Università degli Studi della Campania *Luigi Vanvitelli*

Avio Aero
A GE Aviation Business

## Tesi di Laurea in Ingegneria Meccanica

# Experimental study for shaped holes manufacturing by fiber laser technology for aerospace superalloys: statistical approach and technological interpretation.

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Ing. Silvio Genna (DI Roma"Tor Vergata")

# Avio Aero: The Company

Avio Aero
A GE Aviation Business

A leading aerospace company





# The roots of thesis work

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Previous thesis of this project:

- Iacobelli V, Necula C (2015) Experimental study on fiber laser drilling of aerospace alloys: statistical approach and technological interpretation.
- Siviero D (2016) Statistical approach in aerospace industry innovation. A case study: the shaped holes drilling process.
- Amato V, Panetta A (2017) Experimental study for shaped holes manufacturing by fiber laser technology for aerospace applications.

Now this project is part of a research contract with the name
« Analisi ed ottimizzazione del processo di foratura laser e controllo degli shaped holes con l'ausilio di metodi statistici avanzati»;
this contract establish the collaboration between the following partners:

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DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

# Agenda

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1 2 3 4 5 6

1. Technological Context
2. Aims
3. Experimental Equipment
   - Material
   - Measurement Methods
   - Laser Systems
4. Experimental Activities (EA 1 – LS 900/9000)
5. Experimental Activities (EA IV – LS 1200/12000)
6. Conclusions/Future Developments

# Technological context

# Technological Context

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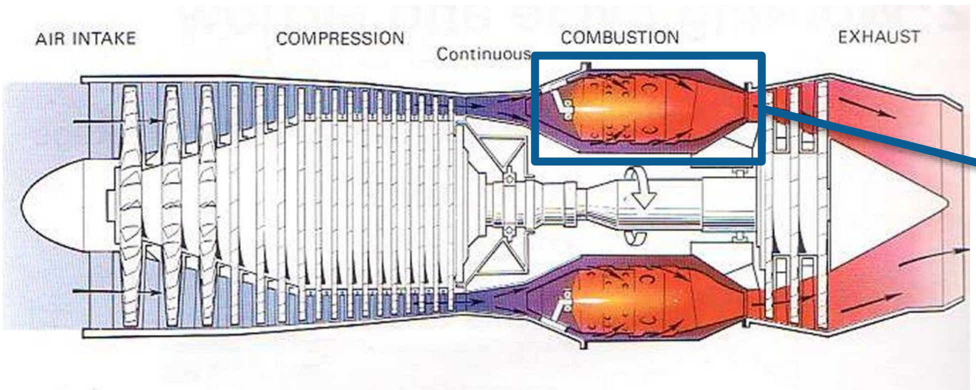
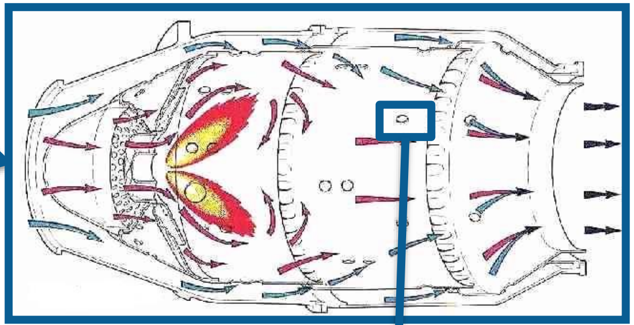
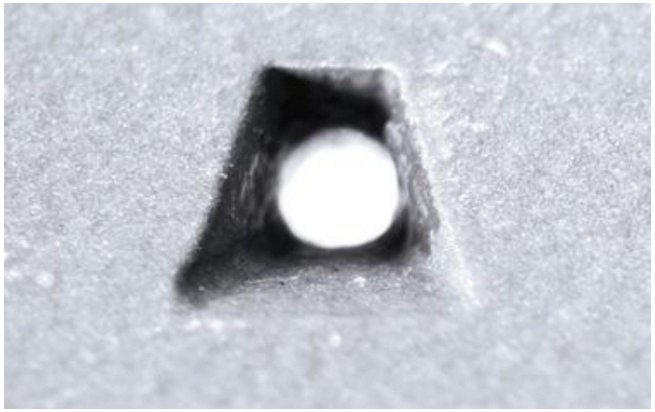


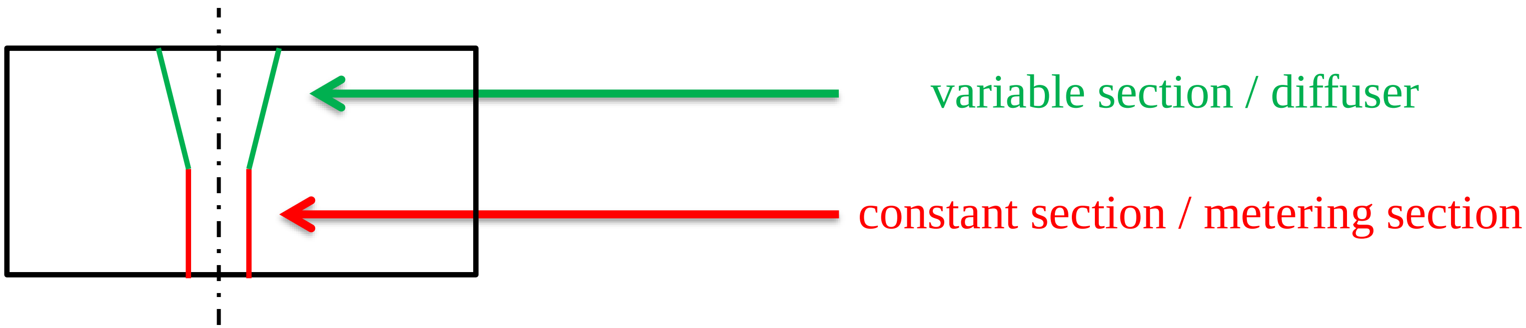



In some aerospace application, variable section hole are made, called ***Shaped Holes,*** to increase the combustion chamber cooling.

