)

SH optimization: solutions to the diffuser asymmetry

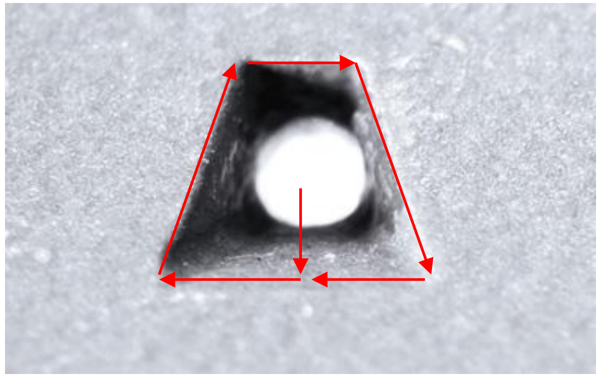
In order to understand the source of the diffuser asymmetry and to eliminate it, the pathway of the beam in Phase II was varied, holding the laser parameters setting constant.



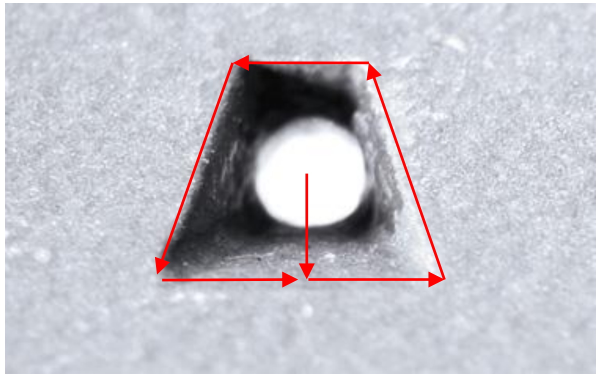
Test 1: Clockwise starting from the top – standard.



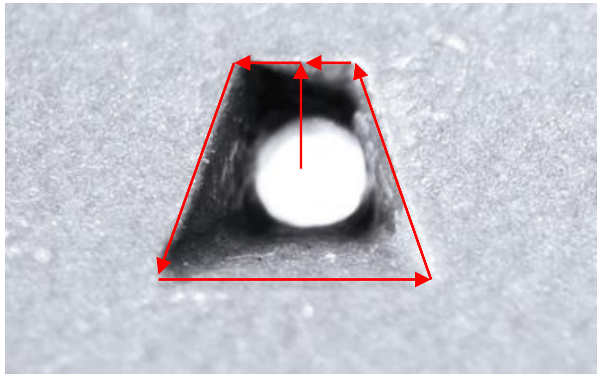
Test 2: Clockwise starting from the bottom.



Test 3: Counterclockwise starting from the bottom.



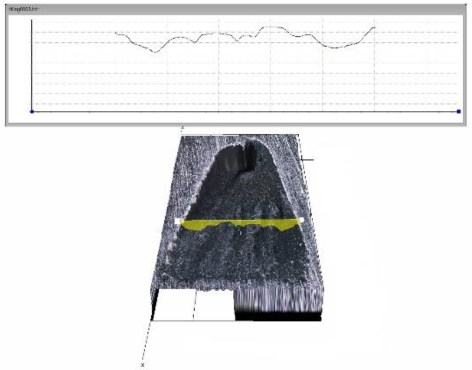
Test 4: Counterclockwise starting from the top.



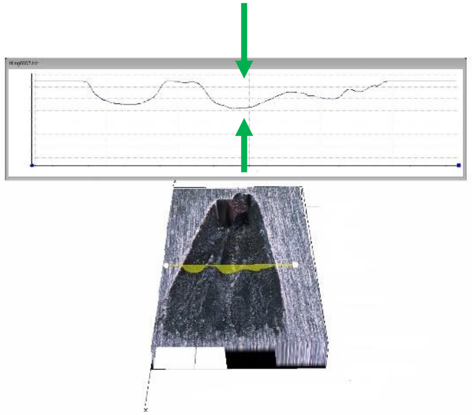
SH optimization: achieved results for the diffuser asymmetry

All the produced holes were observed through digital microscopy. In addition, surface profiles were extracted for each hole in different sections along its axis to evaluate the presence and the amount of the recast layer.

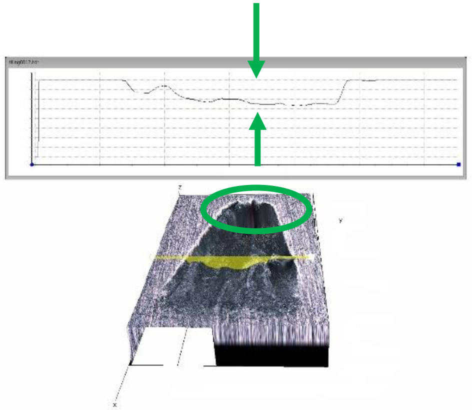
Clockwise starting from the top – standard.



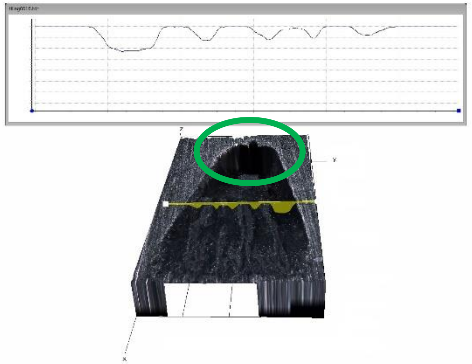
Clockwise starting from the bottom.



Counterclockwise starting from the bottom.



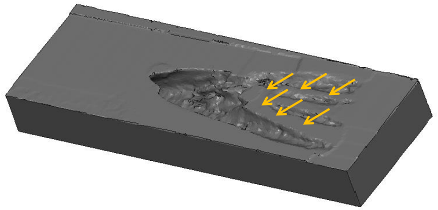
Counterclockwise starting from the top.



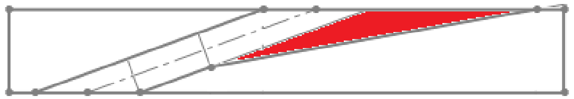
Microscopical analysis pointed out that:

- ''counterclockwise'' pathways allowed to reduce the asymmetry and even to avoid it, probably because of the efficiency of electric motors and the inertias of laser head, that could be slightly different depending of the actual spin direction;
- in addition, ''starting from the bottom'' pathways turned out to reduce the recast layer on the diffuser floor. Probably, the switch of direction on the diffuser floor leads to a longer interaction between the laser beam and the material and an extended action of assistant gas.

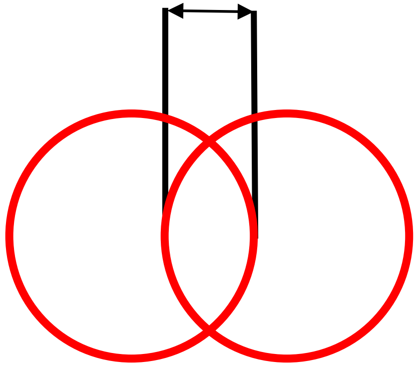
SH optimization: solutions to the recast layer in the diffuser



With regards to the presence of recast layer on the diffuser floor, 3 tests were performed:



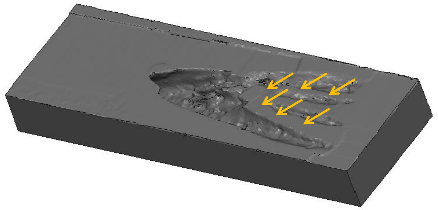
Considering the machining allowance, the overlap of pulses was increased from 50% to 75%.



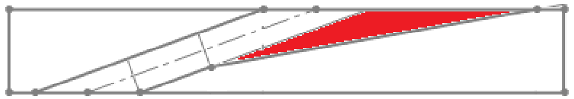
Test 1: **Reduced feedrate** while machining the diffuser floor (Overlap 75%).

Test 2: **Increased** pulse **frequency** while machining the diffuser floor (Overlap 75%).

