Materials and their production processing for ET's beam pipes

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Beampipes for Gravitational Wave Telescopes 27 March 2023

Outline

Materials science at CERN: MM Section

ET pipes considerations

Specimens and pre-prototypes: work in progress

Pre-prototypes: quality assurance

Cost assessment

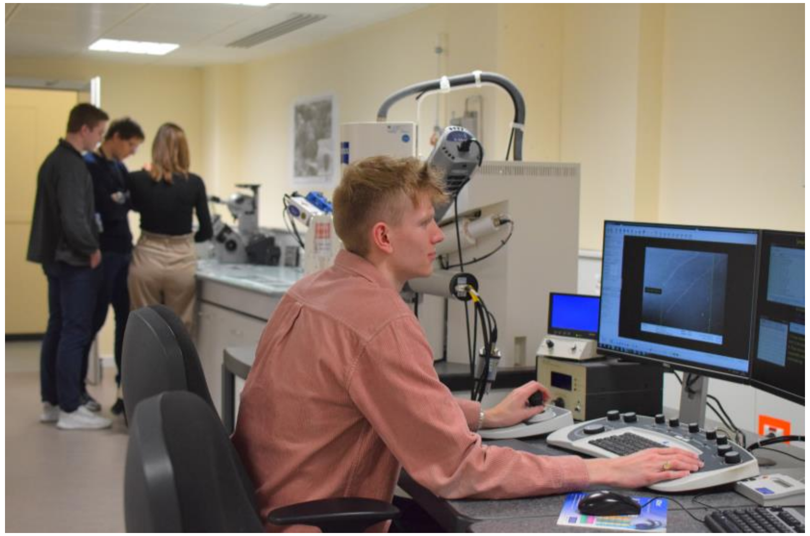
Materials science at CERN: MM Section

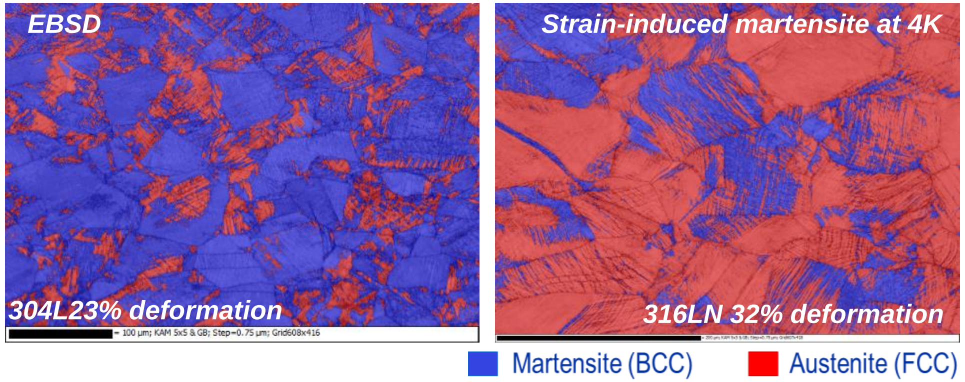
MM Section have an extensive experience in materials characterization and our equipment covers conventional and advanced techniques in microstructural and mechanical testing, dimensional control and NDT

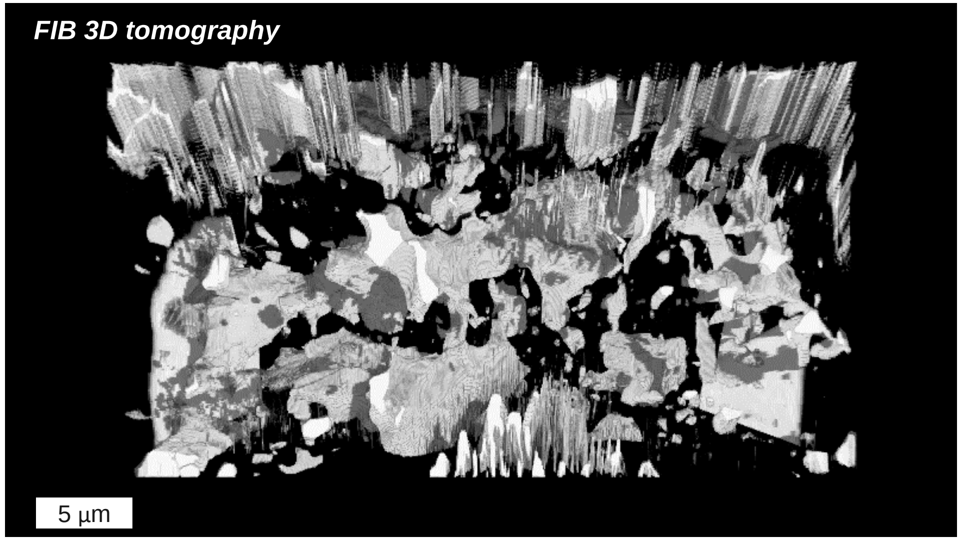
OM, SEM, FIB-SEM, STEM, EDS, EBSD, APA, XRD, residual stress, hardness, tensile testing, fatigue, FT, nano-indentation, µCT, UT, RT…

UHV, magnets, cryogenics, irradiation zones…

Materials selection, technical specifications, researching, qualification, failure analysis…







ET pipes considerations

120 km (3 arms x 10 km x 4 tubes)