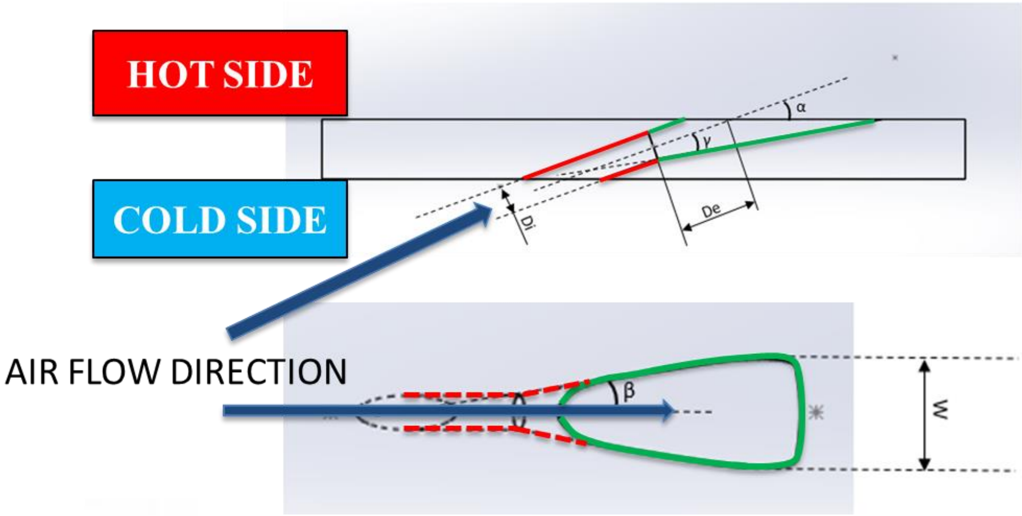


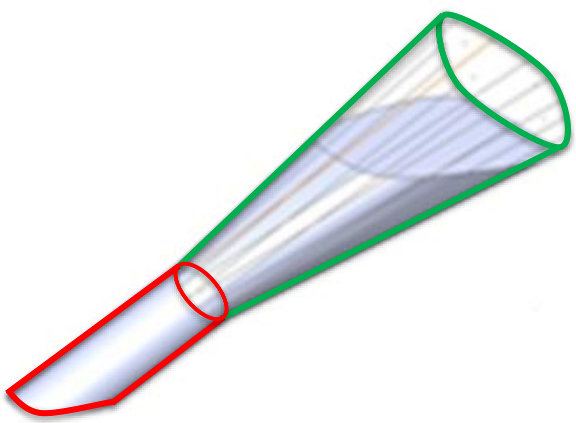
It's an hole composed by two parts:

## Plate section




## How Shaped hole works:



# Research Aims

1 2 3 4 5 6

Technological contest

**Currently, Avio Aero produces shaped hole under GE license.**

**AVIO intends to acquire a own know-how for the shaped holes developing and manufacturing.**

# Research Aims

1 2 3 4 5 6

Aims

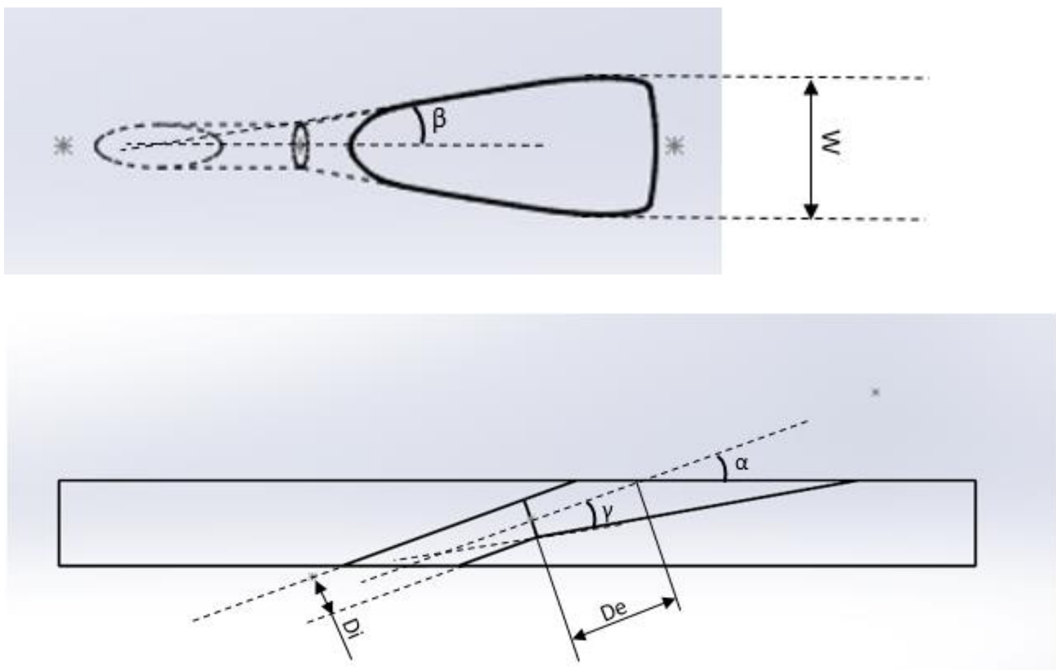
Aims of the thesis are:

- Develop and assess **procedures** and methods to produce shaped holes with an assigned geometry

- Investigate the **drilling process parameters** in order to satisfy the geometrical specifications

- Minimize the **working time**

| | α* | β* | γ* | Di* | W* | De* |
|---|---|---|---|---|---|---|
| **Job 1** | a° | b° | c° | --- mm | --- mm | --- mm |
| **Job 2** | d° | e° | f° | --- mm | --- mm | --- mm |




**SH characteristic parameters:**

- Diameter - Di
- Width - W
- Depth - De
- SH axis slope - α
- Diffuser slope - β
- Diffuser width - γ

*Data have been occulted.

# Experimental Equipment

# Material: Haynes 188 Alloy

**Description:**

Haynes 188 is a cobalt-based alloy which possesses a unique combination of properties. It has excellent high temperature strength and oxidation resistance to 2100 ° F (1150 ° C) combined with good post-aging ductility.

**Application:**

Because of its excellent strength, ductility and oxidation resistance, Haynes 188 meets the critical high-temperature material requiredments for gas turbine applications as well as many of those in the airframe, chemical and nuclear fields. Typical uses are as transition ducts, combustor cans, spray bars, flame-holders and afterburner liners in jet engines.

| | C | Mn | Si | Cr | Ni | W | La | B | Fe | Co |
|---|---|---|---|---|---|---|---|---|---|---|
| **MIN** | 0.05 | — | 0.20 | 20.0 | 20.0 | 13.0 | 0.02 | — | — | — |
| **MAX** | 0.15 | 1.25 | 0.50 | 24.0 | 24.0 | 16.0 | 0.12 | 0.015 | 3.0 | Bal |

| Yeld Strenght | Tensile Strenght | Elongation at break |
|---|---|---|
| **MPa** | **MPa** | **%** |
| 446 | 963 | 55 |

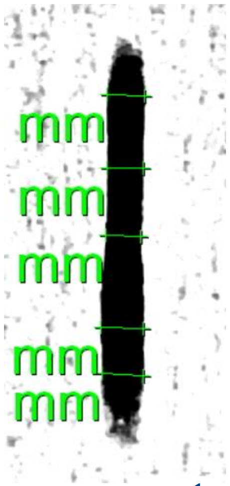
This system provides a 2D radiography of the holes:

Due to the hole irregularity, the diameters of five hole sections have been measured and the resulting mean value was considered as the measure (response variable) of the hole diameter.

In addition, the variance of these five measurements was used as a *hole irregularity* index.

For the analysis, the mean diameter has been considered.

