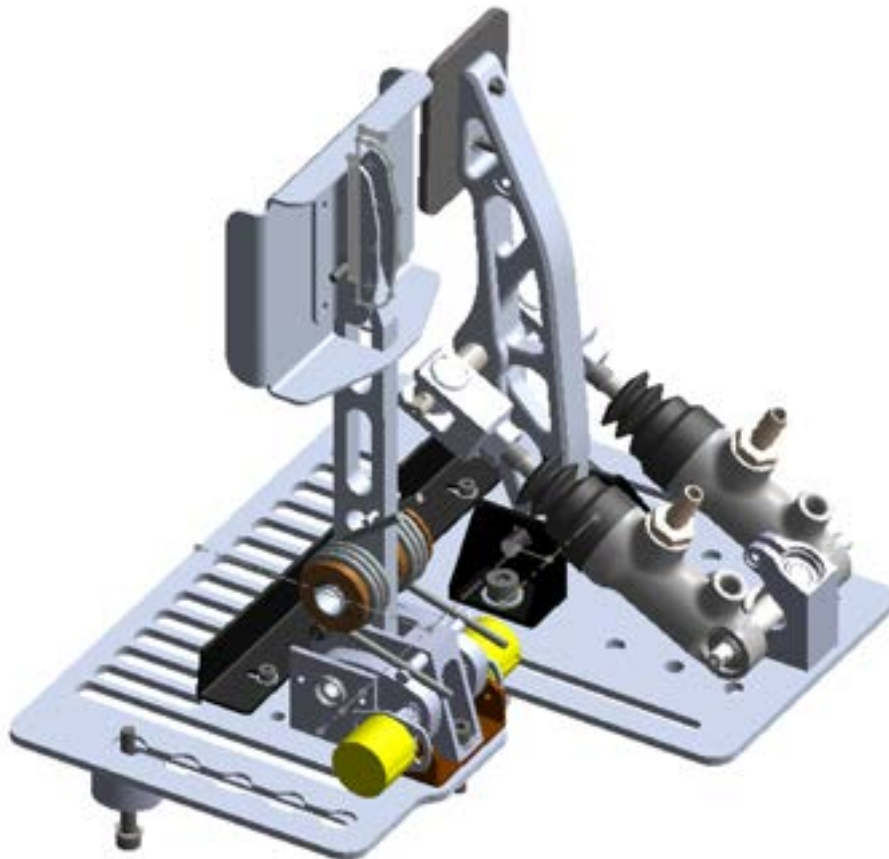




UNIVERSITÀ DI PISA

Tecnologia Meccanica

Brake system



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INTRODUCTION

This report describes the manufacturing processes used to produce selected components of the braking system of the Formula Student single-seater, ET-17. For each of the main manufacturing technologies considered—casting, machining, plastic forming, additive manufacturing (3D printing), and welding—a representative component has been analyzed.

The components examined are, respectively: the brake pedal lever, sensor gear, accelerator pedal plate, adjustment gear, and brake pedal plate.

To distinguish the contributions of the two authors, the sections of the report are highlighted using two different colors:

- **Black:** Sara Squeglia (677183)
- **Blue:** Lavinia Bertini (681895)

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1. Project objective

The objective of this project is to define the manufacturing processes of selected components of a chosen product and to document the entire study within a technical report.

After selecting the product and designing the corresponding assembly, the manufacturability of some of its components will be analyzed. These components will also be investigated through their respective digital models created using CAD software.

The work includes the creation of photorealistic renderings of the individual components, the exploded view, and the complete assembly within the CAD environment. Subsequently, the technical drawings of the analyzed components and of the overall assembly will be developed.

The analysis of the manufacturing processes will include the study of some of the most widespread industrial technologies, such as casting, plastic forming, additive manufacturing (3D printing), machining processes, and welding.

During the design phase, the production times and costs associated with manufacturing will also be evaluated, in order to ensure a technically and economically optimized solution.

1.1. Assembly selection

The selected assembly is the braking system of the 2025 single-seater developed by the University of Pisa's racing team, E-Team Squadra Corse.