UHV is requested in laser interferometers for GW detection

Large diameter to avoid interaction with the beam

Segment length depends on integration of optics, pumps…

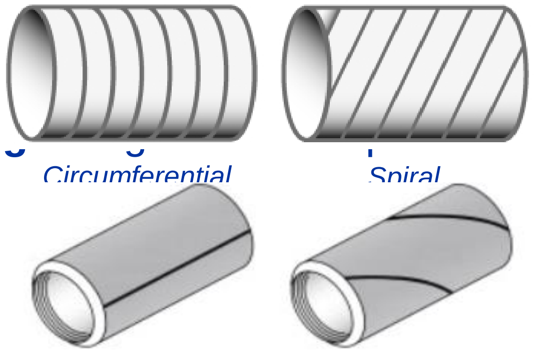
Thickness to prevent tubes from buckling and collapsing

Thick walls + external stiffeners / **Thin walls** + corrugation

Forming int … r coil/strip

Weldi … cular

ET infrastruc … 50 years...



Rolled and welded *Spiral-welded*

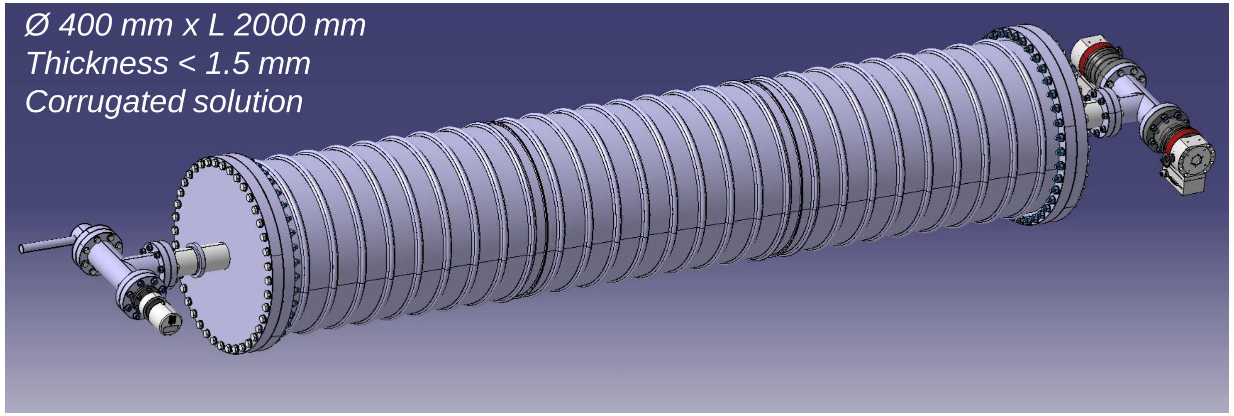
Material requirements?

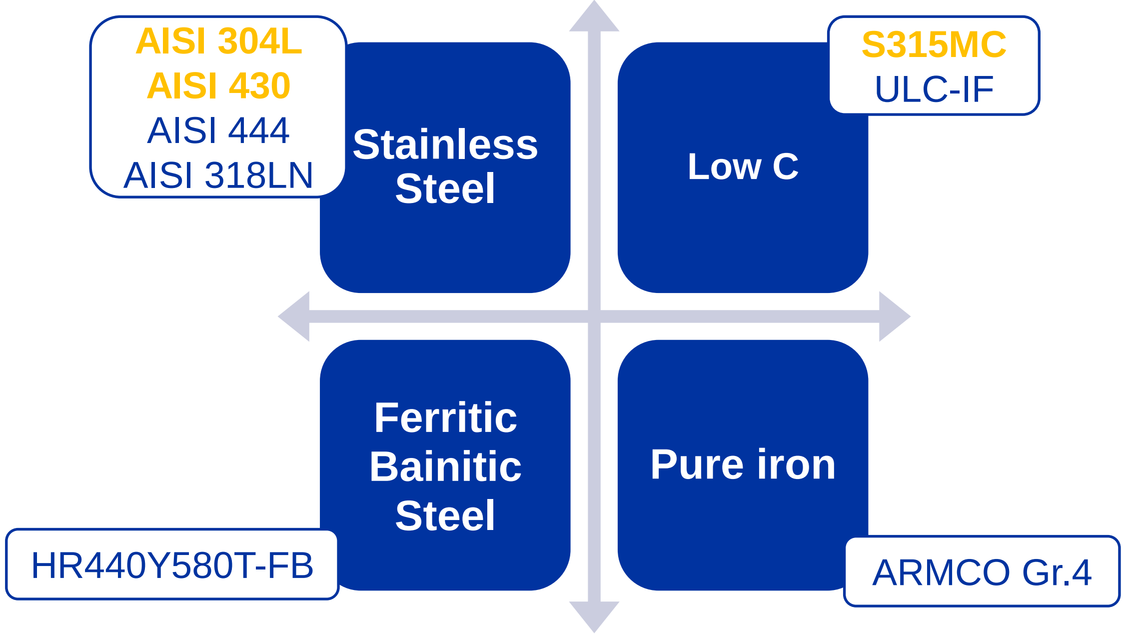
1. ***Fine and homogenous microstructure***
2. ***Sufficient mechanical strength***
3. ***High melting and boiling points***
4. ***Adapted thermal expansion behaviour***
5. ***Corrosion resistance***
6. ***Favorable degassing properties***
7. ***High gas tightness***
8. ***Low intrinsic vapor pressure***
9. ***Low foreign gas content***
10. ***Clean surfaces***

