**Topic:** Numerical simulation of manufacturing processes: AM and FSW.

I have done the industrial training with professor Michele Chiumenti in CIMNE. During the industrial training I have been working in two different projects doing the validation and calibration of the software to solve specific problems. In the first part of the industrial training I have been working in in the numerical simulation of Additive Manufacturing of plastic pieces. And in the second part of the industrial training I have been working in the numerical simulation of Friction Stir Welding process.

# 1. ADDITIVE MANUFACTURING

The main tasks of this first part of the industrial training where:

- Validation of the software interface Add2Man for the numerical simulation of Additive Manufacturing (AM) processes by FDM technology
- Validation of the software kernel of Add2Man for the numerical simulation of Additive Manufacturing (AM) processes by FDM technology: isotropic, transversal-isotropic and orthotropic constitutive models

In the past few years additive manufacturing (AM) has evolved to one of the most promising techniques for creating components of virtually any shape based on digital models. AM (also named 3D-printing) is achieved by successively generating layers of material of different shapes and often also of varying material properties. Applications range across many fields in engineering, from non-load bearing design models for mere visualization, to parts under severe loads as in lightweight components for the automotive or aerospace industry; furthermore, AM is currently used on a day-to-day basis in medical applications, e.g. to produce patient specific implants or even to print tissue.

Over a long time the formulation and development of advanced numerical methods in the area of shape and topology optimization, even though holding great promises in improving specific objective functions, were often plagued by the non-manufacturability of the optimized parts. Thus today's additive manufacturing also represents the formerly missing link between the computer aided optimization of design and its one-to-one realisation, since from a geometric design point of view there are hardly any obstacles for AM processes.

The objective of this project is to develop a software platform for the evaluation of the mechanical performance of components fabricated by Additive Manufacturing (AM) process. In particular, the Fused Deposition Modelling (FDM) also known as Fused Filament Fabrication (FFF) will be the selected as the manufacturing technology addressed in this project.

The resulting performance of the components will be evaluated in terms of ultimate strength, component stiffness, distortions and residual stresses induced by the fabrication process. Consequently, the software platform will enable the design optimization of the components produced by AM process.

ADD2MAN is a Graphical User Interface where the end user can easily define the simulation strategy oriented to the AM process by FDM technology. This software has a mechanical solver that can consider the homogenized isotropic material behaviour, that corresponds to the simplest level of approximation, the transversely isotropic material behaviour, that takes into account the orientation of the component during the manufacturing process, and the orthotropic nature of the material behaviour due to the layer – by – layer nature of the manufacturing process.

The validation that I have been done in this first part the industrial training is only for the constitutive models for isotropic, transversely isotropic and orthotropic models. The ADD2MAN program has to take into account other properties of the process like effect induced by the thermos plastic bonding and the pre-stress effect due to the thermal shrinkage during the manufacturing process.

To perform FEA simulations and to predict the behaviour of the pieces manufactured by FDM we have to select a constitutive model governing their behaviour. Pieces manufactured by AM technologies have anisotropy. Depending on their manufacturing direction pieces have different mechanical behaviour, it depends on how the different layers are arranged in relation to the applied stress.

ADD2MAN can solve Isotropic, transversely isotropic and orthotropic materials. In the following sections we explain how this three models are defined.

## Isotropic Material

Isotropic materials are characterized by properties which are independent of direction in space. Physical equations involving isotropic materials must therefore be independent of the coordinate system chosen to represent them.

Stress and strain are related to each other by Hooke's Law where the strain is assumed to be sufficient small that stress and strain depend linearly on each other. Such a medium is called linear elastic. In its general form Hooke's law reads:

$$\boldsymbol{\sigma} = \mathbb{C} : \boldsymbol{\varepsilon}$$

where $\sigma$ is the stress tensor, $\varepsilon$ is the strain tensor and $\mathbb{C}$ is the elastic stiffness tensor.

The derivation of Hooke's Law in 3D for an isotropic material can be expressed as:

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} 1/E & -\nu/E & -\nu/E & 0 & 0 & 0 \\ & 1/E & -\nu/E & 0 & 0 & 0 \\ & & 1/E & 0 & 0 & 0 \\ & sym & & 1/G & 0 & 0 \\ & & & & 1/G & 0 \\ & & & & & 1/G \end{pmatrix} \cdot \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}$$

- $E$, is the Young's modulus.
- $G$, is the shear modulus.
- $\nu$, is the Poisson's ratio.
- $\varepsilon_i$ is the normal strain in direction $i$.
- $\gamma_{ij}$ is the shear strain in the plane $ij$.