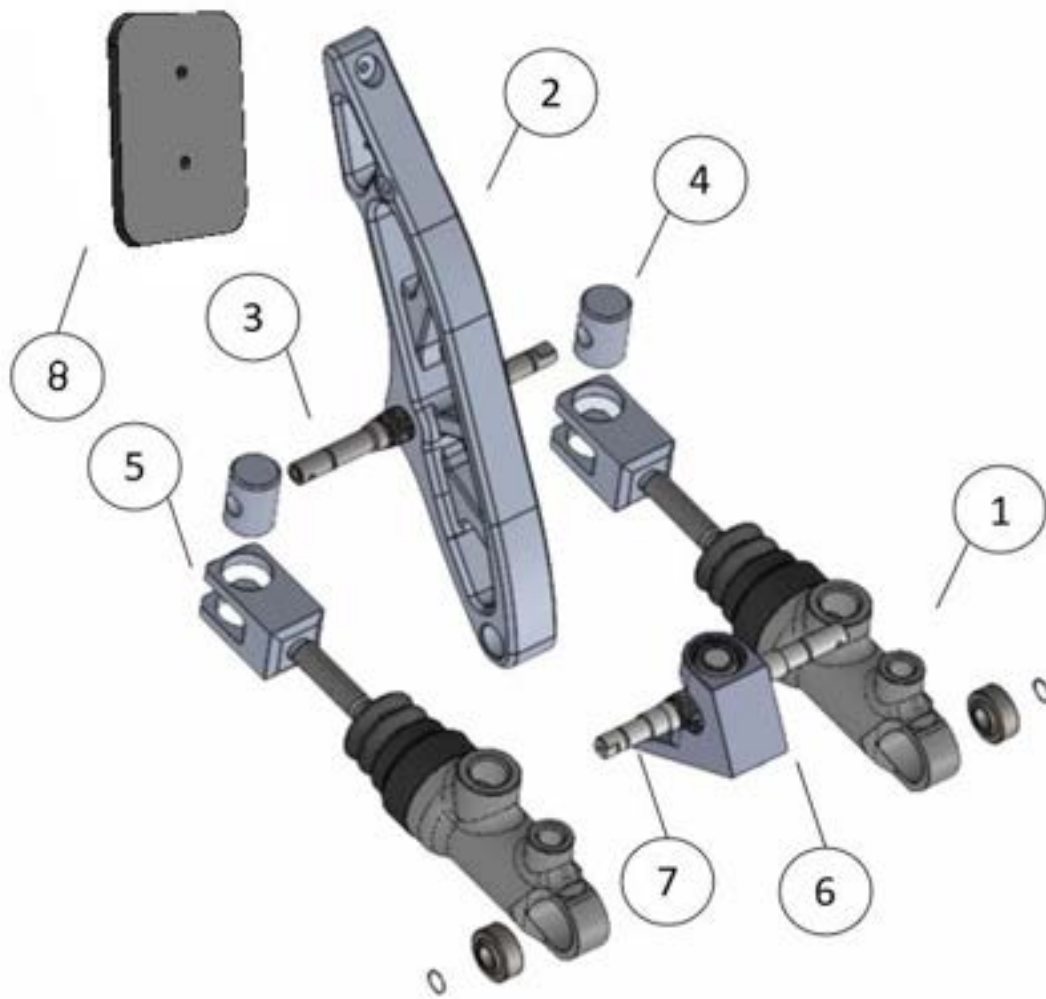
The selection of this assembly was driven by a combination of personal and educational motivations. In particular, active participation in the racing team provided direct experience with this type of product, while the interest in vehicles and their operating dynamics further influenced the choice.

2. Identification of subassembly components

Due to the considerable complexity of the complete braking system assembly, which consists of a large number of commercial and detailed

components (approximately 123), the system has been divided into its main functional subassemblies.

This approach allows for a clearer representation of the system structure and enables the components selected for the subsequent manufacturing analysis to be identified more easily. For each subassembly, an exploded view is therefore provided, together with the corresponding component numbering.