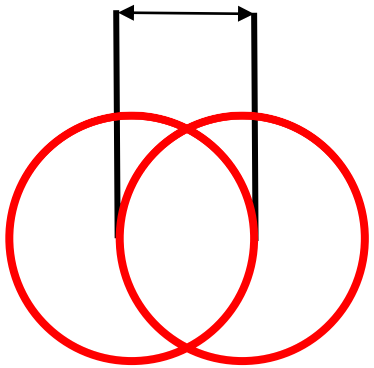
SH optimization: solutions to the recast layer in the diffuser



With regards to the presence of recast layer on the diffuser floor, 3 tests were performed:



Considering the machining allowance, the overlap of pulses was increased from 50% to 75%.

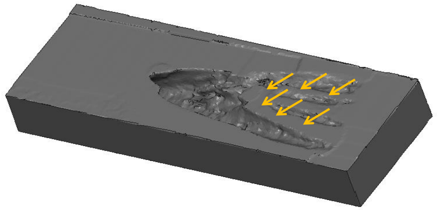


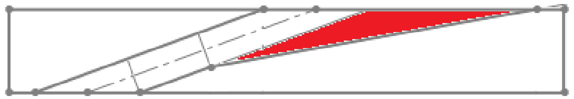
Test 1: **Reduced feedrate** while machining the diffuser floor (Overlap 75%).

Test 2: **Increased** pulse **frequency** while machining the diffuser floor (Overlap 75%).

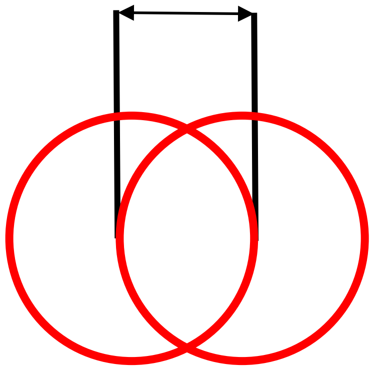
SH optimization: solutions to the recast layer in the diffuser

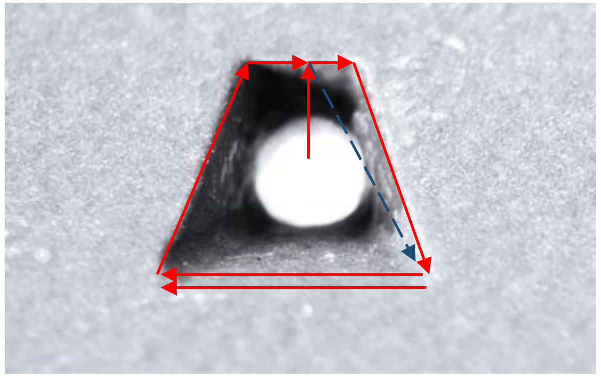
With regards to the presence of recast layer on the diffuser floor, 3 tests were performed:





Considering the machining allowance, the overlap of pulses was increased from 50% to 75%.





Test 1: **Reduced feedrate** while machining the diffuser floor (Overlap 75%).

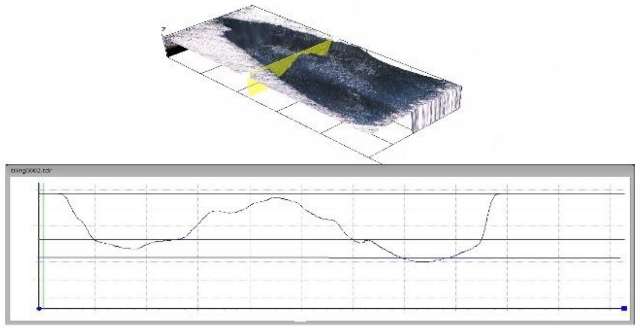
Test 2: **Increased** pulse **frequency** while machining the diffuser floor (Overlap 75%).

Test 3: **Double scan** on the diffuser floor, holdind the laser parameters setting constant.

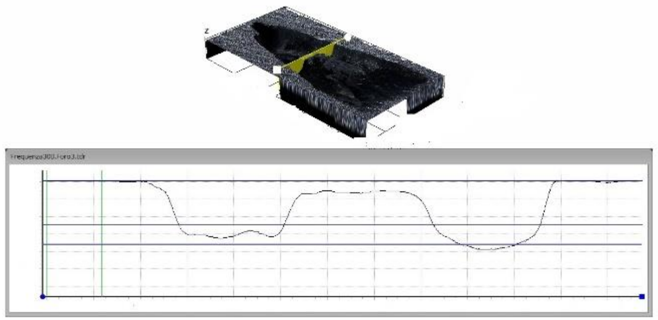
SH optimization: achieved results for recast layer in the diffuser

All the produced holes were observed through digital microscopy to evaluate the presence of the recast layer. As well as for previous tests, surface profiles were extracted for each hole in different sections along its axis to evaluate the amount of the recast layer. To comply with assigned requirements, profiles should be contained within the 2 straight lines.

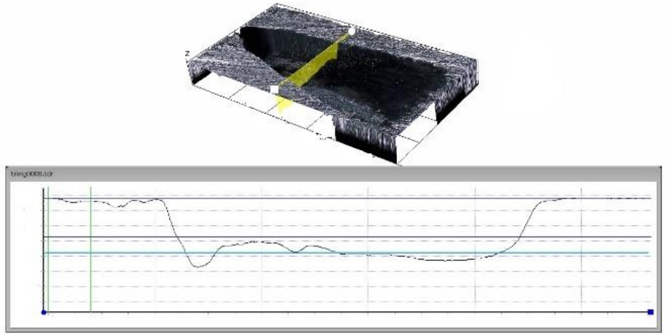
1) **Test 1**: reduced feedrate (Overlap 75%)



Test 2: increased pulse frequency (Overlap 75%)



Test 3: double scan



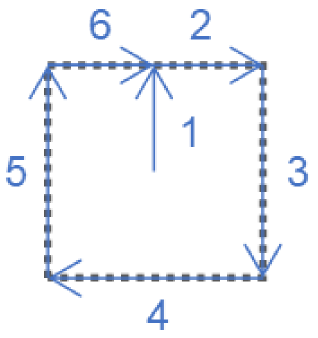
Microscopical analysis pointed out that recast layer in the diffuser can be avoided by performing a double scan in the diffuser floor area.

SH optimization: Optimal drilling strategy (*best practice*)

Based on the results achieved in previous tests, optimal drilling strategy was defined by further modifying the beam pathway to avoid unnecessary idle movements (with laser beam turned off) of the laser head. The only idle movement in the pathway in path section 7 (grey dotted arrow), which is required to reposition the laser head along the hole axis to perform phase III.

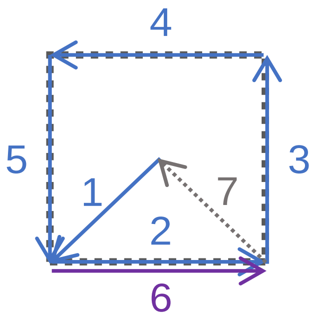
Standard drilling strategy

- Optimal laser parameters
- Beam angle compensation
- *Clockwise – starting from the top* pathway



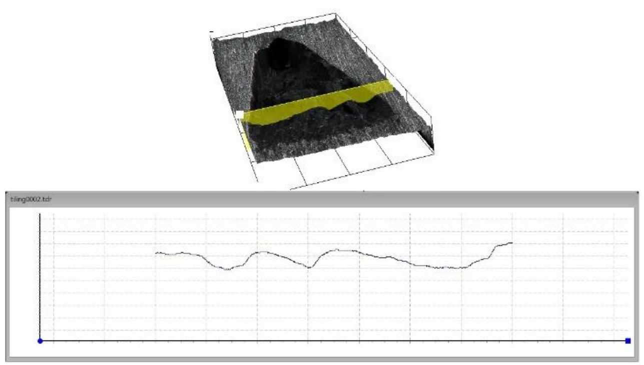
Best practice

- Optimal laser parameters
- Beam angle compensation
- *Counterclockwise – starting from the bottom left corner* pathway

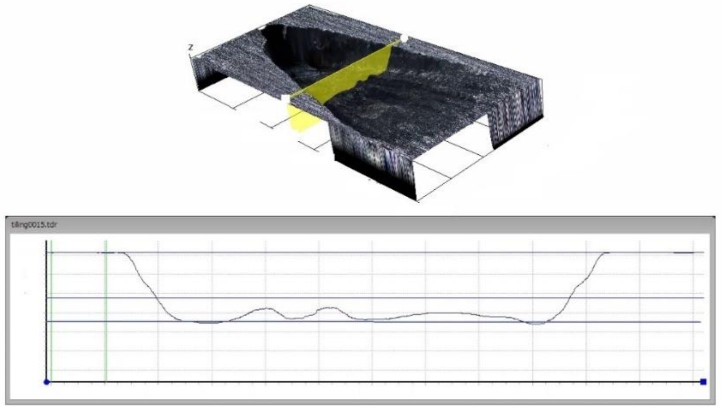


SH optimization: achieved enhancement by using the *best practice*

The quality of the holes produced with this optimal drilling strategy results significantly higher. On the other hand, the double scan has the consequence of increasing the drilling time per single hole, if compared to the stategy with standard beam pathway and beam angle compensation.