- $\sigma_i$ normal stress in direction $i$.
- $\tau_{ij}$ shear stress in the plane $ij$.

As the properties are independent of the direction in space we have only two independent parameters which correspond to the Young modulus and the Poisson's ratio and we obtain the shear modulus as a function of these two.

$$G = \frac{E}{2(1+\nu)}$$

## Transversely Isotropic Material

The simplest anisotropic model is the a transversely isotropic medium. A transversely isotropic material is one with physical properties which are symmetric about an axis that is normal to a plane of isotropy. This transverse plane has infinite planes of symmetry and thus, within this plane, the material properties are the same in all directions.

The constitutive law for this type of material is Hooke's law, and can be written as:

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} 1/E_x & -\nu_{xy}/E_y & -\nu_{xz}/E_z & 0 & 0 & 0 \\ & 1/E_y & -\nu_{yz}/E_z & 0 & 0 & 0 \\ & & 1/E_z & 0 & 0 & 0 \\ & sym & & 1/G_{yz} & 0 & 0 \\ & & & & 1/G_{xz} & 0 \\ & & & & & 1/G_{xy} \end{pmatrix} \cdot \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}$$

Considering an isotropic plane corresponding to the $xy$ plane, we can obtain the relation between parameters and reduce the unknowns to 4 instead of 6 which corresponds to an anisotropic case.

$$E_x = E_y$$

$$\nu_{yz} = \nu_{xz}$$

$$G_{xz} = G_{yz}$$

$$G_{xy} = \frac{E_x}{2(1+\nu_{xy})}$$

The elasticity matrix can be rewritten as:

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} 1/E_x & -\nu_{xy}/E_x & -\nu_{yz}/E_z & 0 & 0 & 0 \\ & 1/E_x & -\nu_{yz}/E_z & 0 & 0 & 0 \\ & & 1/E_z & 0 & 0 & 0 \\ & sym & & 1/G_{xz} & 0 & 0 \\ & & & & 1/G_{xz} & 0 \\ & & & & & 1/G_{xy} \end{pmatrix} \cdot \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}$$

## Orthotropic Material

Orthotropic materials are a subset of anisotropic materials; their properties depend on the direction in which they are measured. They are a subset of anisotropic materials, because their properties change when measured from different directions. Orthotropic materials have three planes/axes of symmetry.

For orthotropic materials the elasticity matrix has 6 unknown parameters.

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ & S_{22} & S_{23} & 0 & 0 & 0 \\ & & S_{33} & 0 & 0 & 0 \\ & & & S_{44} & 0 & 0 \\ & sym & & & S_{55} & 0 \\ & & & & & S_{66} \end{pmatrix} \cdot \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}$$

Where:

- $\varepsilon_i$ is the normal strain in direction $i$.
- $\gamma_{ij}$ is the shear strain in the plane $ij$.
- $\sigma_i$ normal stress in direction $i$.
- $\tau_{ij}$ shear stress in the plane $ij$.

We can express this equation in terms of the Young modulus, Poisson coefficient and the shear modulus.

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} 1/E_x & -\nu_{xy}/E_y & -\nu_{xz}/E_z & 0 & 0 & 0 \\ & 1/E_y & -\nu_{yz}/E_z & 0 & 0 & 0 \\ & & 1/E_z & 0 & 0 & 0 \\ & & & 1/G_{yz} & 0 & 0 \\ & sym & & & 1/G_{xz} & 0 \\ & & & & & 1/G_{xy} \end{pmatrix} \cdot \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}$$

Where:

- $E_i$ is the Young's modulus along axis $i$
- $G_{ij}$, is the shear modulus in direction $j$ on the plane whose normal is in direction $i$
- $\nu_{ij}$, is the Poisson's ratio that corresponds to a contraction in direction $j$ when an extension is applied in direction $i$

Usually we use the product between the stiffness matrix and the deformation tensor.

# 2. FRICTION STIR WELDING

Main task for this part:

- Validation of the software for the numerical simulation of the FSW process. Calibration of the numerical tool with respect to the experimental evidence when using cylindrical pin-shape
- Calibration of the numerical tool with respect to the experimental evidence when using threaded pin-shape

In Friction Stir Welding (FSW), a rotating tool with a given profile moves forward along the weld line and generates heat. The frictional contact between the FSW tool and the workpiece and the plastic dissipation are responsible for this heat generation. As the tool moves forward, a weld is being formed by the large deformation of a thin layer of surrounding plasticized material.