No.	Name	Quantity
1	Rear Master Cylinder	2
2	Brake pedal lever	1
3	Auxiliary Bar	1
4	Pin	2

5	Clevis	2
6	BB. Main Body Supp.	1
7	Balance Bar	1
8	Pedal Plate	1



No.	Name	Quantity
1	Accelerator pedal lever	1
2	Accelerator pedal plate	1

3	Throttle pedal spring bushing	2
4	Adjustment gear	2
5	Pedals spring	2
6	Throttle pedal spring shaft	1
7	Sensor cover	2
8	Hall effect sensor	2
9	Hex socket head cap screw	4
10	Pedal support	1
11	Sensor gear	2

3. 3D rendering of the components

The following section includes the 3D renderings of some of the most relevant components considered in the analysis. Each component was modeled using SolidWorks, and the complete assembly was also created within the same software environment.

The renderings were subsequently generated using SolidWorks Visualize.

Not all the components listed in the following sections will be considered for the purposes of our analysis and technical report. The selected components will be easily identifiable, as they are highlighted.



Auxiliary Bar



Pin



Brake Pedal Lever



Sensor gear



Support plate



Brake pedal plate



Adjustment gear

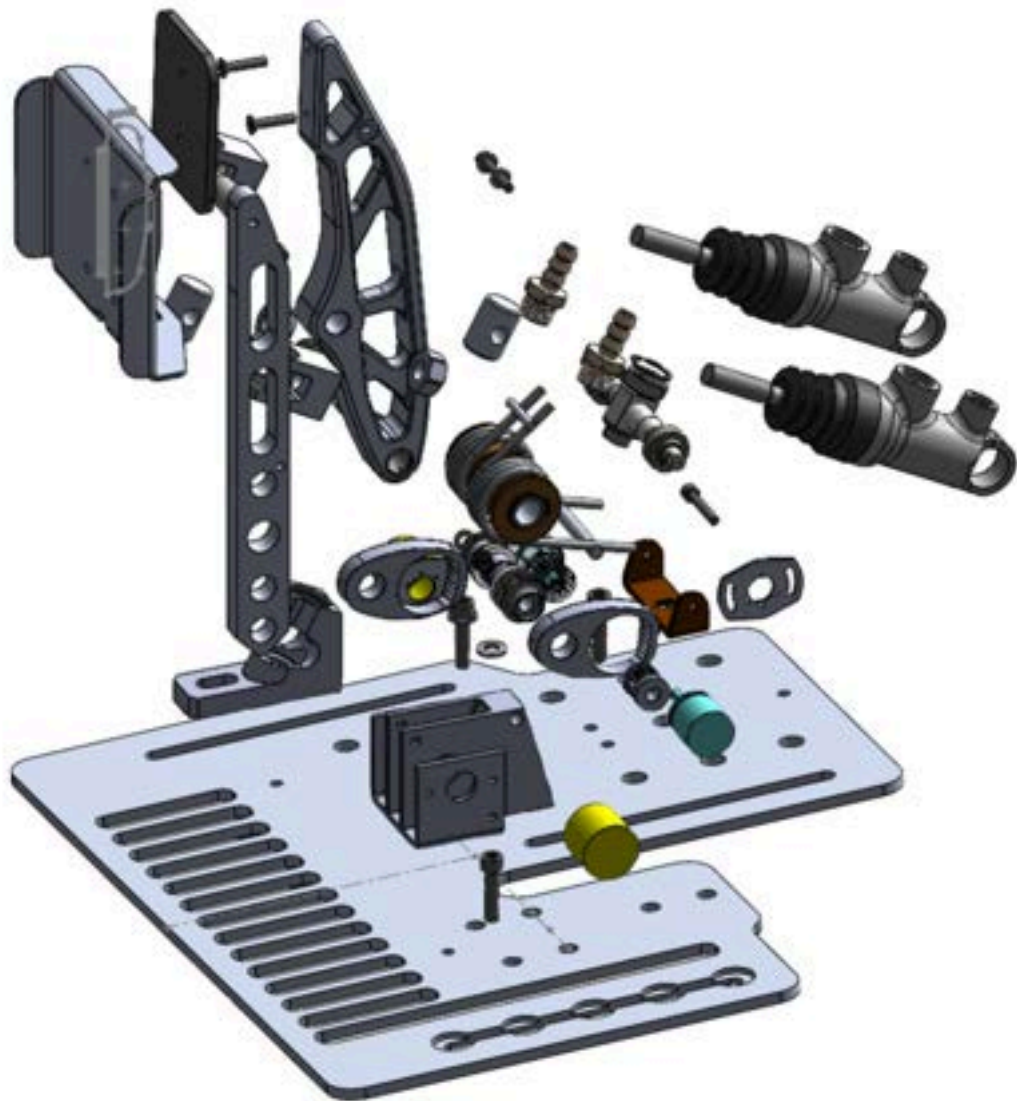


Rear Master Cylinder



Throttle pedal plate

4. Exploded view of the assembly



5. Customer requirements

In this project, the customer is represented by E-Team, the University of Pisa's Formula Student racing team.