$x_1$ mm
$x_2$ mm
$x_3$ mm
$x_4$ mm
$x_5$ mm



$$Mean\ Diameter = \frac{1}{5} \cdot \sum_{i=1}^{5} x_i$$

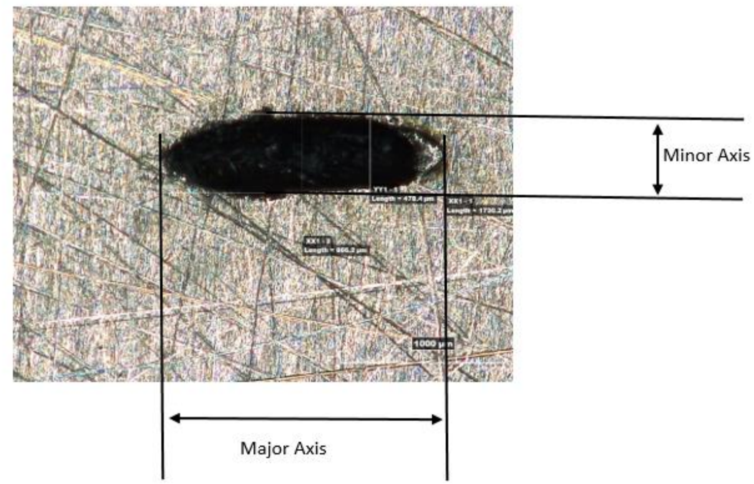
# Measurement Method by Digital Microscope

1 2 3 4 5 6

Experimental equipments

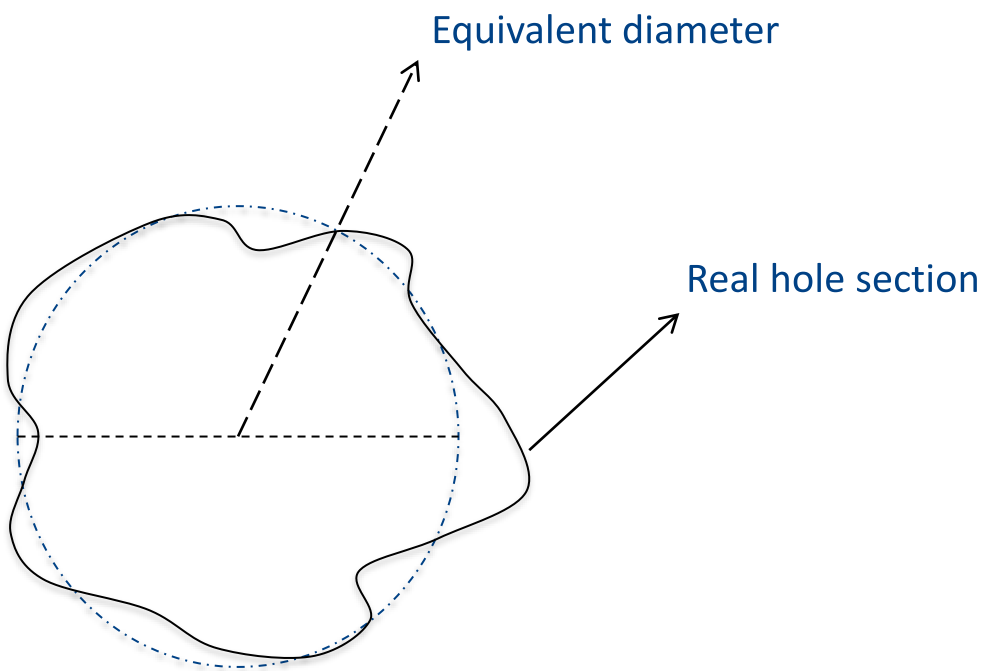
Being the hole axis sloped with respect to the plate surface, the entry and exit hole footprints appears like an ellipse.

The major axis (AmaxIN, AmaxOUT) and the minor axis (AminIN, AminOUT) of these ellipses could be measured by digital microscope.




| Derivated response variable | Measurement instrument |
|---|---|
| Ellipse area IN | $AmaxIN * AminIN * \frac{\pi}{4}$ |
| Ellipse area OUT | $AmaxOUT * AminOUT * \frac{\pi}{4}$ |
| Taper Amin | $\frac{AminIN - AminOUT}{2 * 4{,}53}$ |
| Taper Amax | $\frac{AmaxIN - AmaxOUT}{2 * 4{,}53}$ |
| Taper Area | $\frac{AreaIN - AreaOUT}{2 * 4{,}53}$ |

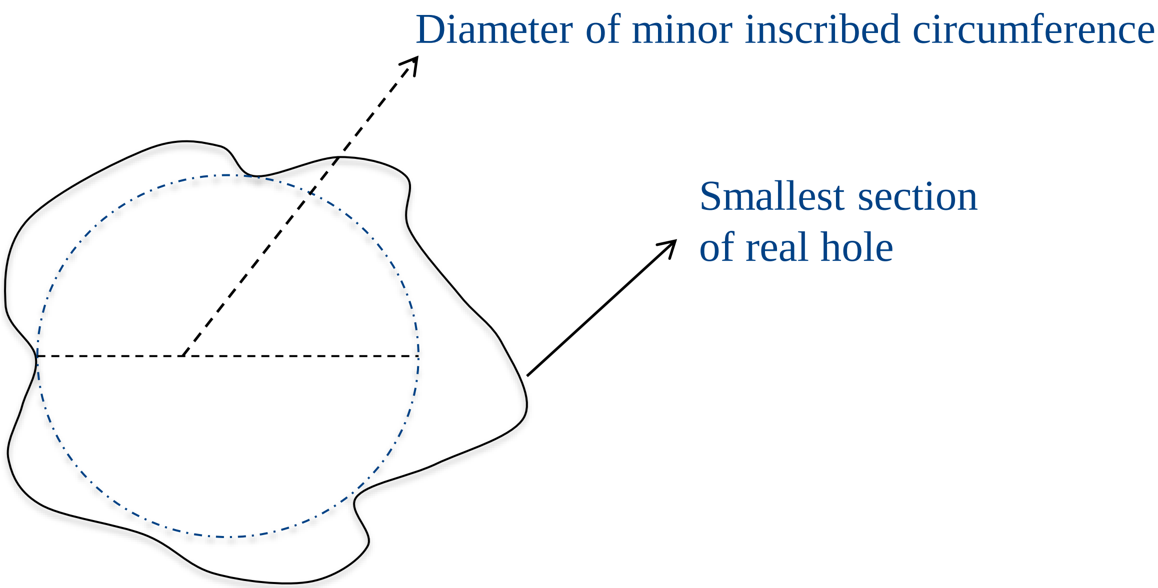
This measurement system blows air into the hole.
On the basis of a contropressure it calculates the equivalent diameter of the hole section.



1 2 3 4 5 6

Experimental equipments


This measurement system works with the go-no go principle: if a calibrated pin passes trough the hole, its diameter corresponds to the diameter of the minor inscribed circumference.