The frictional heat generation occurs predominantly under the shoulder, due to its greater surface area. The contact condition between the shoulder and the workpiece can be of sliding or sticking types, depending on the value of the tangential shear strength. This strength is a function of the temperature and strain rate.

At the first glance, the process is simple as it involves only the movement of a tool through a weld line. However, the real FSW mechanism is complex as it is highly nonlinear and coupled.

During this part of the industrial training have been reading and studying how the FSW problem works. To solve this type of problem a problem type for GiD has been developed. First of all I have been working with the 2D problem to know how to define the boundary conditions and I have been reproducing the work done in different papers to be familiarized with the FSW problem.

The domain of the analysis is divided into three parts which are the Pin, the Plates and the heat affected zone (HAZ), associating a specific kinematic framework to each one of them.

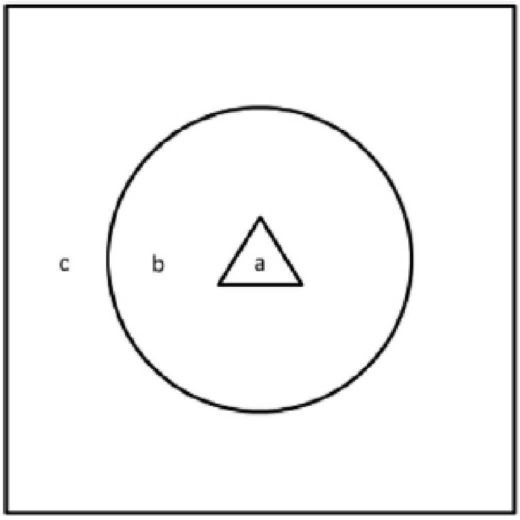


*Figure 1 Kinematic zones (a) Pin (b) HAZ (c) plate*

<u>Pin:</u> The pin (Fig. 1a) undergoes exclusively a rigid-body rotation at a constant speed and its deformation is not considered in the analysis. Thus, a Lagrangian framework is a natural choice for the description of the pin's movement.

<u>HAZ:</u> HAZ is a part of work-piece close to the pin where most of the material deformation takes place (Fig. 1b). The extent of the deformation in the vicinity of the pin is such, that it cannot be efficiently handled with a classical updated Lagrangian scheme, since it would lead to the mesh degradation and therefore necessity of a continuous re-meshing. At the same time, use of an Eulerian formulation would not be straight-forward for any pin shapes other than circular. In the case of non-circular pins, additional techniques for tracking the moving boundary would be necessary as well as redefinition of the integration domain at every time step. The ALE formulation allows overcoming the above mentioned problems provided a feasible mesh-moving strategy.

<u>Plate</u>: The area lying outside the HAZ is characterized by the material flow predominantly in the welding direction (Fig. 1c). As in this area the domain neither changes its shape nor contains moving boundaries, the Eulerian framework can be used. The use of fixed mesh facilitates the application of boundary conditions on the inflow and outflow.

It is easy to notice that the 2D problem is a simplification of the real problem. To reproduce the real problem, we are using 3D models. First of all, an as in the 2D case, I have been studying and reading what has been done for the moment and reproducing the problems. I have been working with 3D models with circular pins, which are a simplification of the problem. The same parts described above are considered having a ALE formulation in the HAZ zone, an Eulerian formulation in the plate and a Lagrangian formulation in the Pin.

A more realistic simulation has been carried out using the pin geometry given by the industrial partner (SAPA) in Fig. 2 the threaded pin can be seen.