S. Sgobba: Materials for high vacuum technology: an overview

Specimens and pre-prototypes: work in progress

- **Materials analysis** to complement fundamental vacuum studies
- Interesting **vacuum performance** and **industrially available**
- Three grades selected for the **pre-prototypes manufacturing**





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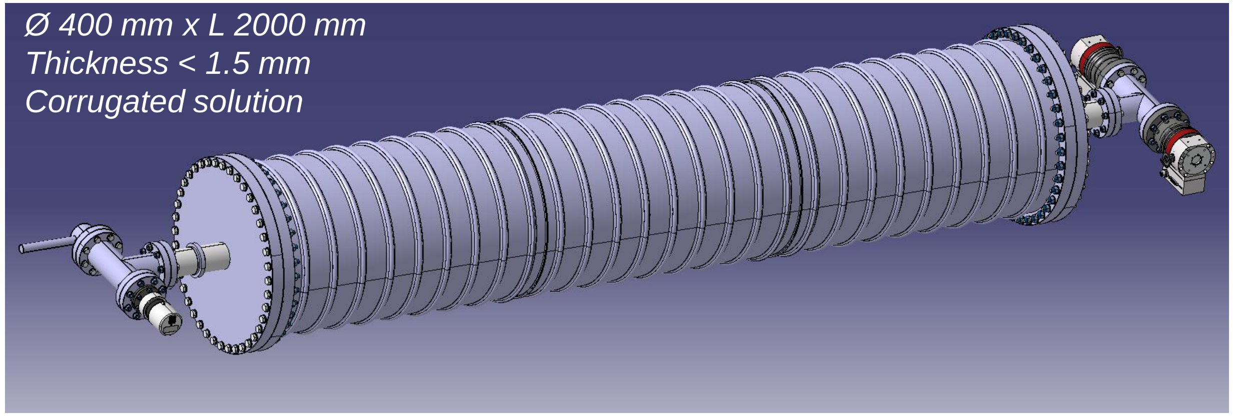