The requirements of the braking system are therefore derived from the performance objectives of the race car, the constraints imposed by the Formula Student regulations, and the driver's safety requirements.

Safety Requirements

- Ensure sufficient deceleration to successfully pass the Brake Test specified in the Formula Student regulations.
- Guarantee complete system reliability under all operating conditions.
- Ensure the structural integrity of all components.

Regulatory Requirements

- Full compliance with the official Formula Student regulations.
- The braking system must be capable of locking all four wheels simultaneously during the Brake Test.
- Components must comply with the prescribed dimensional requirements.

Performance Requirements

- High braking performance.
- Excellent pedal modulation and sensitivity.
- Thermal stability during prolonged operation, particularly throughout the Endurance Event.
- Proper front-to-rear brake bias.

Economic and Manufacturing Requirements

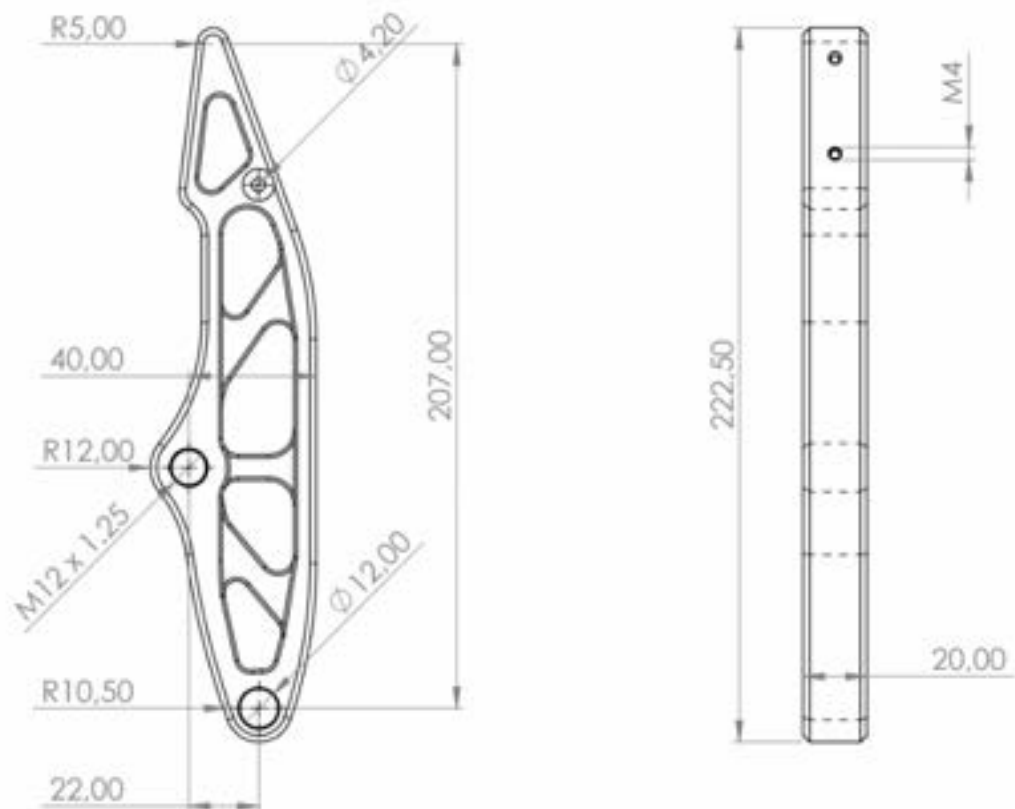
- Manufacturing costs compatible with the team's budget.
- Components manufacturable using the available production processes.
- Production lead times compatible with the Formula Student competition schedule.