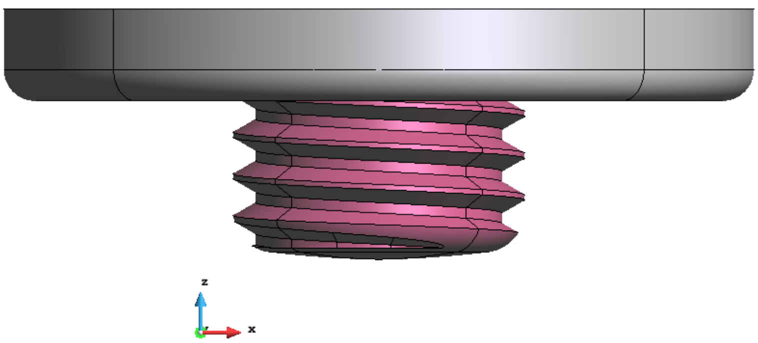


*Figure 2 Threaded pin*

To reproduce the FSW problem one of the important things is to define properly the friction law between the pin and the HAZ and the shoulder and the HAZ. There exist some friction models to describe this, but during the industrial training I have been working with the modified Norton's friction law proposed by the researchers. This modified Norton's law takes into account the effects of a non-uniform distribution of the pressure filed below the shoulder. The experimental evidence suggests higher values of friction at the front side of the shoulder reducing in the rear part. This is consistent with the pressure distribution in FSW where the head of the pin-tool suffers higher compression than the rear part. Hence, the model proposed assumes a modified consistency parameter depending on the actual position of each point at the contact interface with respect to the rotation axis and the advancing velocity. The modified equation reads:

$$\tau_T = \alpha(x,T)\|\Delta \boldsymbol{v_T}\|^{q-1}\Delta \boldsymbol{v_T} = \alpha(\theta,T)\|\Delta \boldsymbol{v_T}\|^{q}\boldsymbol{n}$$

The non – symmetric definition of the consistency parameter $\alpha(\theta,T)$ is defined by the following expression

$$\alpha(x,T) = 0.5(\alpha_{max} + \alpha_{min} - (\alpha_{max} - \alpha_{min})tanh\frac{x}{R/6})$$

being x the distance of each point located at the tool/workpiece interface from the rotation axis projected along the welding direction and R the shoulder radius.

Many simulations have been carried out using this friction model. It is important to notice that when $\alpha \approx \infty$ reproduces a stick condition between the pin and the HAZ, and when $\alpha \approx 0$ we are reproducing a slip condition. In table 1 some are showed some of the ran simulation to calibrate the model respect to the experimental evidence when using threaded pin-shape. The obtained results are compared with the circular pin and the experimental results given by SAPA.

It is important to notice that we have defined a finer mesh in the threaded pin and around the pin to capture the higher temperature gradient originated in the HAZ. In Fig. 3 it can be seen the used mesh.