Standard drilling strategy

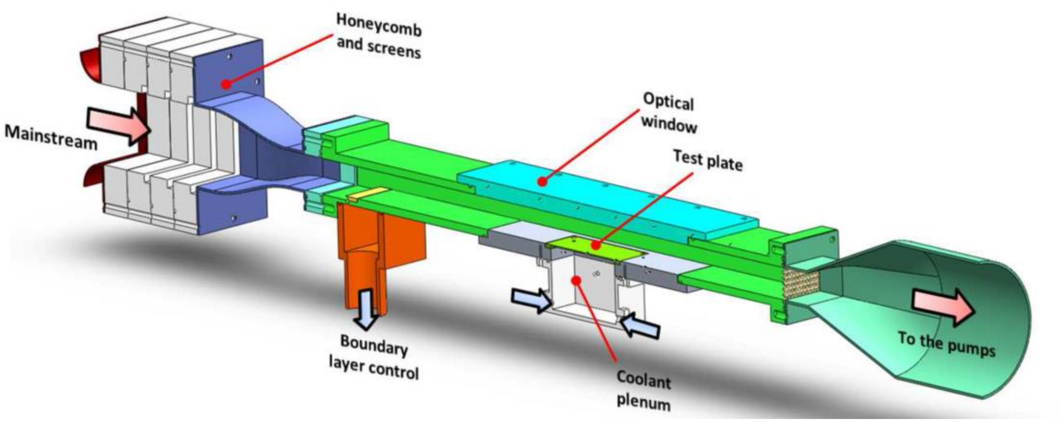


Best practice

Based on results achieved for Job 1, laser beam pathway was modified also for Job 2, involving a counterclockwise movement starting from the bottom without double scan (since the diffuser of Job2 has no slope), so the drilling time per single hole is always the same.

Flow Tests through Pressure Sensitive Paint (PSP) technique

It is an optical measurement method, which measures the film cooling effectiveness on surfaces.



Source DOI: 10.3390/ijtpp4020014

The test plate is coated with a special paint containing an oxygen sensitive tracer and placed in a wind tunnel.

LED lamps of a specific wavelength (UV) are used to excite the pressure-sensitive paint.

Once excited, the pressure-sensitive tracer is transitioned to a higher energy state where it may either emits a photon or be quenched by local oxygen present.

This competing process of emission and quenching determines the intensity response of the paint layer, from which cooling effectiveness can be evaluated

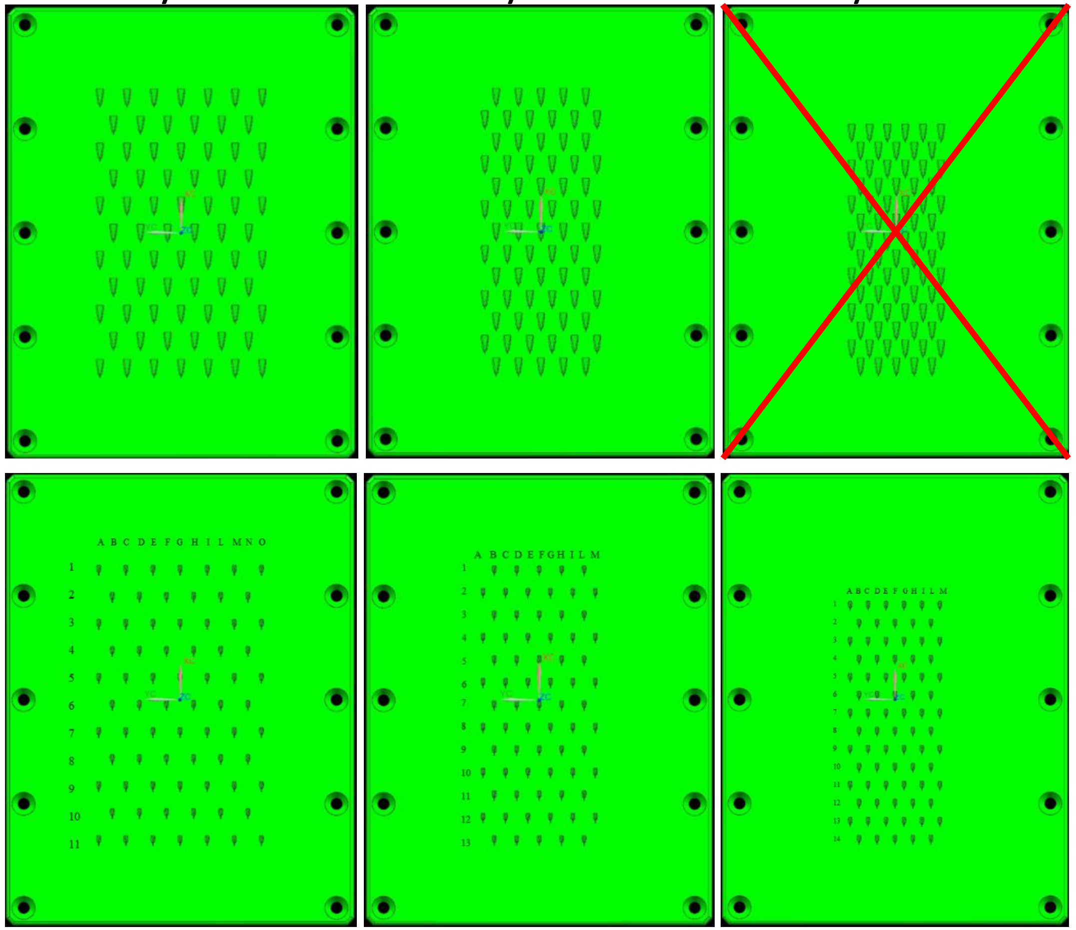
Sample plates for flow tests

3 different layouts of shaped holes were identified to undergo flow tests.

	Layout 1	Layout 2	Layout 3

Job 1

Job 2



The extremely dense holes layouts can cause serious deformation of the plates during laser processing.

Indeed, the *layout 3* for Job 1 turned out to be unfeasible due to the extreme plate warping caused by the combination of the pattern density and the high energy contribution.

For each layout 2 plates were produced.

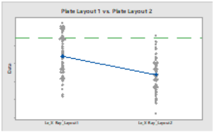
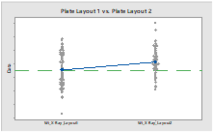
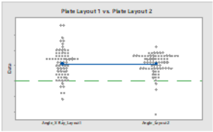
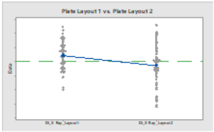
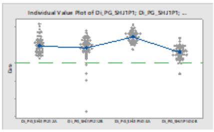
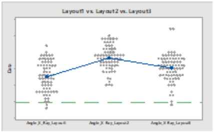
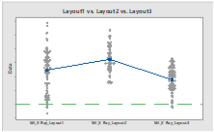
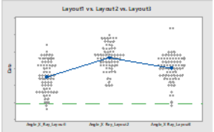
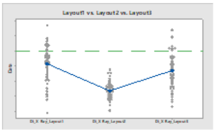
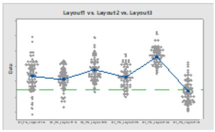
Comparison analyses

To evaluate the variability ascribable to the different layouts, comparison analyses were performed, for both Job 1 and Job 2, in three subsequent steps:

1. Test for Normal distribution.

2. Test for equal variances, with or without the assumption of normally distributed data depending on step 1 results.

3. Test for equal means, with or without the assumption of data with equal variances depending on step 2 results.

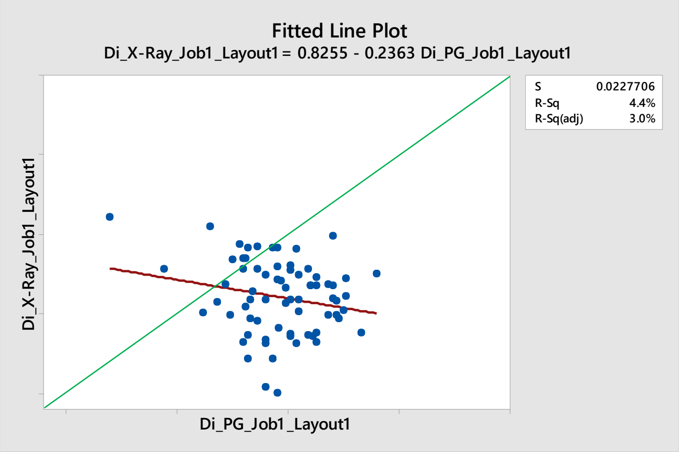
Job 1 = Layout 1 vs. Layout 2					Job 2 = Layout 1 vs. Layout 2 vs. Layout 3				
X-Ray				Pneumatic Gauge	X-Ray				Pneumatic Gauge
Metering Length	**Width**	**Angle 2β**	**Diameter**	**Diameter**	**Metering Length**	**Width**	**Angle 2β**	**Diameter**	**Diameter**
Equal variances (*p*-value = 0.203) **Different means** (*p*-value = 0.000)	**Different variances** (*p*-value = 0.000) **Different means** (*p*-value = 0.001)	**Different variances** (*p*-value = 0.004) Equal means (*p*-value = 0.984)	**Different variances** (*p*-value = 0.000) **Different means** (*p*-value = 0.001)	**Different variances** (*p*-value = 0.000) **Different means** (*p*-value = 0.000)	**Different variances** (*p*-value = 0.000) **Different means** (*p*-value = 0.000)	**Different variances** (*p*-value = 0.000) **Different means** (*p*-value = 0.000)	Equal variances (*p*-value = 0.057) **Different means** (*p*-value = 0.000)	**Different variances** (*p*-value = 0.000) **Different means** (*p*-value = 0.000)	**Different variances** (*p*-value = 0.000) **Different means** (*p*-value = 0.000)
									

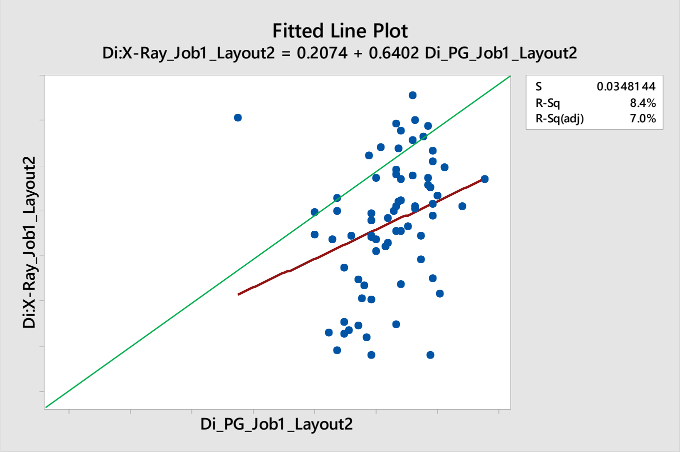
Correlation analyses on diameter: X-Ray vs. Pneumatic gauge

Measurements of the diameter performed through X-Ray and pneumatic gauge resulted **not correlated** with each other.

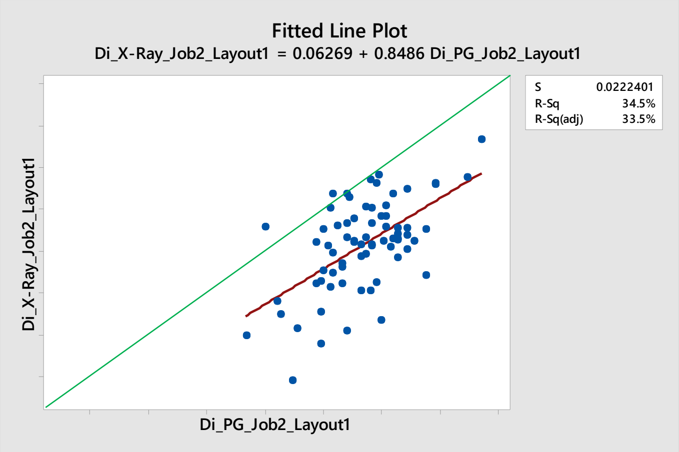
	Layout 1	Layout 2	Layout 3

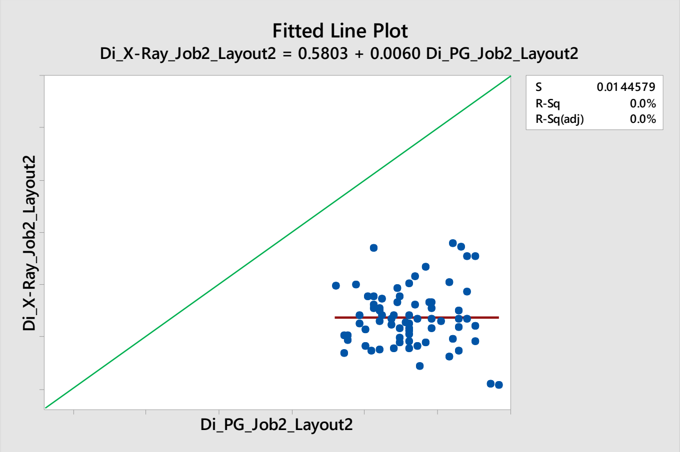
Job 1

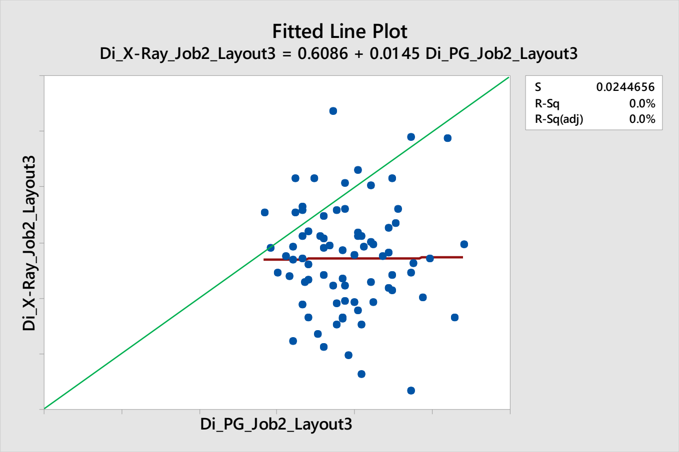




Job 2



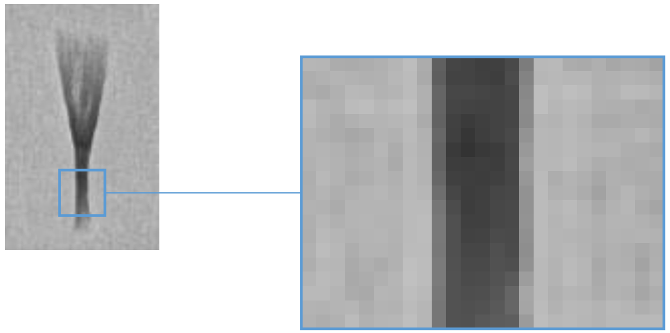




Measuring systems adequacy: X-Ray vs. Pneumatic gauge

X-Ray

It is affected by a **large variability.**



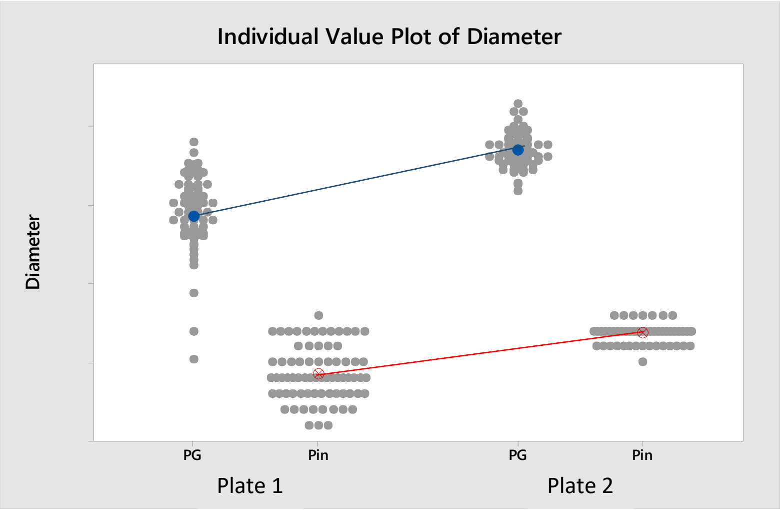
- The diameter measure is subjective due to the low contrast (abruptness) around the hole contour
- Grey scales are likely to result slightly different depending on the plate and on the variability ascribable to scanning operation