Since the braking system is intended for a one-off Formula Student race car, it is not designed for mass production.

6. Component introduction: brake pedal lever

The brake pedal lever is a mechanical component used in braking systems for vehicles and industrial machinery. In this application, the lever transmits the force applied by the driver's foot to the braking mechanism.

The component features a lightweight design with hollow sections and internal reinforcing ribs, reducing weight without compromising structural strength. Several holes are incorporated to enable the assembly of the component within the larger braking system.



6.1. Material selection

For the manufacture of the component, the **AlSi7Mg (EN AC-42100)** aluminum alloy was selected, as it provides an excellent balance between

castability, mechanical strength, and low weight. After an appropriate T6 heat treatment, the alloy exhibits suitable mechanical properties and good fatigue resistance, which is a key requirement for a component such as the brake pedal lever that is subjected to cyclic loading.

The main factors that motivated this material selection are:

- **Compatibility with the Casting Process**

AlSi7Mg exhibits excellent castability, characterized by high fluidity, low susceptibility to hot cracking, good weldability, and good machinability after casting. These characteristics make it particularly suitable for the selected manufacturing process.

- **Mechanical Requirements**

The brake pedal lever is subjected to bending loads, cyclic stresses, and potential stress concentrations around the pivot hole. Consequently, the material must provide:

- High tensile strength;
- Good ductility;
- Low density;
- Adequate yield strength.

The **AlSi7Mg-T6** alloy offers an excellent compromise between these requirements.

Mechanical and Physical Properties

Property	Value
Yield Strength (Rp _{0.2})	190-230 MPa
Ultimate Tensile Strength (Rm)	250-320 MPa
Elongation at Break	3-8 %
Density	2.68 - 2.70 g/cm ³
Young's Modulus	≈ 70 GPa
Thermal Conductivity	150 - 170 W/mK

Economic Considerations

Since this project is developed within the Formula Student framework, manufacturing costs must also be taken into account.

The AlSi7Mg alloy is widely available, economically affordable, and typically costs approximately €3–5/kg, depending on market conditions. Given the relatively low mass of the brake pedal lever, the material cost represents only a small fraction of the overall manufacturing cost.

Furthermore, because the alloy is commonly used in the foundry industry, it does not require special procurement procedures or significant logistical expenses.

6.2. Manufacturing process selection: investment casting

The brake pedal lever will be manufactured using the **investment casting** process. This manufacturing route was selected primarily because of the very low production volume, consisting of a single component. Under these conditions, processes requiring dedicated permanent tooling, such as permanent mold casting, would not be economically viable.

Investment casting enables the production of components with complex geometries, high dimensional accuracy, and excellent surface finish, thereby minimizing the amount of subsequent machining required. These characteristics are particularly advantageous for the brake pedal lever, which incorporates weight-reduction features and intricate geometric details designed to minimize mass without compromising structural strength.

Since the component is intended as a one-off prototype, investment casting represents the most suitable solution, providing the best compromise between tooling costs, design flexibility, and the quality of the final component.

6.3. Component analysis

6.3.1. Thickness analysis

A preliminary wall thickness analysis was performed on the CAD model to assess the compatibility of the component geometry with the investment casting process. A uniform wall thickness distribution helps minimize differential solidification, thereby reducing the likelihood of casting defects such as shrinkage cavities and microporosity.

The component exhibits an excellent overall uniformity of wall thickness, making its geometry fully compatible with the selected manufacturing process. The only significant variations in cross-section occur at the junctions of the internal reinforcing ribs.

In these localized regions, the risk of differential solidification and localized shrinkage is mitigated by both the excellent castability of the AlSi7Mg alloy and the appropriate design of the fillet radii, which prevent abrupt geometric transitions and promote a sufficiently uniform solidification process.

6.3.2. Critical areas

A critical areas analysis was carried out to identify the regions of the component that are most susceptible to defect formation during the investment casting process and to evaluate potential structural criticalities.

The brake pedal lever features a lightweight design incorporating internal pockets and reinforcing ribs, a design solution that reduces the overall mass while maintaining high bending stiffness. However, the intersections between the ribs and the outer walls create localized increases in the effective wall thickness. These regions act as thermal nodes (hot spots), where the molten metal cools and solidifies more slowly than in the surrounding thinner sections.