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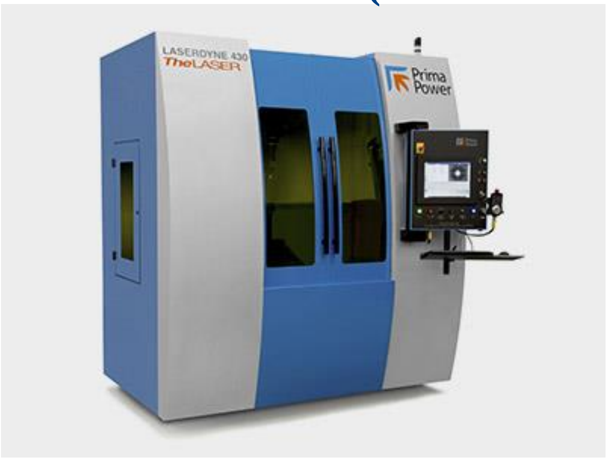
Experimental equipments

## LASERDYNE 430 (900/9000 LS)




- *Work area*
  5-6 axes:
  X 585 mm, Y 400 mm, Z 500 mm, C 900°, D 300°, Rotary 360
- *Axis speed*
  5-6 axes:
  X, Y, Z: 15 m/min; C, D: 90 rpm; Rotary: various options
- *Laser source* QCW **900/9000** pulsed fiber laser
- *System 94P Interface*
- *Special features*
- **PSC** → **Part Surface Control**
- *Assist Gas*
- $O_2$, $N_2$

## LASERDYNE 606D (1200/12000 LS)


- Work area
  X 600 mm – Y 600 mm – Z 600 mm
  BeamDirector®: C 900° – D 300°
- 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*
- $O_2$, $N_2$

**Courtesy of Prima Power for the images**

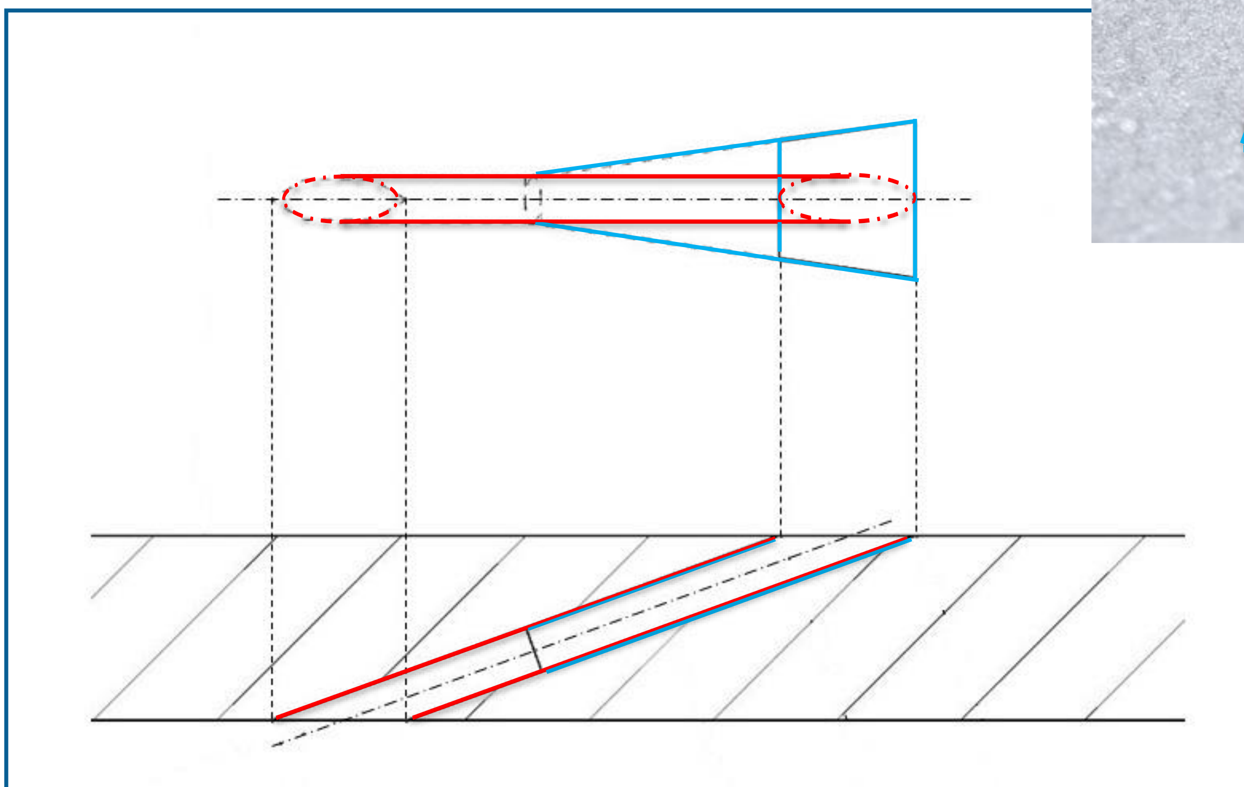
# How a Shaped Hole is made

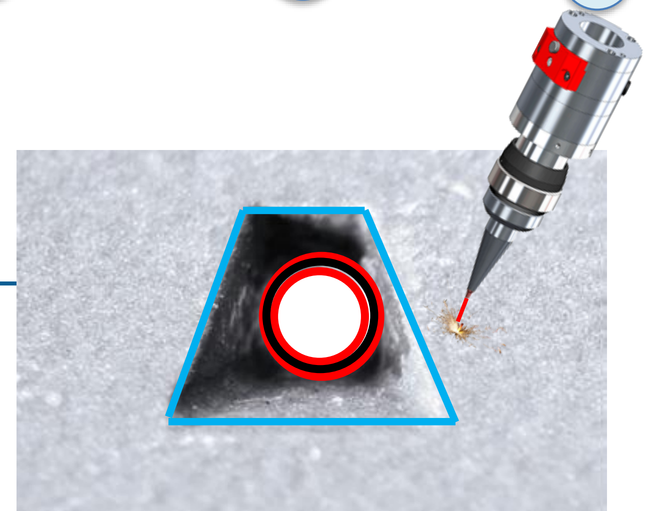
1 2 3 4 5 6

Experimental equipments

## Phase 1: Calibration and cleaning

## Phase 3: Drilling

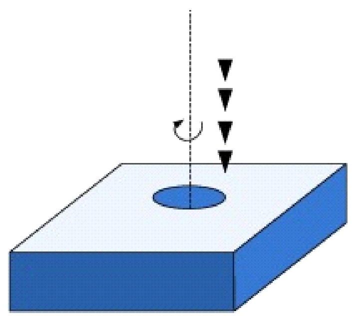




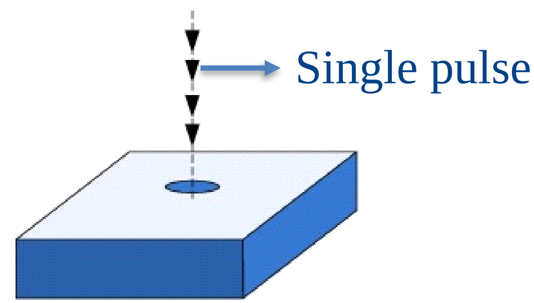
# Laser Pulsed Drilling Methods



Different drilling methods can be used to produce shaped holes:



Trepanning




Percussion

- Percussion allows faster drilling operations but with lower accuracy
- Trepanning is slower but it allows to achieve holes with complex geometry due to its higher accuracy