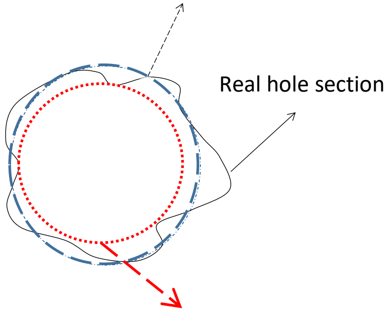
This critical issue negatively affects also measurements of the other geometrical features.

Pneumatic Gauge

It is affected by **a systematic error** – it overestimates the actual diameter – due to the fact that it is conceived for measuring cylindrical hole perpendicular to the surface, rather than sloped shaped holes.

However, it is affected by a **low variability** and results suitable to reliably detect differences between hole diameters.

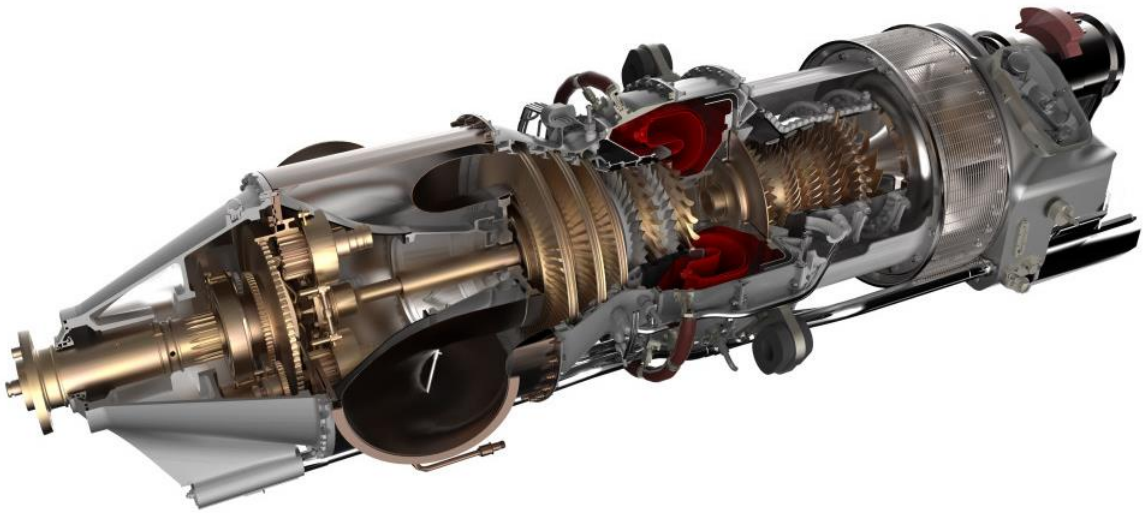




The mean difference detected through the pneumatic gauge and the pin gauge is almost the same.

In light of this, the most reliable measuring technique for measuring Diameter is the Pneumatic Gauge (after being properly calibrated for measurement of shaped holes).

Production of the Shaped Holes on a real test case

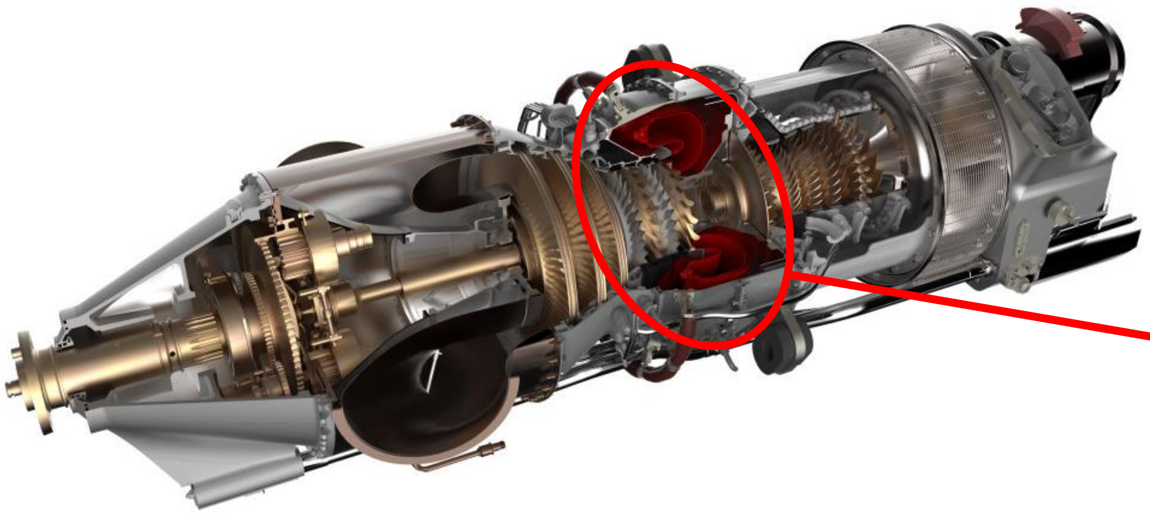


The image is only intended to be indicative and not exhaustive

A further aim of the experimental activity is to achieve the necessary know-how to produce shaped holes on a real aeronautical combustion chamber.

The first application may refer to the liner outer of a generic reverse flow combustor.