During solidification, this difference in cooling rate may promote the formation of shrinkage microporosity if the feeding system is unable to adequately compensate for the volumetric contraction of the alloy.

Particular attention was also paid to the filleted transitions between the central body of the lever and its mounting ends, where the component experiences the highest mechanical stresses during operation. In these areas, appropriately sized fillet radii reduce stress concentrations while simultaneously improving molten metal flow during mold filling and promoting a more uniform solidification process.

The analysis shows that the component does not exhibit significant section thickness variations or mass concentrations that could compromise casting quality. Therefore, the identified critical areas can be effectively managed through the proper design of the gating and feeding systems.

6.3.3. Component geometry evaluation

The geometry of the brake pedal lever is overall well suited to the investment casting process. The component features relatively simple and regular shapes, nearly uniform wall thicknesses, and numerous fillet radii, all of which promote efficient mold filling and a progressive, uniform solidification of the casting.

6.4. Prototype manufacturing technology selection

To produce the pattern required for the investment casting process, 3D printing using castable resin was selected. This solution is particularly suitable because the component is intended to be manufactured as a single prototype. Consequently, producing a conventional metal mold would not be economically justified.

The manufacture of a permanent mold would require a significant initial investment, which can only be justified for high-volume production. In the case of a one-off component, such an approach would unnecessarily increase both production costs and lead times.

The use of castable resin makes it possible to directly produce the sacrificial pattern required for investment casting, eliminating the need to design and manufacture dedicated tooling. During the ceramic shell preparation process, the resin pattern is subsequently removed by thermal burnout, leaving a cavity that precisely reproduces the geometry of the component to be cast.

This approach significantly reduces tooling costs and production time while maintaining high dimensional accuracy, making it particularly well suited for prototype and low-volume manufacturing.

6.5. Casting pattern design

Starting from the final CAD model, several modifications were introduced exclusively for the design of the casting blank.

These modifications do not affect the functional geometry of the component but are intended to ensure that the casting meets the required quality standards.

6.5.1. Definition of fillet radii

In the analyzed component, most of the sharp edges were eliminated during the CAD design stage by introducing fillet radii between adjacent surfaces. This design choice promotes a smoother flow of the molten metal within the ceramic shell cavity and reduces the likelihood of turbulence during mold filling.

The existing fillet radii are fully compatible with the investment casting process and do not require any further modifications to the original design geometry.

The fillet radii already incorporated into the design are highlighted in blue.



6.5.2. Definition of machining allowances

Although investment casting enables the production of components with high dimensional accuracy and good surface finish, some surfaces of the brake pedal lever require subsequent machining operations to ensure compliance with the dimensional and geometric tolerances specified in the design.

For this reason, appropriate machining allowances were introduced in the casting blank design exclusively on the functional surfaces that will undergo machining processes. In particular, machining allowances were applied to the main bore intended for the rotation pin, the hole dedicated to the auxiliary bar, and the reference surfaces used for component positioning during subsequent machining operations.

For components manufactured through investment casting in AlSi7Mg alloy, machining allowance values are generally between 0.5 mm and 1 mm

per side, depending on the component size and the required accuracy. In this project, a value of 0.8 mm was adopted, as it was considered suitable to ensure the complete removal of the surface layer resulting from the casting process and to achieve the final dimensions through machining operations.

The application of machining allowances was limited exclusively to functional surfaces, avoiding unnecessary increases in casting volume and consequently reducing both material consumption and subsequent machining times.

6.5.3. Shrinkage compensation

During cooling after pouring, the aluminum alloy undergoes shrinkage due to solidification and the reduction in temperature until reaching ambient conditions. This phenomenon causes a reduction in the casting dimensions compared to the original pattern and must therefore be taken into account during the tooling design phase.

For the AlSi7Mg alloy, the linear shrinkage can be assumed to be approximately 1.2%, a value commonly adopted for components manufactured through investment casting.

Shrinkage compensation is achieved by appropriately increasing the dimensions of the pattern used to manufacture the wax injection die. This operation allows the final component, after solidification, to achieve dimensions close to the nominal design values.