To reduce the production time per single hole it was decided to make:

- Phase I and III by Percussion
- Phase II by Trepanning

# Experimental Activities

# Statistical Approach

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1 — 2 — 3 — 4 — 5 — 6

Experimental activities

*All the activities were carried out adopting a **systematic approach** by use of **Design of Experiments***

**Literature** | **Expert knowledge** | **Preliminary test**

↓

**Collection of information on apposite pre-design sheets**

↓

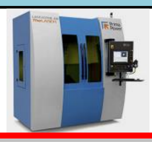
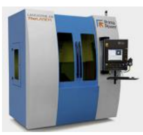
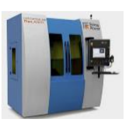
**Design Of Experiments (DOE)**

↓

**Statistical Analysis and technological interpretations**

- CAD and Part Program development
- Process characterization in terms of geometrical requirements
- Tests implementation on fiber laser machine:
- Data analysis and measurement methods comparison

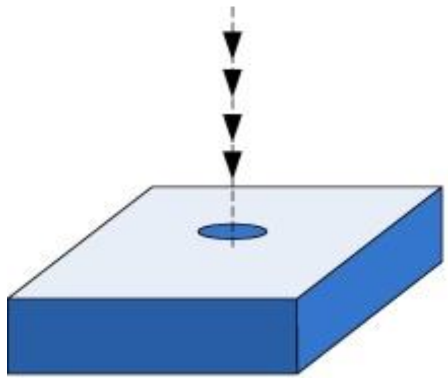
Experimental activities

| Laser System | Experimental Activities | Description |
|---|---|---|
|  | Experimental Test I | First approach to the the drilling process by laser percussion drilling. |
|  | Experimental Activity I (EA I) | Experimental study on Phase I with 900/9000 LS<br><br>Statistical comparison of the measurement methods |
|  | Experimental Activity II (EA II) | First experimental study on Phase I with 1200/12000 LS |
|   | Experimental Activity III (EA III) | Comparison between the 900/9000 and 1200/12000 LS |
|  | Experimental Activity IV (EA IV) | Second experimental study on Phase I with 1200/12000 LS<br><br>Choosen of the best treatment for Phase I |
|  | Experimental Activity V (EA V) | Experimental study on Phase II with 1200/12000 |

# Experimental Activity I

In this phase, the aim is to produce sloped cylindrical holes, by percussion drilling, with an assignement diameter.

| Experimental factor | Control/Constant | N° of levels | Levels* |
|---|---|---|---|
| Defocus (mm) | Control | 3 | -1; 0; 1 |
| Gas Pressure (bar) | Control | 2 | -1; 1 |
| Pulse Width (ms) | Control | 3 | -1; 0; 1 |
| No. of Pulses | Control | 3 | -1; 0; 1 |
| Peak Power (W) | Constant | 1 | k |
| Average Power (W) | Constant | 1 | q |



Percussion

DOE method

Experimental Plan: Full Factorial

$3^3$ x 2 with 3 replicates = 162 holes

*Levels have been coded.

# Experimental Activity I – Phase I, 900/9000 LS

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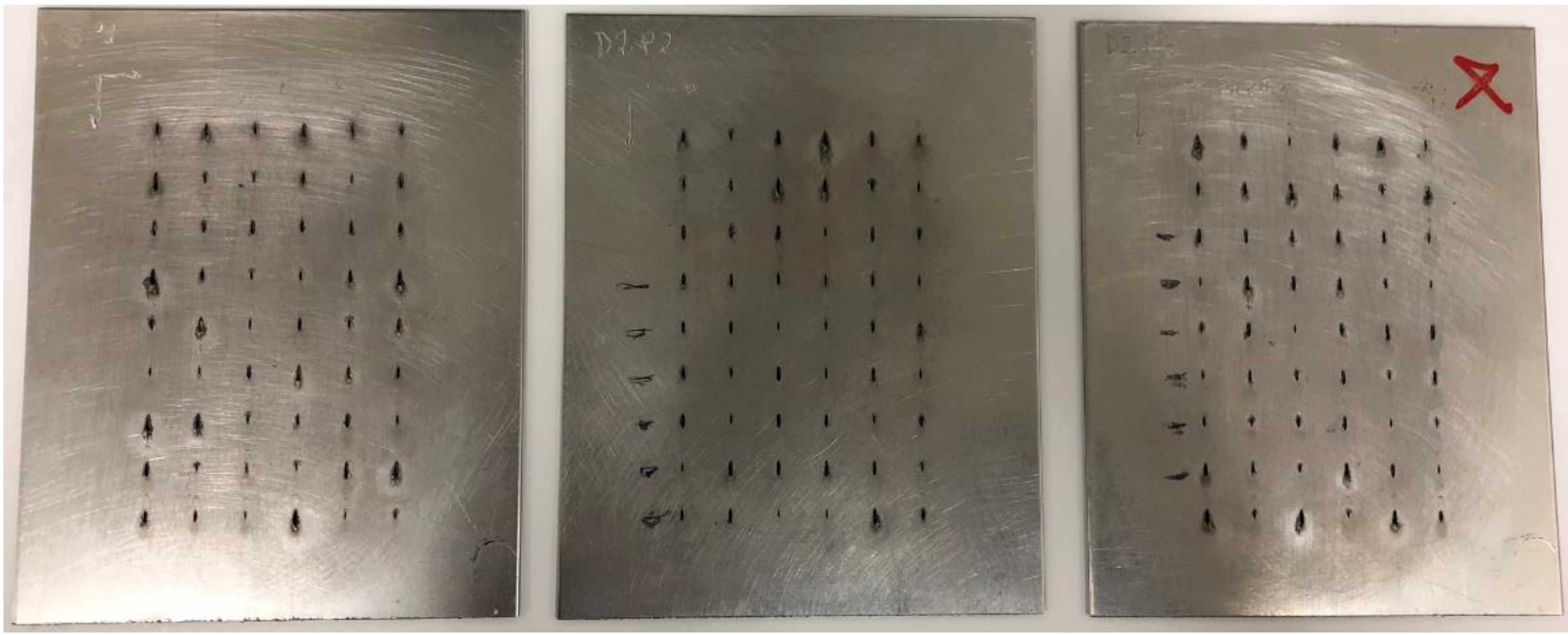
1 2 3 4 5 6