Production of the Shaped Holes on a real test case

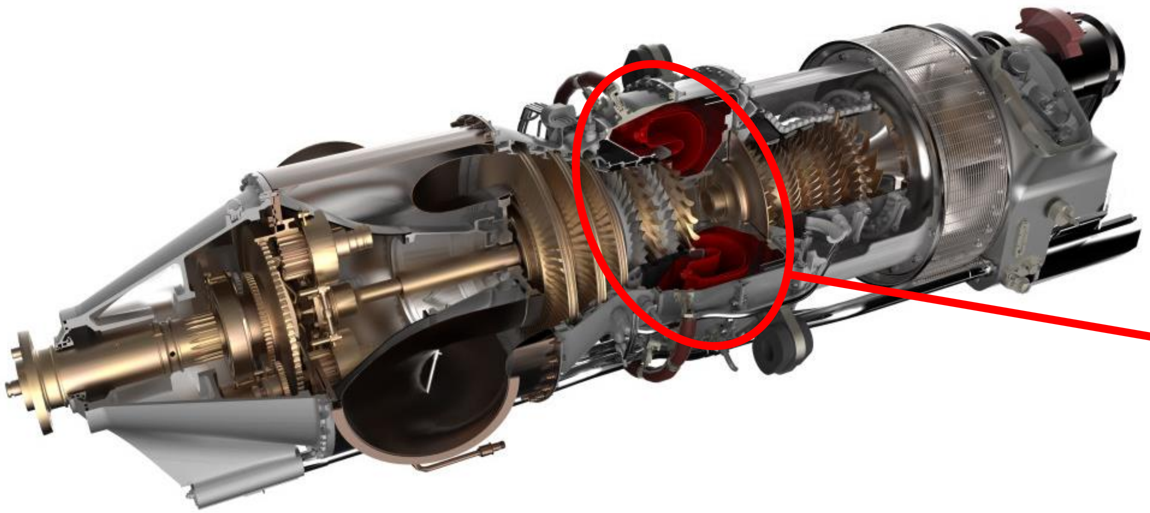


The image is only intended to be indicative and not exhaustive

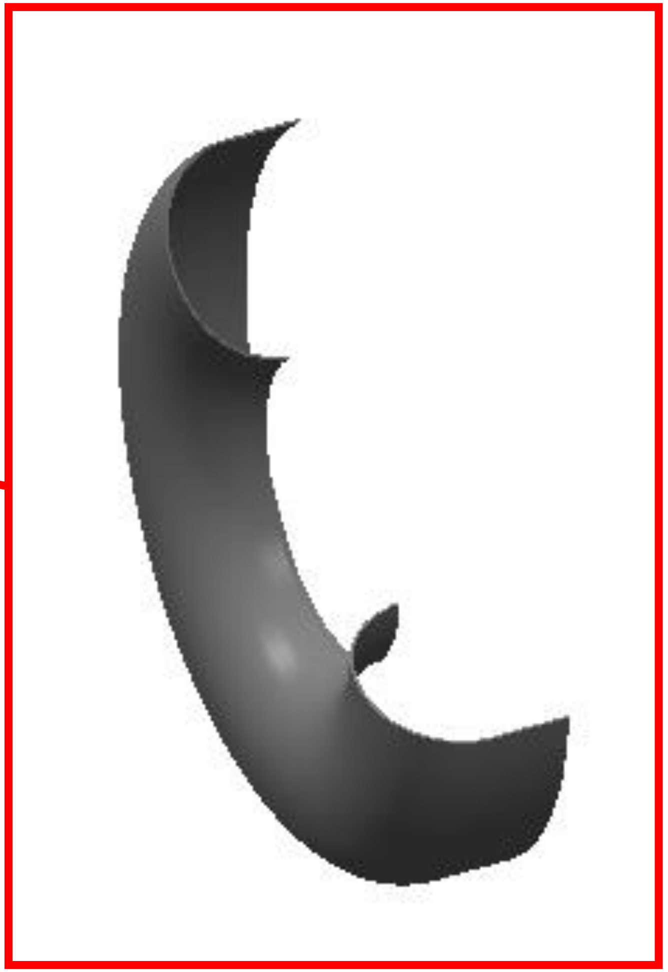
A further aim of the experimental activity is to achieve the necessary know-how to produce shaped holes on a real aeronautical combustion chamber.

The first application may refer to the liner outer of a generic reverse flow combustor.

Production of the Shaped Holes on a real test case



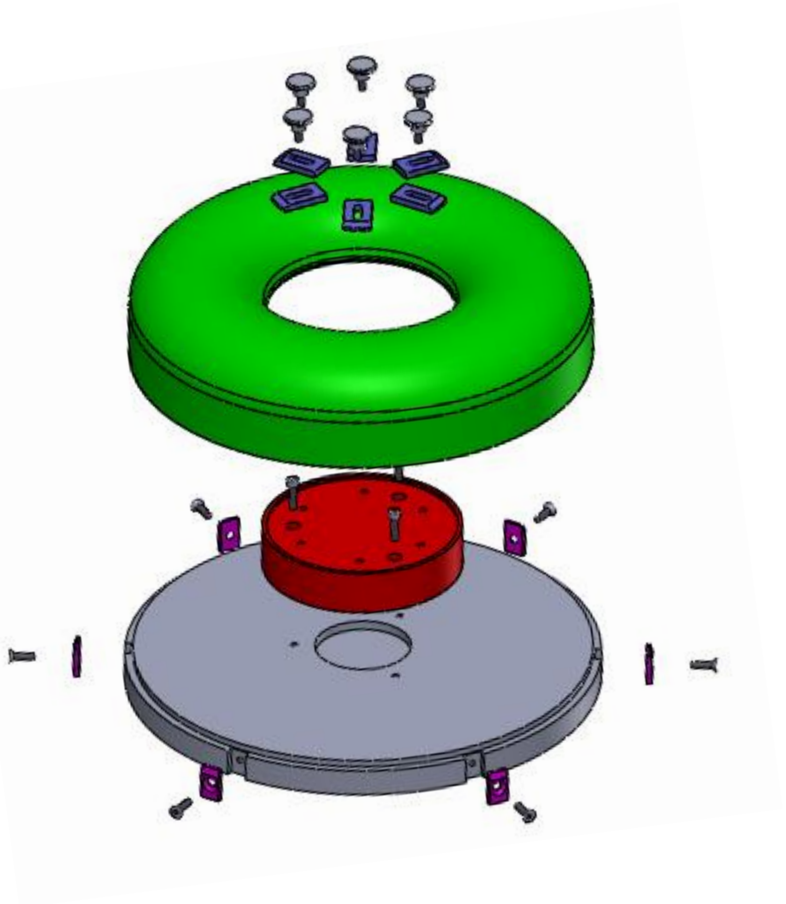
The image is only intended to be indicative and not exhaustive

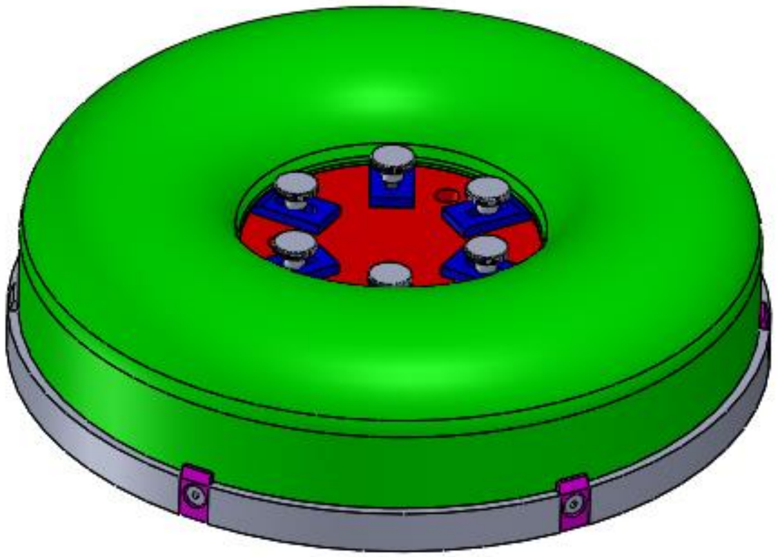


A further aim of the experimental activity is to achieve the necessary know-how to produce shaped holes on a real aeronautical combustion chamber.

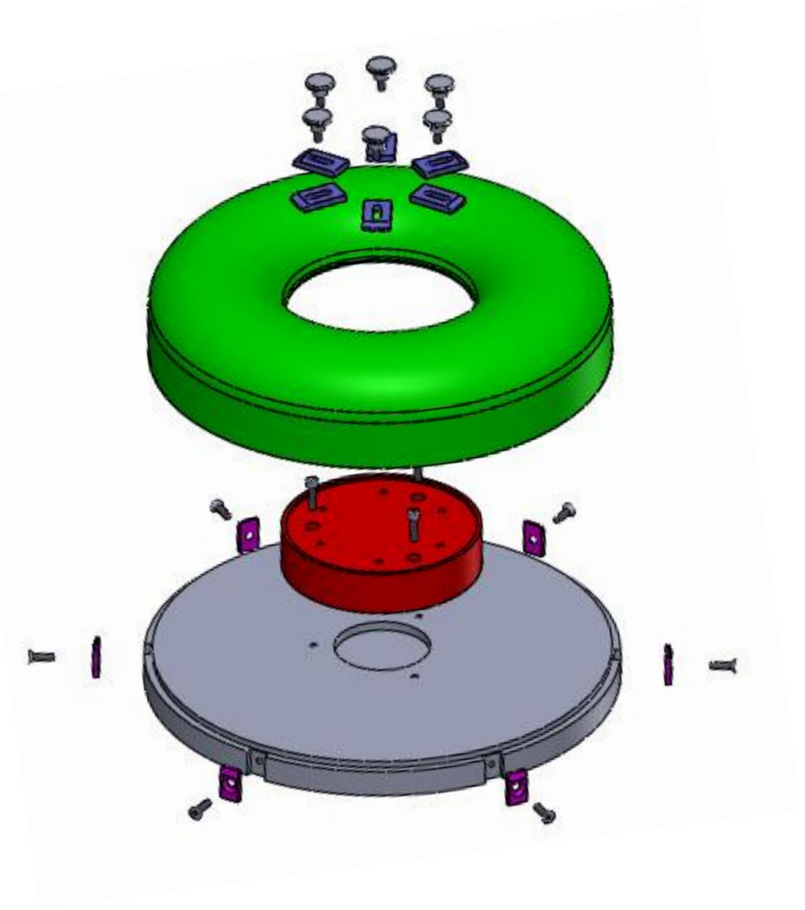
The first application may refer to the liner outer of a generic reverse flow combustor.