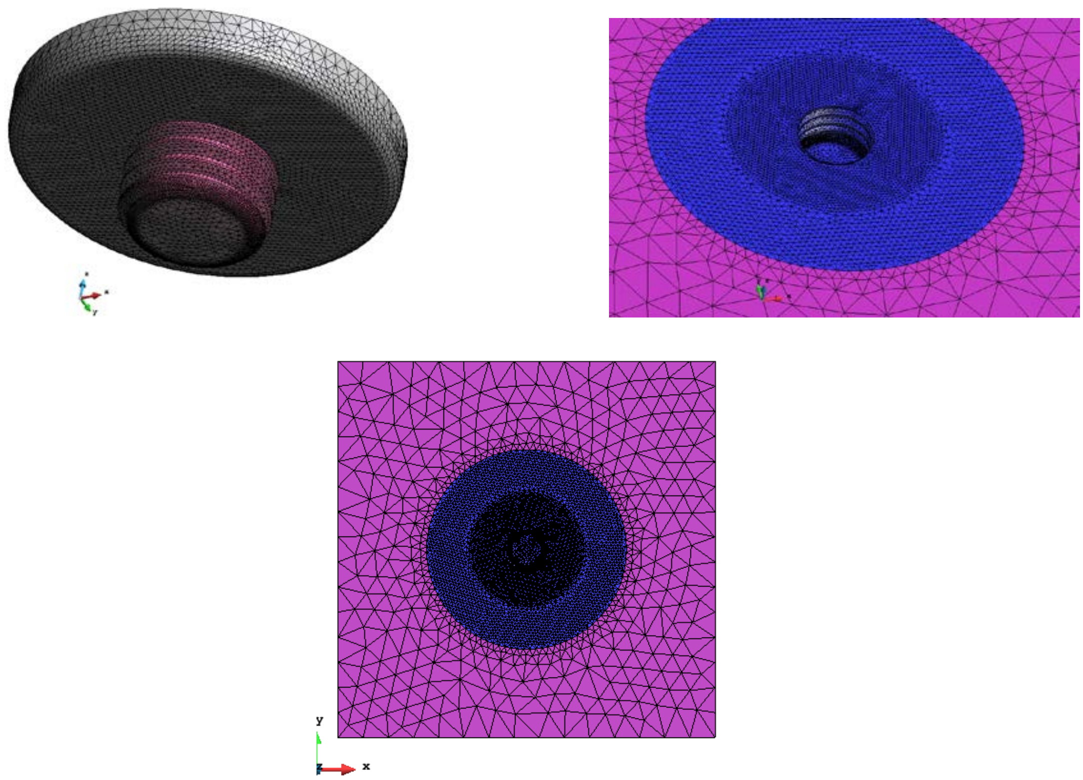

*Figure 3 Mesh for the modeled pice*

This model is not implemented in the FSW GiD problem type, so to solve this problem I have been using COMET (Coupled Mechanical and Thermal Analysis) where the modified Norton's friction law is implemented and the friction condition between the Pin – HAZ and Shoulder –HAZ can be changed.

In Fig. 4 the temperature distribution for **PIN_SAPA_fric_pin_shol_3_2** is showed.