Experimental activity I



# Experimental Activity I – Phase I, 900/9000 LS Measurement Method Comparison

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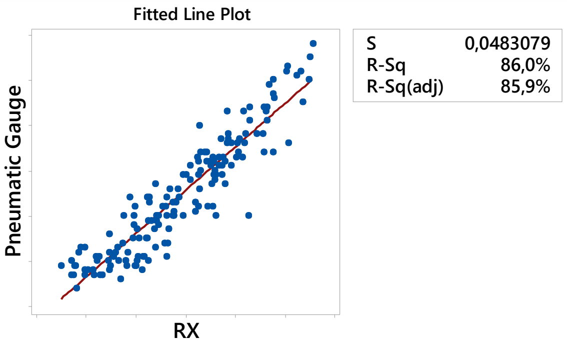
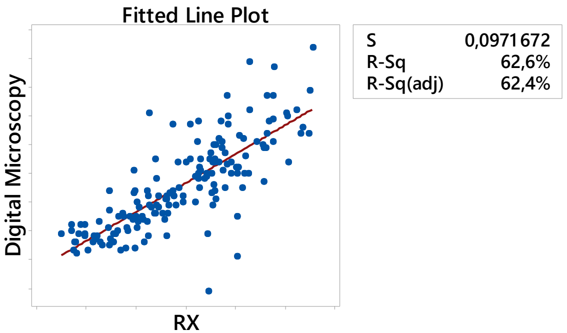
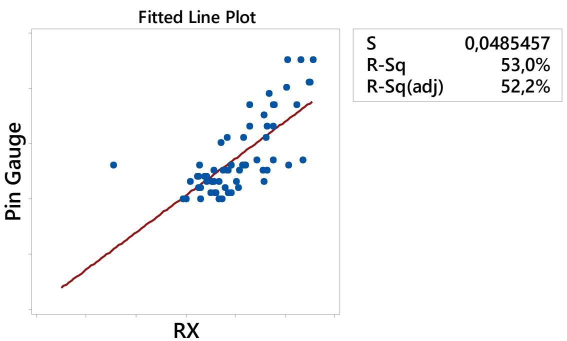
1 2 3 4 5 6

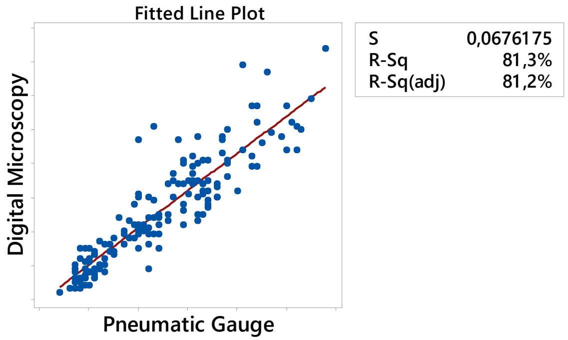


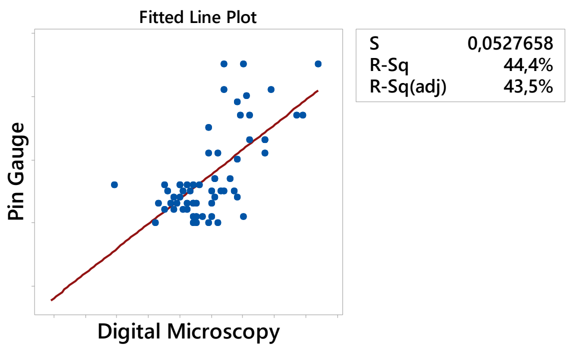




scale unit = 0,1 mm

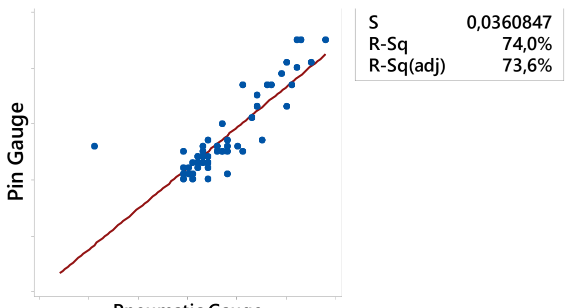
Experimental activity I




scale unit = 0,1 mm




scale unit = 0,1 mm




scale unit = 0,1 mm

- Rx is the most accurate measurement method validate by Avio Aero
- These regression analyses showed that there is a high correlation between RX and Pneumatic Gauge measurement methods.
- The Pneumatic Gauge can be faster and reliable measuring method.

Export Control Classification: NECT

# Experimental Activity II

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1 2 3 4 5 6

Experimental activity II

To achieve the best asset of PHASE I on the 1200/12000 laser system, a new experimental campaign was executed to test higher defocus levels.

| Experimental factor | Control/Constant | N° of levels | Levels* |
|---|---|---|---|
| Defocus (mm) | Control | 3 | -1; 0; 1 |
| Gas Pressure (bar) | Control | 2 | -1; 1 |
| Pulse Width (ms) | Control | 3 | -1; 0; 1 |
| No. of Pulses | Control | 3 | -1; 0; 1 |
| Peak Power (W) | Constant | 1 | k |
| Average Power (W) | Constant | 1 | q |

DOE method

Experimental Plan: Full Factorial

$3^3$ x 2 with 3 replicates = 162 holes

**MEASUREMENT METHOD**

*Levels have been coded.

# Experimental Activity IV – Phase I, 1200/12000 Modified Experimental Plan

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1 — 2 — 3 — 4 — 5 — 6

Experimental activity II

| Tratment | Defocus [mm] | Pressure [bar] | Pulse Width [ms] | No. Of Pulses |
|---|---|---|---|---|
| 1 | -1 | -1 | -1 | -1 |
| 2 | -1 | -1 | -1 | 0 |
| 3 | -1 | -1 | -1 | 1 |
| 4 | -1 | -1 | 0 | -1 |
| 5 | -1 | -1 | 0 | 0 |
| 6 | -1 | -1 | 0 | 1 |
| 7 | -1 | -1 | 1 | -1 |
| 8 | -1 | -1 | 1 | 0 |
| 9 | -1 | -1 | 1 | 1 |
| 10 | -1 | 1 | -1 | -1 |
| 11 | -1 | 1 | -1 | 0 |
| 12 | -1 | 1 | -1 | 1 |
| 13 | -1 | 1 | 0 | -1 |
| 14 | -1 | 1 | 0 | 0 |
| 15 | -1 | 1 | 0 | 1 |
| 16 | -1 | 1 | 1 | -1 |
| 17 | -1 | 1 | 1 | 0 |
| 18 | -1 | 1 | 1 | 1 |
| 19 | 0 | -1 | -1 | -1 |
| 20 | 0 | -1 | -1 | 0 |
| 21 | 0 | -1 | -1 | 1 |
| 22 | 0 | -1 | 0 | -1 |
| 23 | 0 | -1 | 0 | 0 |
| 24 | 0 | -1 | 0 | 1 |
| 25 | 0 | -1 | 1 | -1 |
| 26 | 0 | -1 | 1 | 0 |
| 27 | 0 | -1 | 1 | 1 |

| Tratment | Defocus [mm] | Pressure [bar] | Pulse Width [ms] | No. Of Pulses |
|---|---|---|---|---|
| 28 | 0 | 1 | -1 | -1 |
| 29 | 0 | 1 | -1 | 0 |
| 30 | 0 | 1 | -1 | 1 |
| 31 | 0 | 1 | 0 | -1 |
| 32 | 0 | 1 | 0 | 0 |
| 33 | 0 | 1 | 0 | 1 |
| 34 | 0 | 1 | 1 | -1 |
| 35 | 0 | 1 | 1 | 0 |
| 36 | 0 | 1 | 1 | 1 |
| 37 | 1 | -1 | -1 | -1 |
| 38 | 1 | -1 | -1 | 0 |
| 39 | 1 | -1 | -1 | 1 |
| 40 | 1 | -1 | 0 | -1 |
| 41 | 1 | -1 | 0 | 0 |
| 42 | 1 | -1 | 0 | 1 |
| 43 | 1 | -1 | 1 | -1 |
| 44 | 1 | -1 | 1 | 0 |
| 45 | 1 | -1 | 1 | 1 |
| 46 | 1 | 1 | -1 | -1 |
| 47 | 1 | 1 | -1 | 0 |
| 48 | 1 | 1 | -1 | 1 |
| 49 | 1 | 1 | 0 | -1 |
| 50 | 1 | 1 | 0 | 0 |
| 51 | 1 | 1 | 0 | 1 |
| 52 | 1 | 1 | 1 | -1 |
| 53 | 1 | 1 | 1 | 0 |
| 54 | 1 | 1 | 1 | 1 |

*Levels have been coded.