AISI 304L
AISI 430

Stainless Steel

Low C

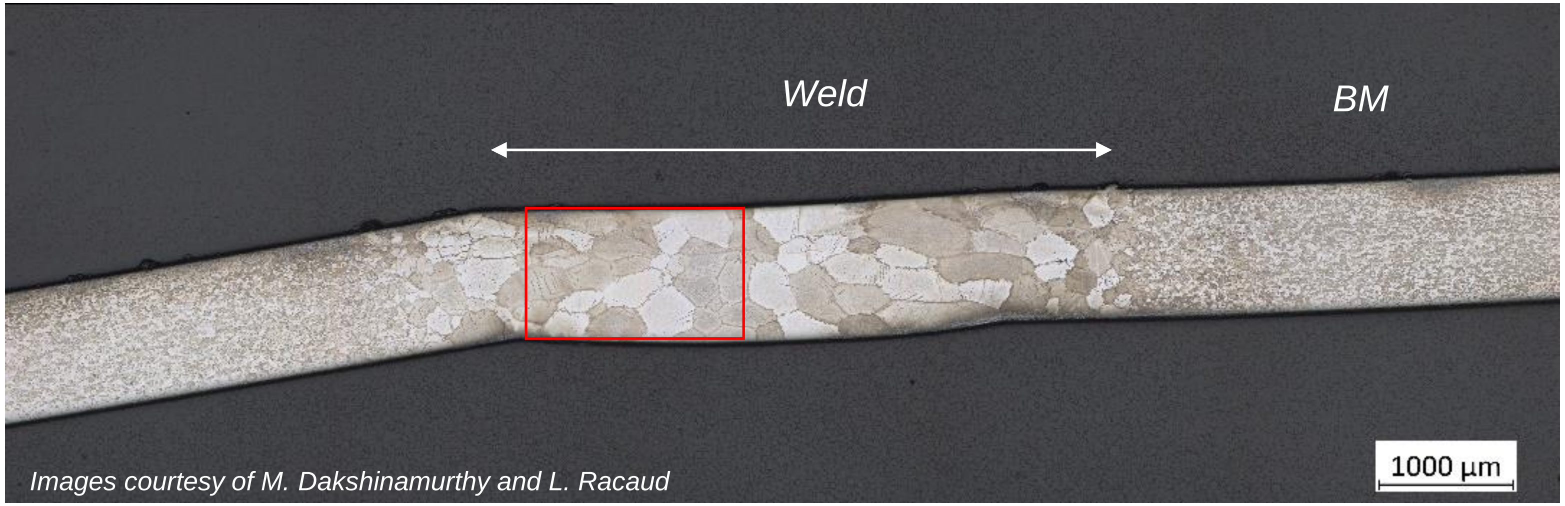
S315MC

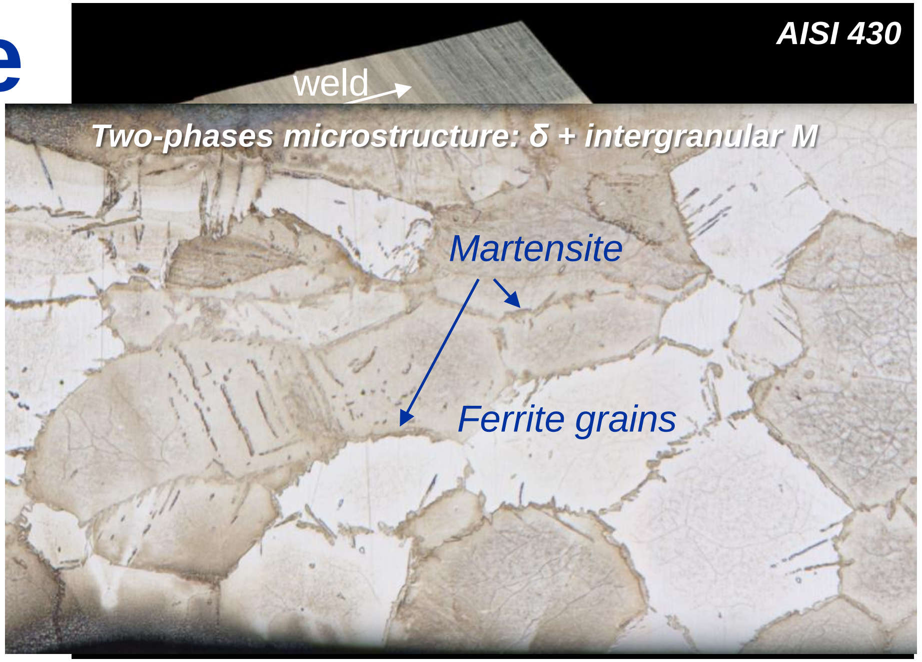
	Rm (MPa)	Rp_{02} (MPa)	A (%)	HB
AISI 304L	≥ 520*	≥ 220*	≥ 45*	≤ 180*
AISI 430	≥ 450 482	≥ 205 349	≥ 22 30	≤ 183 140
S315MC	390-510 425	≥ 315 391	≥ 20 28	- 131

	Structure	C	Mn	P	S	Si	Cr	Ni	N	Cu	Nb+Ti+V	Fe
AISI 304L	Austenitic	< 0.03	≤ 2.0	≤ 0.030*	≤ 0.015*	≤ 1.0	17.0-20.0*	10.0-12.5	0.1	-	-	balance
AISI 430	Ferritic	< 0.12 0.044	≤ 1.0 0.32	≤ 0.040 0.027	≤ 0.030 0.001	≤ 1.0 0.370	16.0-18.0 16.05	0.75 0.22	- 0.042	- 0.070	- -	balance
S315MC	Ferritic	≤ 0.12 0.042	≤ 1.3 0.45	≤ 0.025 0.0055	≤ 0.020 0.0023	≤ 0.5 0.027	- 0.05	- 0.07	- 0.007	≤ 0.22 0.17	≤ 0.22 0.0121	balance

** CERN requirements*

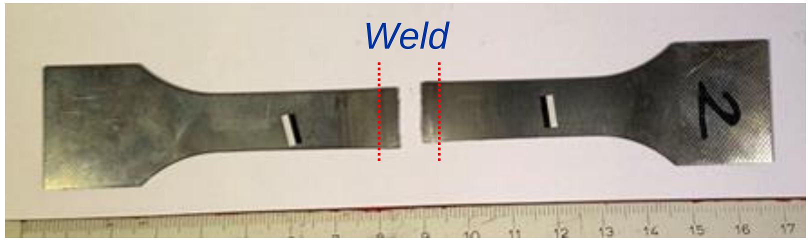
Pre-prototypes: quality assurance





AISI 430 TIG autogenous weld (1st trial): The piece presented a major failure at the level of the longitudinal weld during corrugation operation

- **RT**: The plate was **not compliant** due to the presence of isolated gas pores (Ø > 0.2 mm)
- **Metallurgical examinations:**
  - Grain coarsening → Weld grains are 10 times larger than in base material (BM)
  - Martensite (M) is present in the fusion zone at the ferrite (δ) grain boundaries
- **Mechanical testing:**
  - Tensile test → Final failure occurred along the weld centreline in a completely brittle manner
  - Micro-hardness → Important hardness increase at the fusion zone



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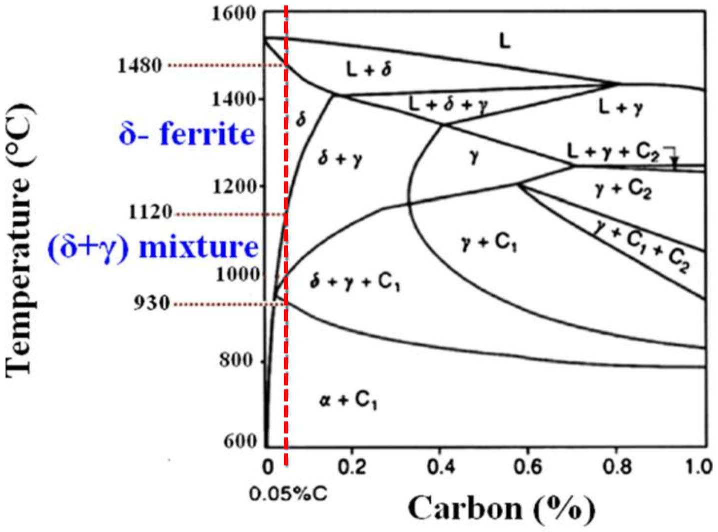


From Castro and Tricot

In the pseudo-binary diagram for a **Cr** content of **17 wt. %** and **C** within the 0.05 - 0.15 wt. % range (corresponding to the AISI 430), some austenite (γ) forms at elevated temperature along the δ-ferrite GB

This austenite transforms to M as the weld fusion zone cools to RT **L → L + F → F → F + A → F + M**

The Kaltenhauser ferrite factor (K-factor) is commonly used to predict if the microstructure is fully ferritic but does not provide information regarding the amount of M that will be present

$$\text{K-factor} = Cr + 6Si + 8Ti + 4Mo + 2Al - 40(C + N) - 2Mn - 4Ni$$

In our raw material the **K-factor = 13.3** (17.0 is the minimum value determined by Kaltenhauser for AISI 430) This factor is normally achieved by reducing C, adding ferrite stabilizing elements (Ti, Nb) or both

Other ferritic stainless steels can present better weldability → **AISI 444 to be tested**

How to improve weldability on AISI 430?