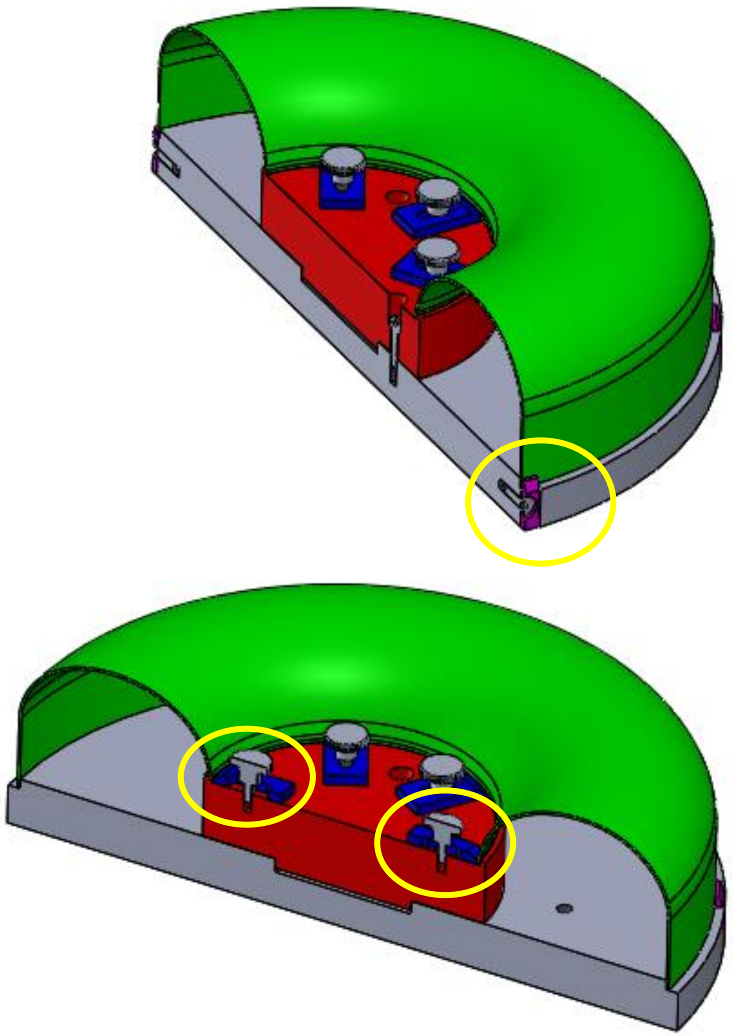
Design and production of the support structure



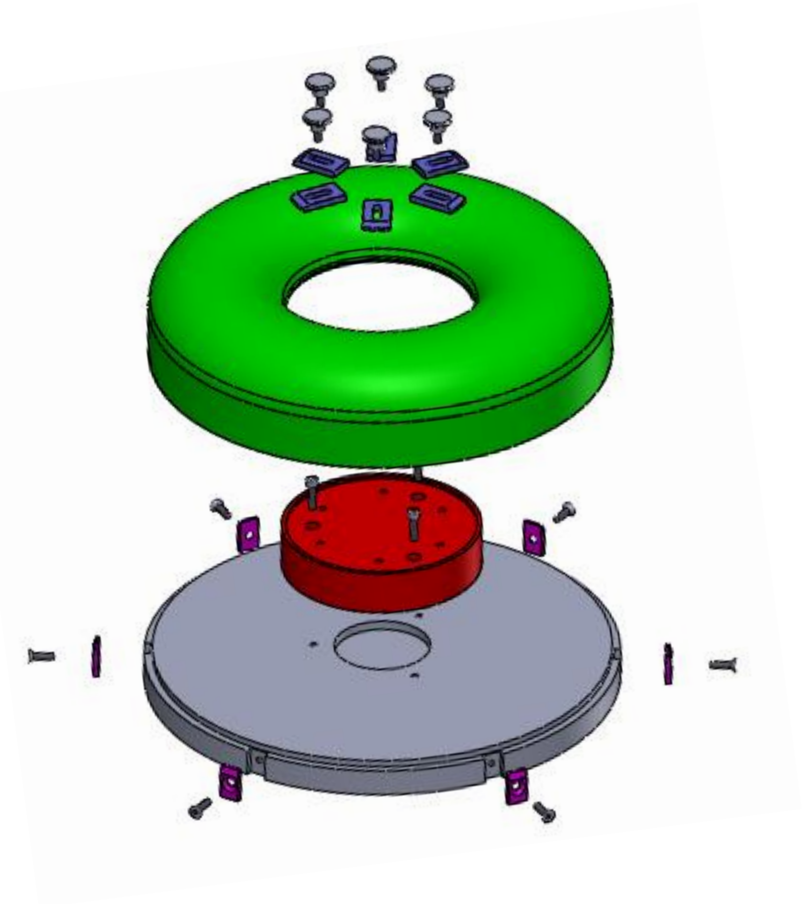


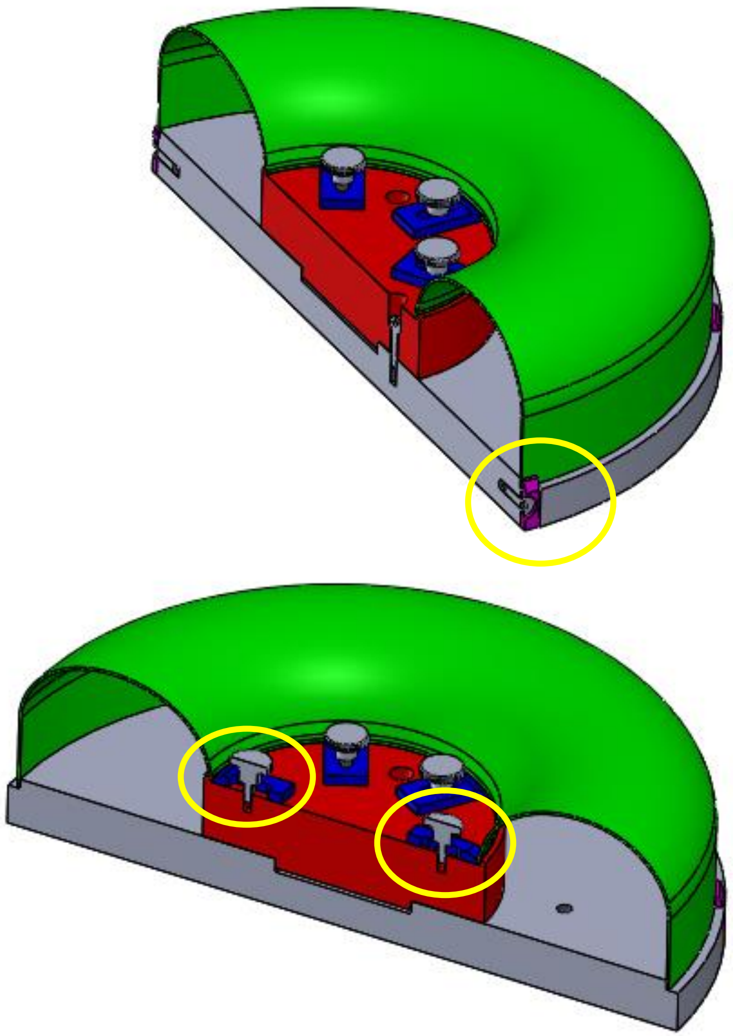
Design and production of the support structure