Since shrinkage affects the entire component uniformly, compensation is applied through a global scaling factor of the pattern and does not alter the relative geometry between the different surfaces. Any remaining dimensional deviations are subsequently corrected through the planned machining operations.

6.6. Solidification analysis

Before carrying out the numerical simulation, it is advisable to perform a theoretical evaluation of the component's behavior during solidification. This analysis allows the identification of areas that, due to their geometric characteristics, are expected to cool more slowly and are therefore more susceptible to the formation of shrinkage porosity.

6.6.1. Calculation of the solidification modulus

The **solidification modulus** is defined by the following relationship:

$$M = V/S$$

where:

- **M**: solidification modulus
- **V**: volume of the analyzed region
- **S**: heat-dissipating surface area

For the evaluation of the component's solidification modulus, the entire geometry was considered as a **single equivalent volume**, avoiding a subdivision into multiple sections characterized by different surface-to-volume ratios. This approach allows the calculation of an average value representative of the overall casting behavior, providing a general indication of the component's ability to retain heat during the solidification process.

The solidification modulus was therefore calculated as the ratio between the total component volume and its overall heat exchange surface:

$$M = V/S$$

where **V** represents the total casting volume and **S** the total surface area through which heat is dissipated to the environment or to the mold material.

$$V=84775,53 \text{ mm}^3$$

$$S=26830,67 \text{ mm}^2$$

$$M= 84775,53/26830,67= 3,1597 \text{ mm}$$

Since the obtained modulus represents an average value referred to the entire geometry, it does not describe the local variations in thermal behavior caused by the presence of regions with different thicknesses. In particular, areas characterized by a higher material accumulation will locally exhibit a higher solidification modulus than the calculated average value and will therefore require longer solidification times.

These regions represent the last portions of the casting to solidify and are potentially critical for the formation of shrinkage defects, requiring particular attention during the design of the feeding system.

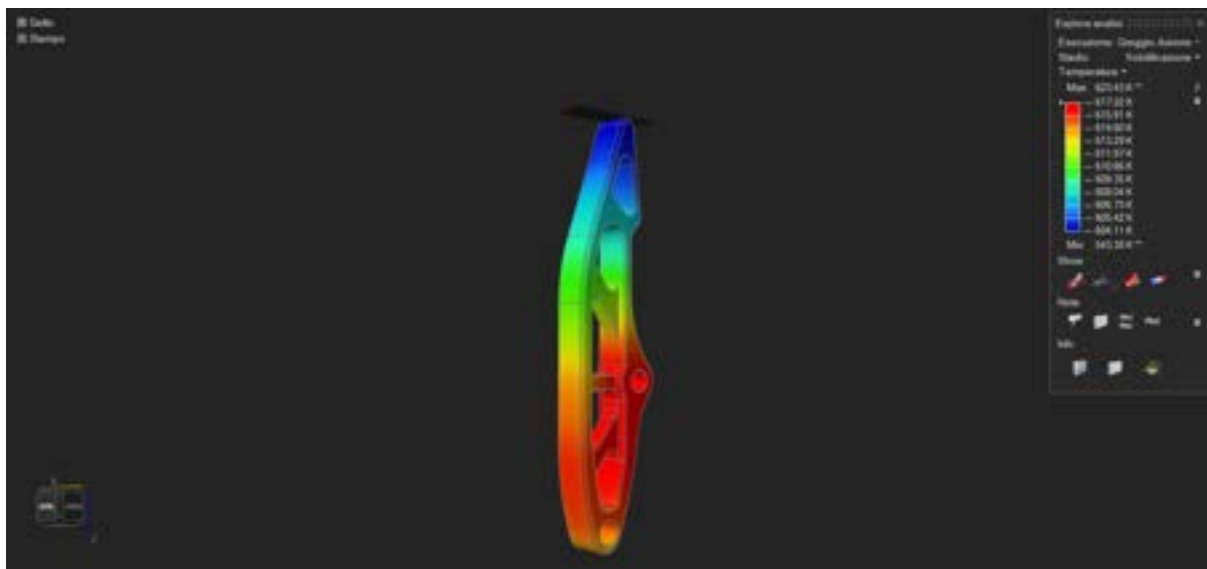
6.6.2. Solidification simulation

Altair Inspire Cast software was used to verify the accuracy of the identification of the final solidification regions.