It is good practice in medium-Cr types to **limit heat input** to minimise grain growth and **optimize the cooling rate** to reduce the martensite presence preventing the degradation of the ductility and toughness at the weld region → **Composition, heat input and cooling rate are characteristics of welding process and thickness**

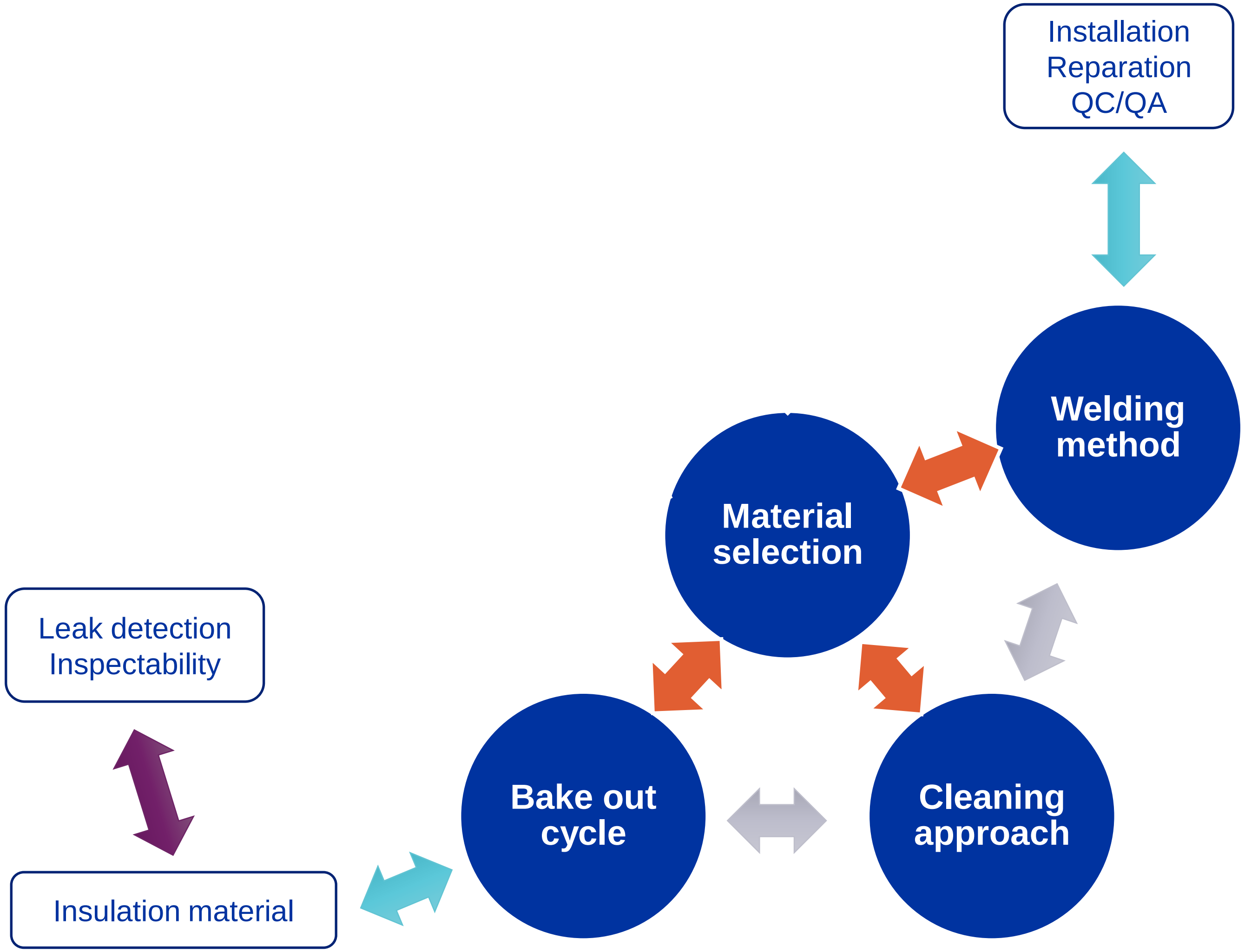
The use of austenitic consumables → Weld qualification plate performed using TIG with 308L as filler metal is for the moment RT and PT compliant → **Feasibility and cost to be evaluated…**

Cost assessment…in progress

Material selection will impact manufacturing strategy, installation and inspection plans but also future actions like service maintenance, or eventual reparations…and by hence the **final cost of the project**

AISI 304L
- ≈ **1.5** times more expensive than **AISI 430**
- ≈ **4** times more expensive than **S315MC**

The material cost per kg is not always the most important economic consideration. The final cost will be affected by other additional costs:



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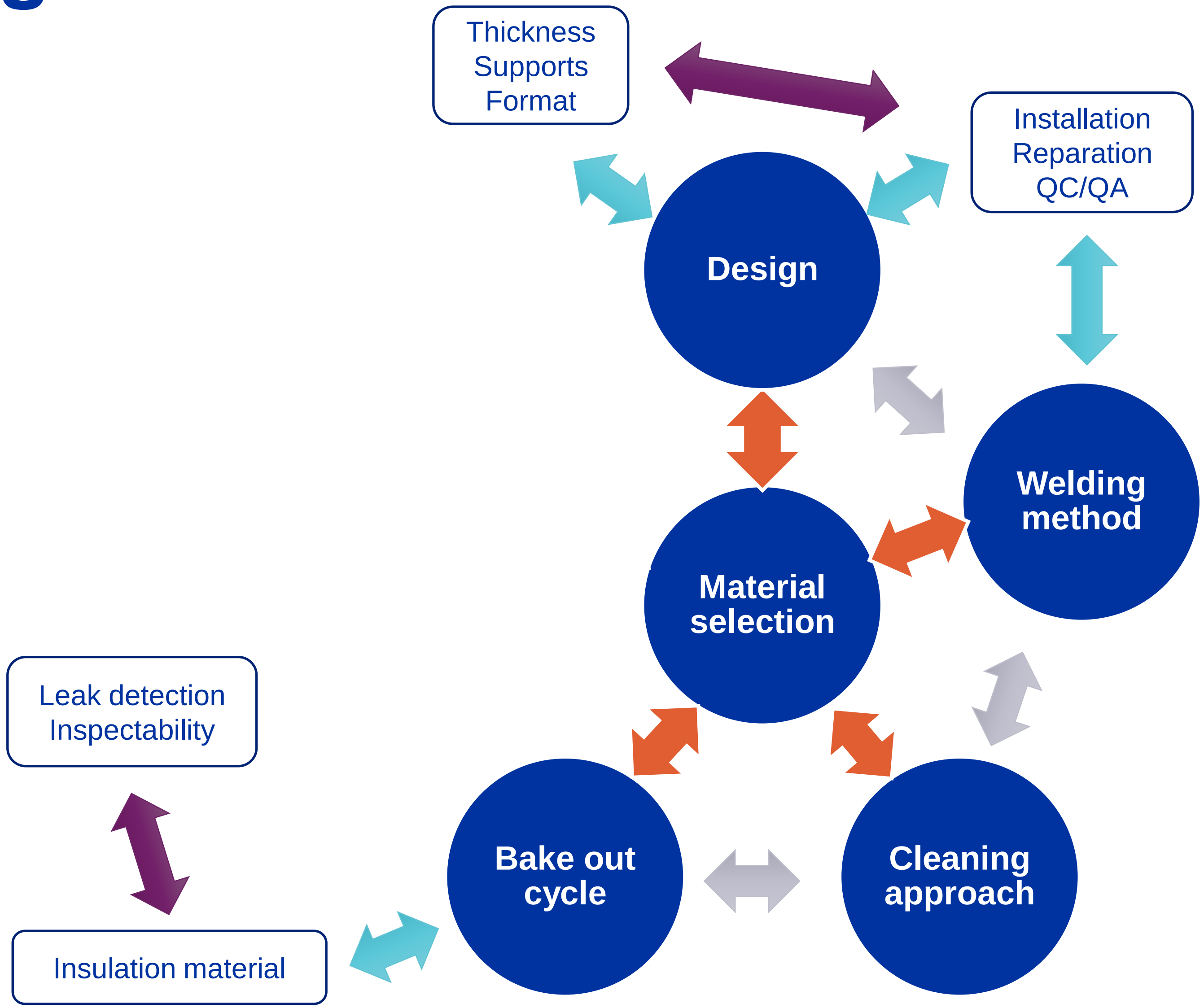