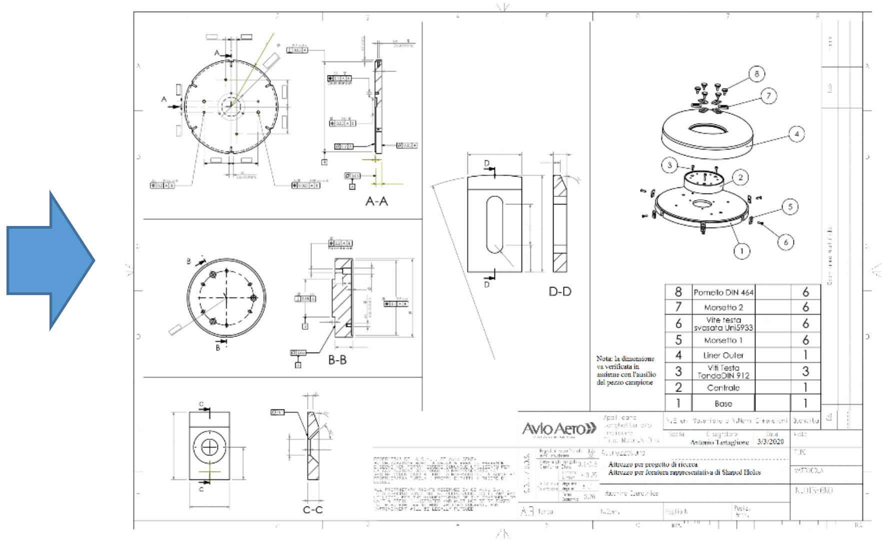


Design and production of the support structure





GD&T



Conclusions: achieved results

The systematic approach based on the design of experiments technique allowed step-by-step optimization of the laser drilling process for the production of the shaped holes.

In particular, the present experimental work successfully achieved the following relevant targets:

Definition of optimal laser beam pathways to optimize the diffuser shape and quality

- Beam angle compensation to reduce width, angle (for both Job1 and Job2) and slope (for Job1) of the diffuser
- Beam pathway variation to avoid the deposit of recast layer on the diffuser floor

Production of 3 different layouts of holes (where possible) to identify the one that allows to obtain the highest cooling effectiveness

- Flow tests are still in progress, so results are not yet available
- However, the large number of holes produced allowed to evaluate the overall process capability and reasonable tolerance ranges

Selection of the first applicative case for the industrialization of shaped holes production

- A liner of a reverse flow combustor was identified as first application
- The support structure for the production of shaped holes on a real combustion chamber was designed and commissioned

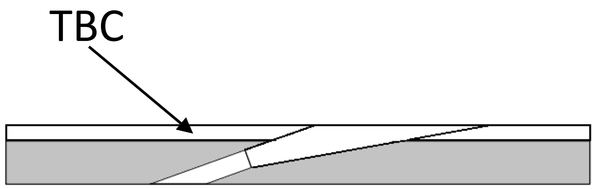
Future developments

Two important projects, directly related to the work just presented, are starting up:

Shaped Holes on TBC

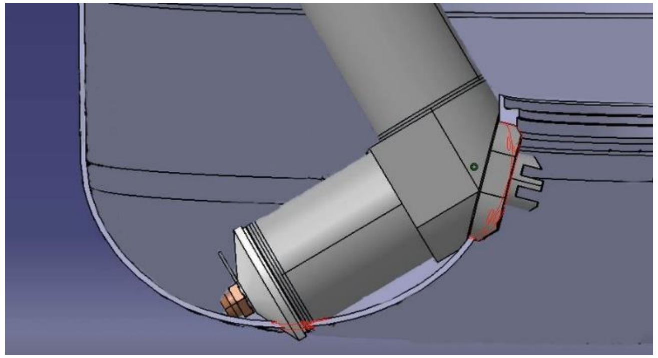
Development of laser drilling methods for the production of *standard (hot side) shaped holes* on plates with a thermal barrier coating (**TBC**).

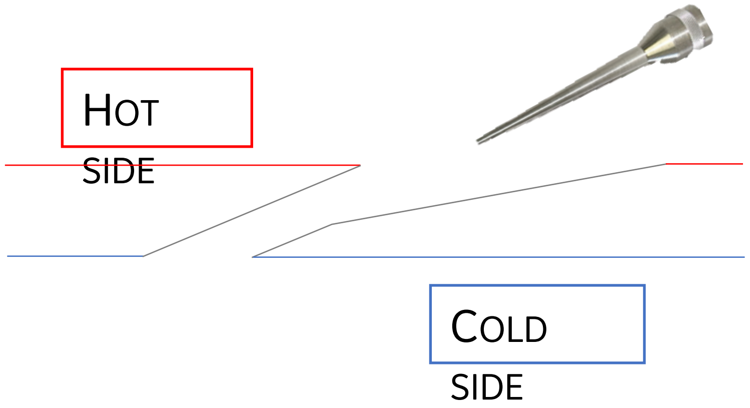
These plates may be obtained through **both conventional and additive manufacturing techniques**.



Reverse Shaped Holes

In reverse flow combustors, it is impossible for a typical laser head to have a complete access to the machining area, *which prevents the production of shaped holes from the hot side*.





Exploration of the applicability fields of ***reverse (cold side) shaped holes*** by identifying classes of shaped holes (in terms of achievable geometrical features) for which it is possible to perform drilling process from the cold side.

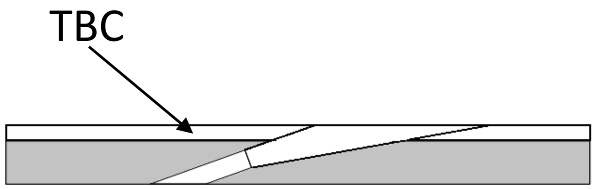
Future developments

Two important projects, directly related to the work just presented, are starting up:

Shaped Holes on TBC

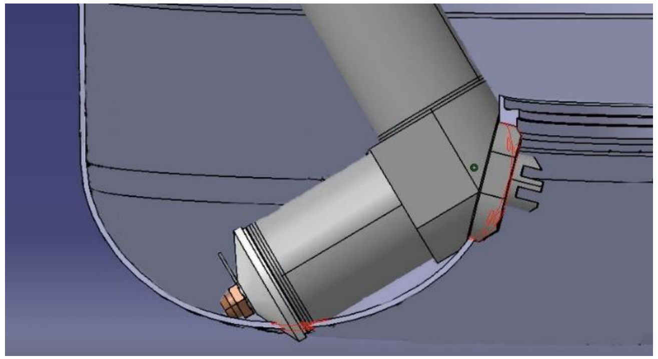
Development of laser drilling methods for the production of *standard (hot side) shaped holes* on plates with a thermal barrier coating (**TBC**).

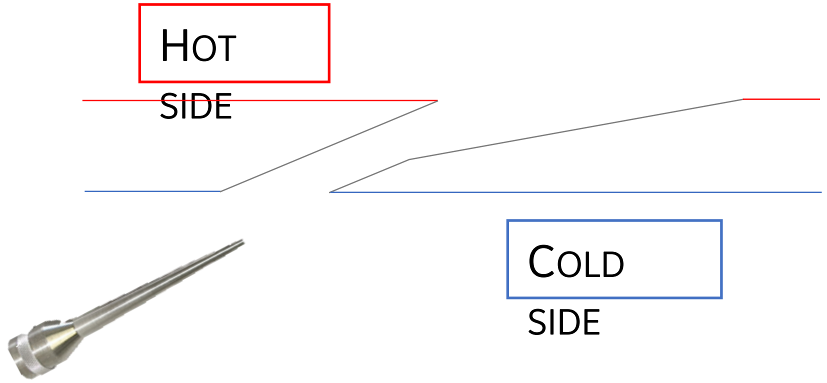
These plates may be obtained through **both conventional and additive manufacturing techniques**.



Reverse Shaped Holes

In reverse flow combustors, it is impossible for a typical laser head to have a complete access to the machining area, *which prevents the production of shaped holes from the hot side*.





Exploration of the applicability fields of ***reverse (cold side) shaped holes*** by identifying classes of shaped holes (in terms of achievable geometrical features) for which it is possible to perform drilling process from the cold side.

THANK YOU

FOR YOUR ATTENTION