# Experimental Activity IV – Phase I, 1200/12000 Modified Experimental Plan

1 — 2 — 3 — 4 — 5 — 6

Experimental activity II

# Experimental Activity IV – Phase I, 1200/12000 Statistical Results

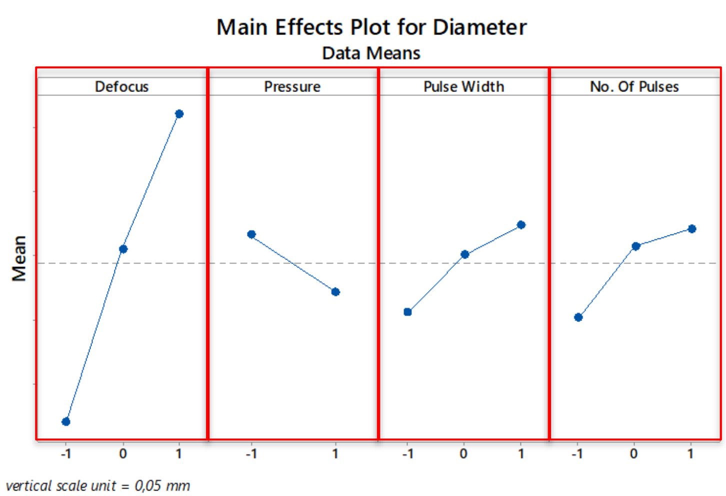
1 2 3 4 5 6

Experimental activity II

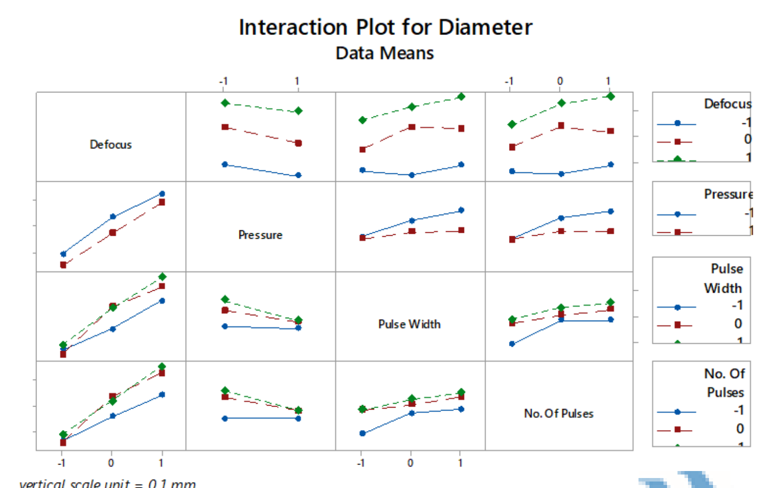
## Hole Diameter – (PNEUMATIC GAUGE)

### Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Defocus | 2 | 1,44114 | 0,720570 | 194,01 | 0,000 |
| Pressure | 1 | 0,06981 | 0,069814 | 18,80 | 0,000 |
| Pulse Width | 2 | 0,12786 | 0,063932 | 17,21 | 0,000 |
| No. Of Pulses | 2 | 0,14439 | 0,072197 | 19,44 | 0,000 |
| Defocus*Pressure | 2 | 0,01385 | 0,006923 | 1,86 | 0,159 |
| Defocus*Pulse Width | 4 | 0,06450 | 0,016125 | 4,34 | 0,002 |
| Defocus*No. Of Pulses | 4 | 0,07350 | 0,018374 | 4,95 | 0,001 |
| Pressure*Pulse Width | 2 | 0,03416 | 0,017078 | 4,60 | 0,012 |
| Pressure*No. Of Pulses | 2 | 0,04222 | 0,021109 | 5,68 | 0,004 |
| Pulse Width*No. Of Pulses | 4 | 0,01559 | 0,003899 | 1,05 | 0,384 |
| Error | 134 | 0,49769 | 0,003714 | | |
| Lack-of-Fit | 28 | 0,13089 | 0,004675 | 1,35 | 0,139 |
| Pure Error | 106 | 0,36680 | 0,003460 | | |
| Total | 159 | 2,56707 | | | |




vertical scale unit = 0,05 mm




vertical scale unit = 0,1 mm

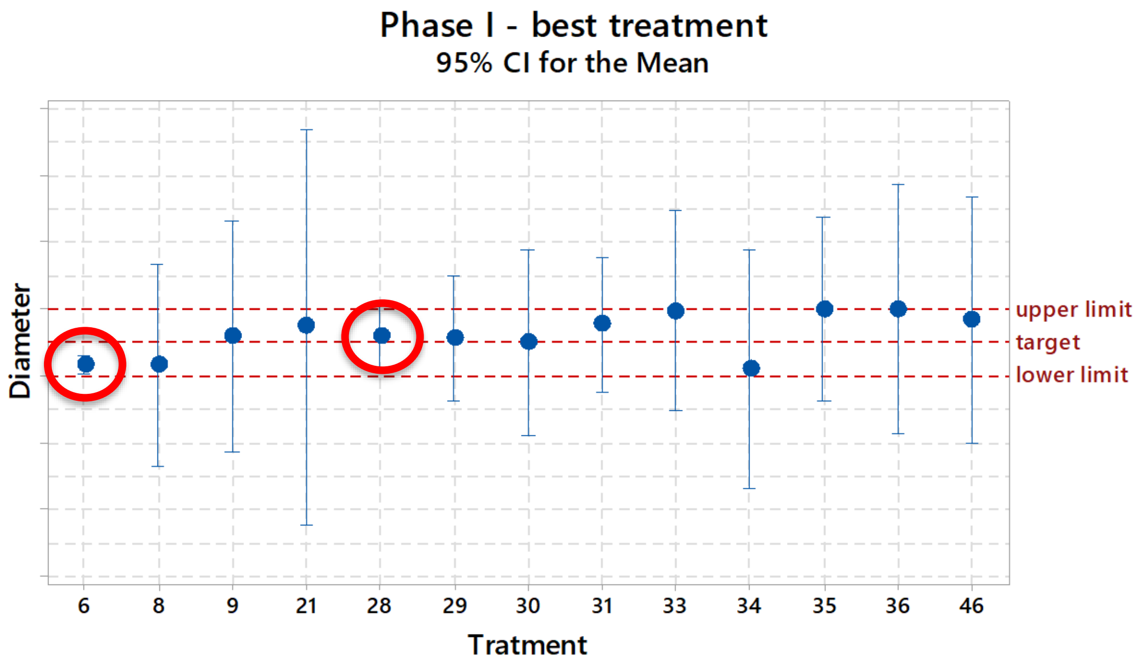
*Levels have been coded.