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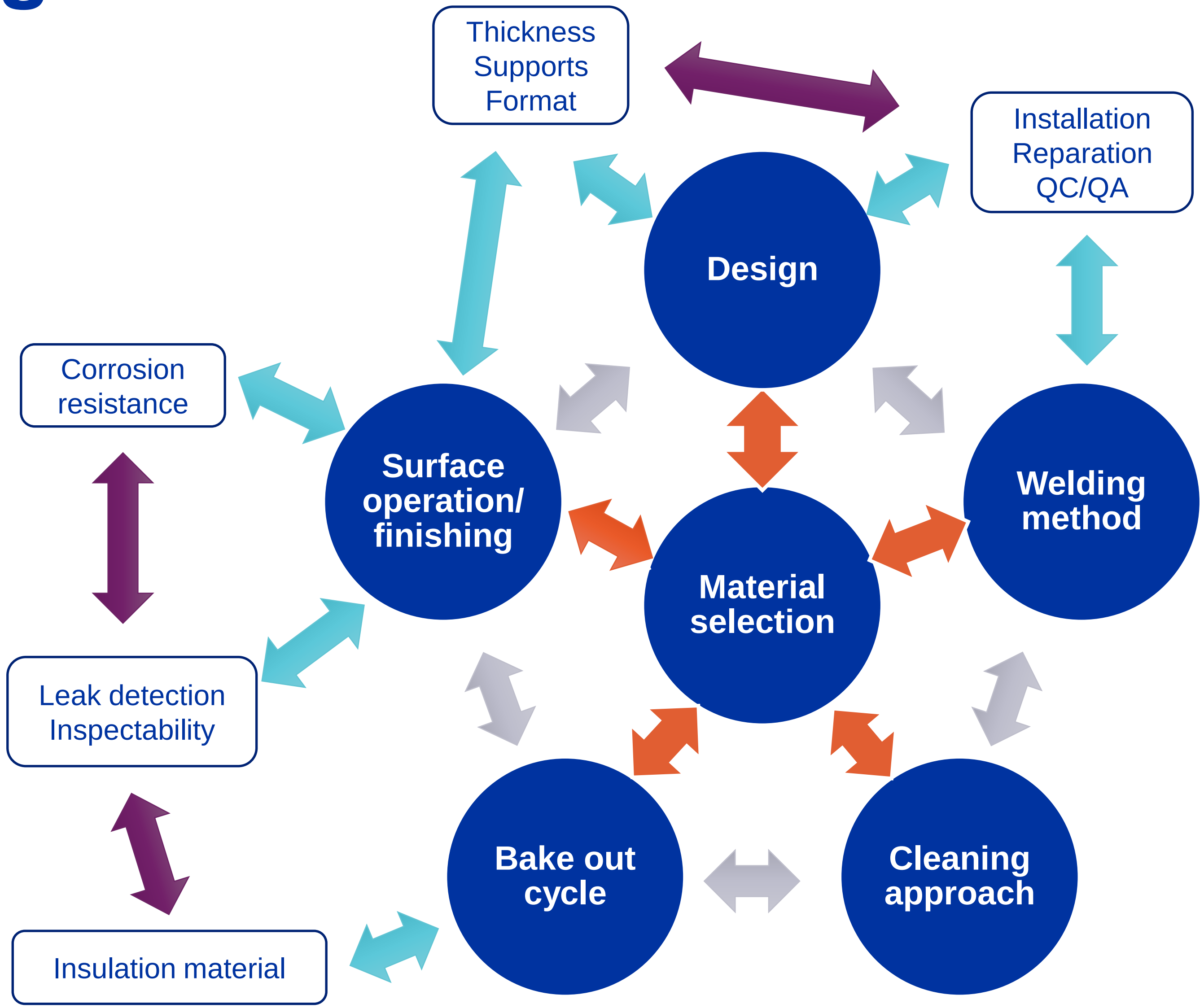

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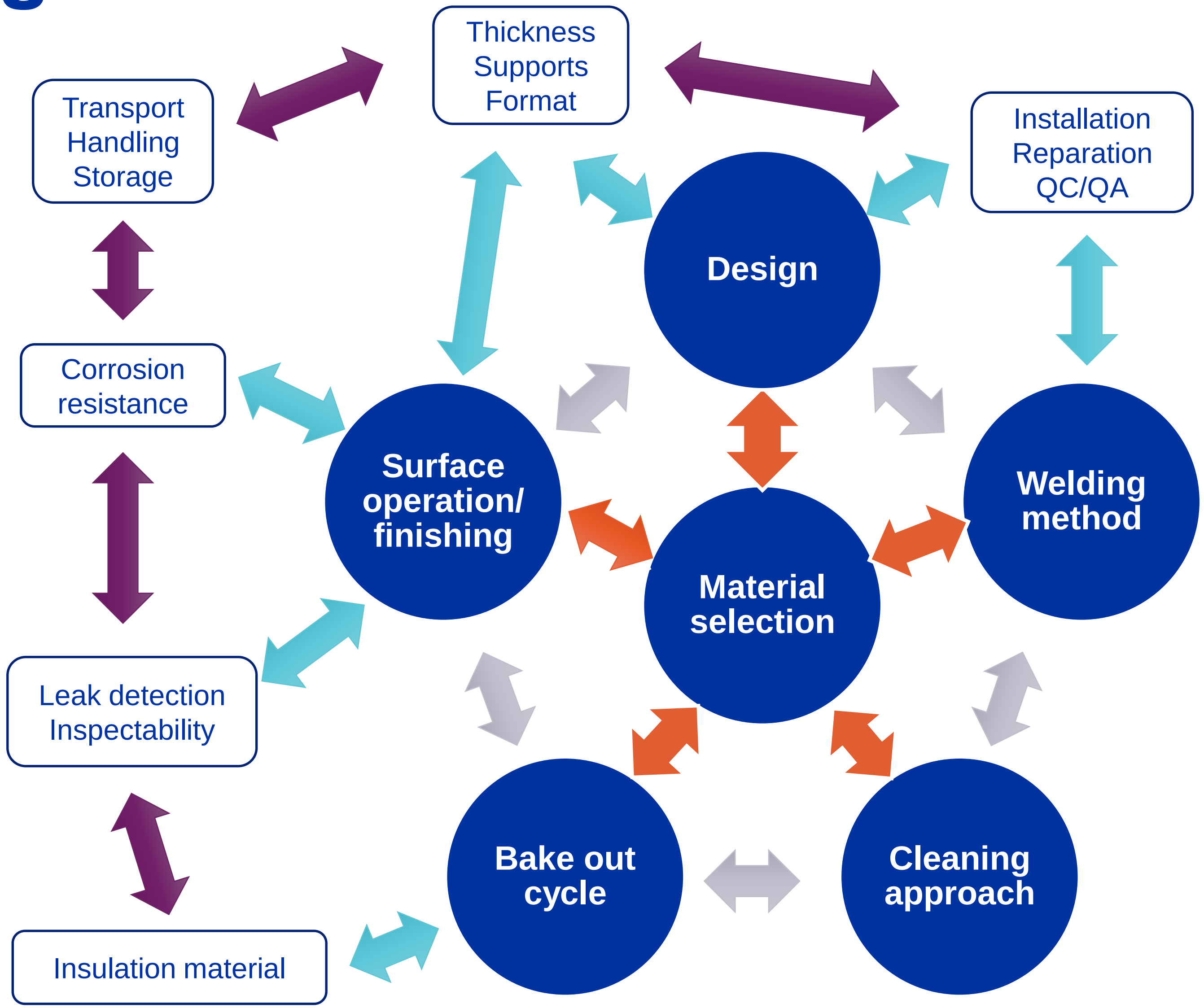
- Steel storing and handling could increase the project cost from 10 to 25% of the initial cost if facilities, taxes, insurance, deterioration, re-handling and re-inspection are considered…
- The unit price of the raw material could be increased by a factor over ten between a material available from the shelf and a material specially produced → adequate material specification