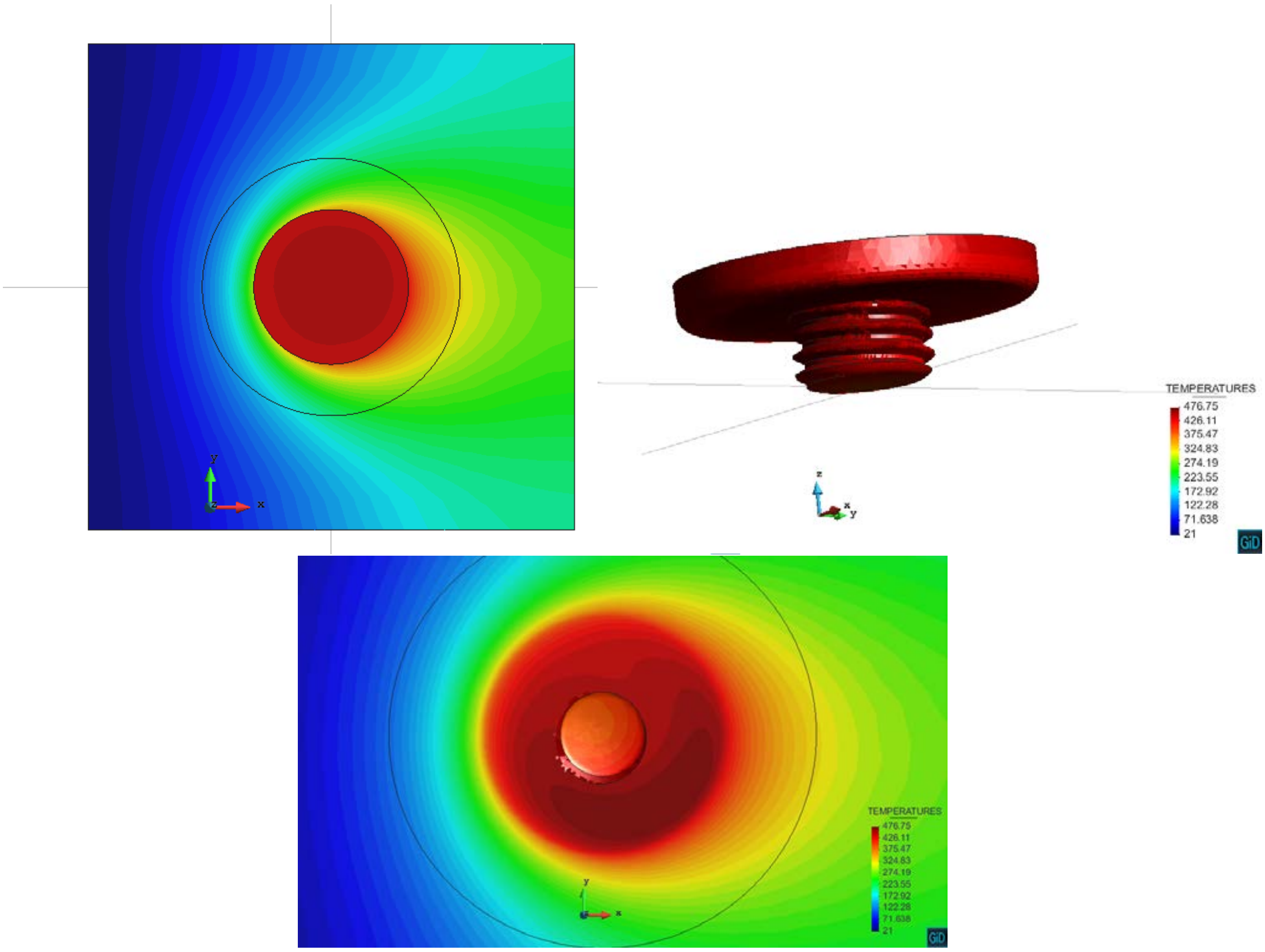


*Figure 4 Temperatures for PIN_SAPA_fric_pin_shol_3_2 model*

For the calibration is also interesting to see the evolution of different thermocouples located in different parts of the workpice to see their evolution. The idea is to compare the experimental result with the results obtained from the simulation. Although it is interesting I did not have time to analyse all the thermocouples for all the studied models.

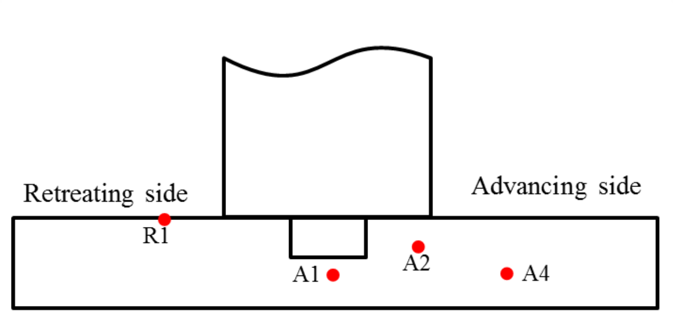


*Figure 5 Scehmatic location of thermocouples*

*Table 1 Parameters used for the diferent 3D simulation to calibrate the threaded pin with the experimental results obtained by SAPA.*

| File name | | FRICT | PREXP | RSHOL | max temperature | min temperature | MAX Reaction x | MAX Reaction y | MAX Reaction z | MAX Torque z |
|---|---|---|---|---|---|---|---|---|---|---|
| PIN_SAPA_fric_pin_shol_3 | Pin<br>Shoulder | 5,00E+08<br>4,00E+08 | 1<br>1 | 5,450E-04<br>1,375E-03 | 473,08 | 21 | 1140,00 | 4360,00 | 6639,99 | 87,40 |
| PIN_SAPA_fric_pin_shol_3_1 | Pin<br>Shoulder | 5,00E+08<br>4,00E+08 | 1<br>1 | 5,450E-04<br>1,375E-03 | 475,72 | 21 | 1150,00 | 4430,00 | 8040,00 | 87,40 |
| PIN_SAPA_fric_pin_shol_3_1_1 | Pin<br>Shoulder | 5,00E+08<br>5,00E+08 | 1<br>1 | 5,450E-04<br>1,375E-03 | 4754,76 | 21 | 1120,00 | 4060,00 | 8040,00 | 87,60 |
| PIN_SAPA_fric_pin_shol_3_1_2 | Pin<br>Shoulder | 6,00E+08<br>6,00E+08 | 1<br>1 | 5,450E-04<br>1,375E-03 | 476,24 | 21 | 1060,00 | 2910,00 | 8080,00 | 90,30 |
| PIN_SAPA_fric_pin_shol_3_2 | Pin<br>Shoulder | 7,00E+08<br>4,00E+08 | 1<br>1 | 5,450E-04<br>1,375E-03 | 476,75 | 21 | 1100,00 | 2450,00 | 8030,00 | 91,60 |
| Circular PIN | Pin<br>Shoulder | 1,00E+06<br>1,00E+08 | 1<br>1 | | 464,22 | 21 | 2800,00 | 1700,00 | 8000,00 | 57,50 |
| SAPA | | | | | | | 500 | 1400 | 8200 | 64 |

FRICT corresponds to $\alpha(\theta, T)$

PREXP corresponds to $q$

$$RSHOL = \frac{radius\ of\ the\ pin\ or\ the\ shoulder}{6}$$

# 3. CONCLUSIONS

Working in the validation and calibration of Additive Manufacturing processes and Friction Stir Welding technology has given me experience in the application of real processes that need to be simulated.

During my degree and the master courses I have been using GiD as a finite element program, but I did not have experience in 3D models and for me has been really useful as in my master thesis I am working with a 3D model and for sure in the future I apply all the knowledge to other processes.

On the other hand I have been learning to deal with new problems like FSW which I had to study and read papers to get to know the problem and see it the obtained solution make sense compared with the experimental results.