Export Control Classification: NECT

1 2 3 4 5 6

Experimental activity II

It is now possible to find the best treatment (so, the best parameters asset) to produce a hole compliant with the geometrical target:




*vertical scale unit = 0,1 mm*
*Individual standard deviations are used to calculate the intervals.*

The best asset is the treatment closer to the target and with the lower variance; for these reasons, the best treatment is the no. 6:

| Tratment | Defocus | Pressure | Pulse Width [ms] | No. Of Pulses |
|---|---|---|---|---|
| 6 | Level -1 | Level -1 | Level 0 | Level 1 |
| 28 | Level 0 | Level 1 | Level -1 | Level -1 |

# Experimental Activity IV – Phase I, 1200/12000 Best Treatment Selection of Phase III

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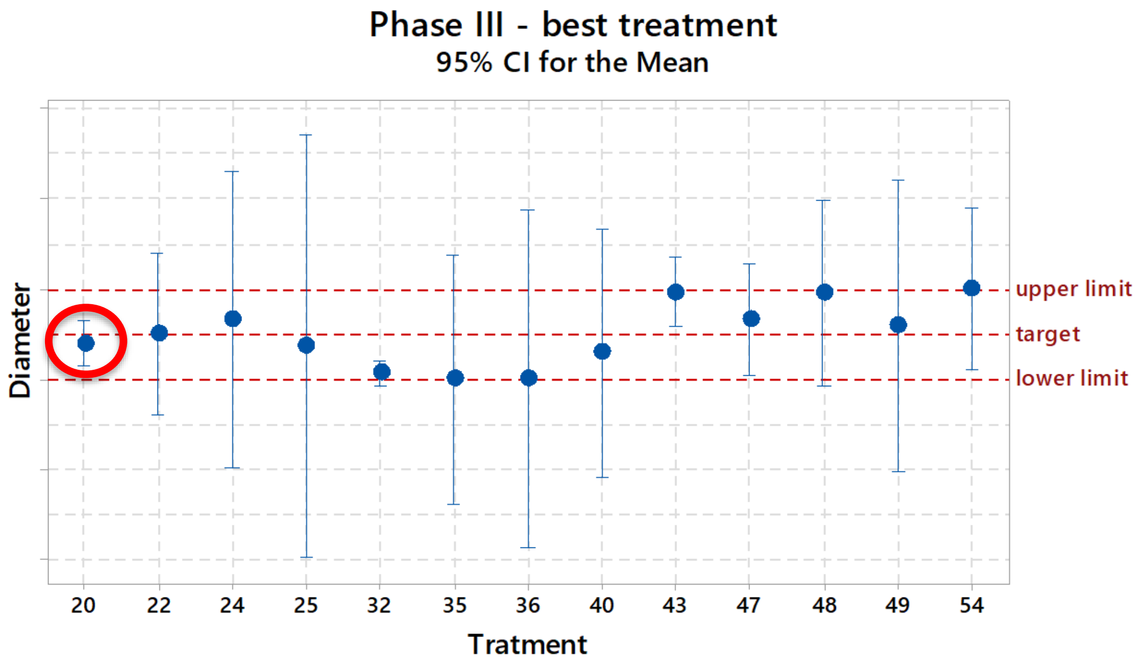
1 2 3 4 5 6

Experimental activity II

Since phase III is performed by percussion drilling, the analysis made can be used to identify the best asset also for of phase III. However, it is required to execute an appropriate experimental plan to understand if, and how, the phases I and II affects the phase III.




*vertical scale unit = 0,1 mm*
*Individual standard deviations are used to calculate the intervals.*

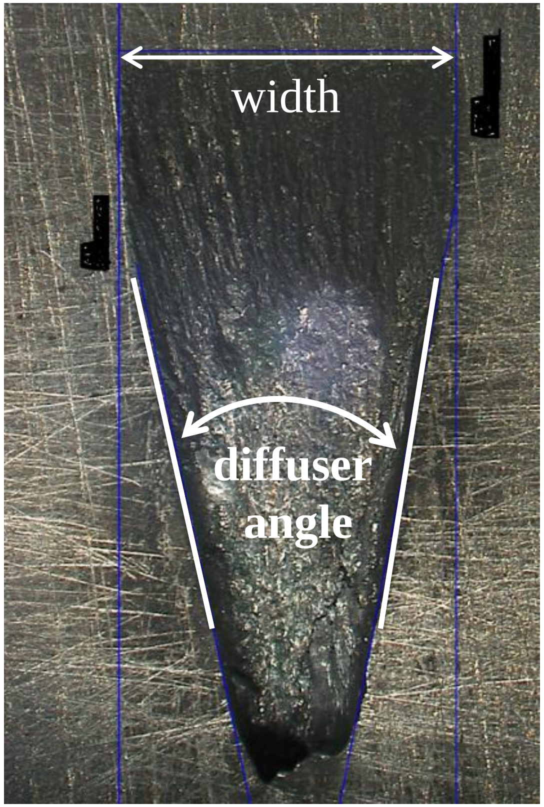
The best asset is the treatment closer to the target and with the lower variance; for these reasons, the best treatment is the no. 20:

| Tratment | Defocus | Pressure | Pulse Width | No. Of Pulses |
|---|---|---|---|---|
| 20 | Level 0 | Level -1 | Level -1 | Level 0 |

# Experimental Activity IV – Phase I, 1200/12000 Best Treatment Selection of Phase III

1 — 2 — 3 — 4 — 5 — 6

Experimental activity II

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1 2 3 4 5 6

Conclusions
Future Development

## CONCLUSIONS:

- **Know-how on laser drilling for Shaped Holes production with both trepanning and hybrid drilling (percussion – trepanning - percussion)**
- **Identification of the OFC feature as the best tool to cope with misalignment issues related to plate warping due to thermal input**
- **Identification of the most suitable measuring meathod in operative context**
- **Identification of the most suitable settings to perform phases I and III**
- **Significant reduction of machining time (about 60%)**
- **Achievement of a first set of Shaped Holes compliant with the provided geometrical requirements**

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Conclusions
Future Development

**Experimental studies will be performed in future:**

- **To understand the behavior of the additive manufacturing Haynes 188**
- **To verify the metallurgical target (in terms of oxyde layer, recast layer and cracks) after the drilling process**
- **To study the shaped holes drilling process on axial-symetrical components that simulate the combustor geometry**

# THANKS FOR YOUR ATTENTION

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