Summary

Selection of the structural materials and the appropriate manufacturing process play a crucial role in a large vacuum system like the one in ET composed by several thousand of leak tight components to be integrated

The successful selection is closely related to obtaining a **controlled microstructure and stable properties** on the **base material** but also on the **welds**

Work is in progress: Specimens fundamental **analysis** and pre-prototypes **manufacturing** and qualification to evaluate the material performance and in parallel validate production routes for each material

Next steps: Complete the manufacturing of **two additional chambers** and start the **cost assessment** of each technical solution in close collaboration with the industrial partners home.cern

Welded pipes manufacturing:

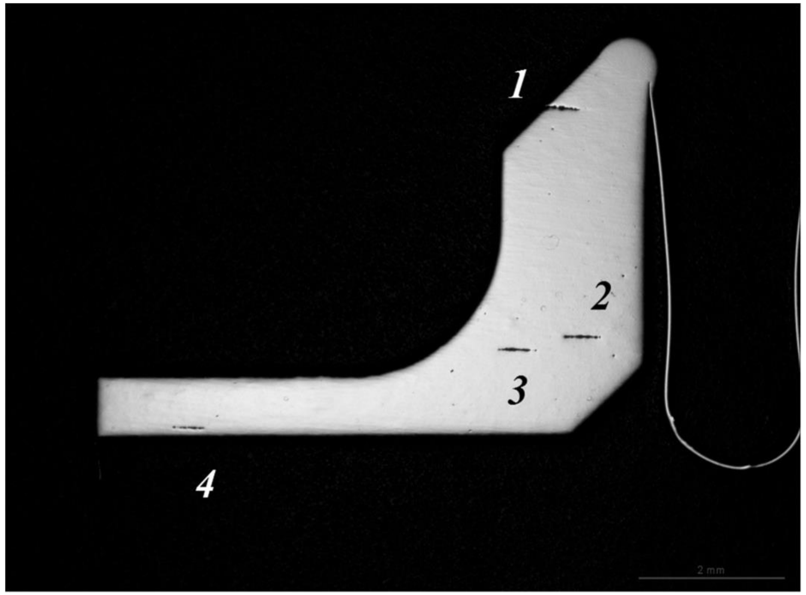
- Tech. Spec.
Analysis → Ingot/ slab production
- NDT inspection
Testing → Sheet/ coil production
- Conditioning
Edge preparation
- NDT inspection → Forming
Welding
Corrugation
- Annealing
Cooling
- NDT inspection
Testing (hydro, flattening…)
Visual and dimensional inspections → Sizing
Cutting
Straightening
- Marking
Coating
- Packaging
Storing
Shipping

Crystal structure and composition
Microstructure and mech. properties
Material cleanliness and homogeneity

Leak tightness
Geometry and tolerances

Surface reflectance
Corrosion resistance

Materials for vacuum applications: CERN



Bellow end fitting machined from an AISI 316LN round bar, showing alignment of oversized (1,2,3) and thick (4) B type inclusions up to class 2, classified according to standard ASTM E45. CERN specification [23] imposes a class of inclusions at most 1 for type B inclusions and a half-class above this limit in up to 2% of the fields counted

Leak tightness is specially critical when it comes to thin wall components like bellows

1) Impose a maximum allowed content of non-metallic inclusions.

2) Since microscopical test methods for determining the inclusion content of steel are not intended for assessing exogenous macroinclusions, impose a steelmaking process. Stainless steels are primary melted in an electric furnace and decarburized through an Argon-Oxygen Decarburization (AOD) or Vacuum-Oxygen Decarburization (VOD). These processes, consisting of a single melting step, might not guarantee alone a sufficient homogeneity of the ingot. Imposing a remelting process such as VAR or ESR ensures the homogeneity of the material will be effectively influenced. In addition, remelting reduces the impurity and the microinclusion content of the final products, allows high density and a lack of macrosegregations with shrinkage cavities to be achieved [34].

3) Specify three-dimensionally, redundantly forged products [24]. Upsetting steps allow the alignment of the inclusions which are elongated by two-dimensional steps of previous forging or rolling to be broken, thus reducing the risk of leak through the thickness.

4) Specify products with a fine and homogenous grain size.

5) Impose a final separate solution annealing rather than allowing mill-annealing from a high temperature process, in order to facilitate the achievement of a controlled, homogeneous and non-segregated microstructure [33], more easily inspectable by Non-Destructive Testing (NDT), see point 7 hereafter.

6) Avoid breaking the fibre of the product by machining walls perpendicular to the direction of the material flow, such as in the example of Fig. 3.

7) Introduce NDT such as Ultrasonic Testing (UT) not only on the final product, but also on semifinished products resulting from intermediate steps of steel processing. NDT procedures and acceptance criteria should be the object of an agreement between supplier and customer.