The areas that maintain low solid fraction values or higher temperatures for a longer period correspond to the regions that complete solidification last.

The simulation therefore confirms the identification of the two areas characterized by the highest material accumulation and the largest local thicknesses as the main critical regions of the component, in agreement with the results obtained from the theoretical calculation of the solidification modulus.

To prevent the formation of shrinkage defects, it is therefore necessary to design an appropriate feeding system capable of ensuring a continuous supply of molten metal to the critical areas during the final stages of solidification, keeping them adequately fed for a sufficient time to compensate for the volumetric contraction of the material.



6.7. Gating system design

6.7.1. Component orientation and feeding system selection

In the initial configuration, the component is positioned with its longitudinal axis in a vertical orientation.

This orientation was selected to promote a progressive bottom-to-top filling, allowing the air trapped inside the cavity to move towards the upper regions without being easily entrapped by the advancing molten metal front.

The lower area of the component, which also corresponds to the region with the greatest thickness, is connected to the feeding system, while the upper extremities represent the final regions reached by the molten metal.

This configuration was selected to promote a controlled solidification process, considering that the most massive regions are characterized by greater thermal accumulation and longer solidification times. Positioning the thickest area close to the pouring connection also improves material feeding during the volumetric contraction associated with solidification, reducing the risk of internal defects such as shrinkage porosity.

Furthermore, this arrangement is preferable compared with a direct top pouring configuration, which could cause free fall of the molten metal and lead to more turbulent filling of the internal pockets.

6.7.2. Riser positioning and sizing

After analyzing the solidification behavior through solidification modulus calculations and numerical simulation, the casting feeding system must be designed. This system consists of risers (feeders), which compensate for the volumetric shrinkage of the metal during the transition from the liquid to the solid state.

During cooling, molten metal tends to reduce its volume. If the last regions to solidify are not properly fed, internal defects such as shrinkage cavities and porosity may form. To prevent this issue, risers must remain molten for a longer time than the casting itself, acting as reservoirs of liquid metal.

The previous analysis showed that the maximum solidification modulus is located in the two areas characterized by the highest material accumulation, near the connection holes.

To ensure proper feeding and avoid the formation of shrinkage cavities inside the casting, one or more risers must therefore be positioned close to these regions.

For a riser to perform its function correctly, its solidification modulus must be greater than that of the region it is intended to feed. In particular, it is assumed that the riser modulus must be at least 20% higher than the maximum casting modulus:

$$M_{\text{riser}} \geq 1,2 \times M_{\text{max}}$$

By substituting the selected casting modulus value:

$$M_{\text{riser}} \geq 1,2 \times 3,16 = 3,8 \text{ mm}$$

This value represents the theoretical minimum modulus required for the riser to solidify after the critical region of the component.

However, considering the geometric complexity of the part, the presence of thickness variations, and the need to ensure a higher level of feeding reliability, a more conservative design value was adopted:

$$M_{\text{riser}} = 4 \text{ mm}$$

This choice increases the solidification time of the riser and ensures more effective compensation of the volumetric shrinkage during solidification.

6.7.3. Geometrical design of the gating system

The selected solution is a **blind cylindrical riser**. In the **investment casting** process, the riser body is incorporated into the ceramic shell, while the molten metal enters through the upper surface of the **sprue**.

The following assumption is made:

$$H_r = D_r$$

where:

- H_r is the riser height;
- D_r is the riser diameter.

The volume of the cylindrical riser is:

$$V_r = \frac{\pi D_r^2 H_r}{4}$$

The heat-dissipating surface includes the lateral surface and the upper surface. The lower base, being connected to the casting, is not considered as a heat exchange surface:

$$S_r = \pi D_r H_r + \frac{\pi D_r^2}{4}$$

By imposing:

$$H_r = D_r$$

the riser solidification modulus becomes:

$$M_r = \frac{V_r}{S_r}$$

$$M_r = \frac{D_r}{5}$$

Therefore:

$$D_r = 5M_r$$

Substituting the design modulus value: $D_r = 4 \times 5 = 20 \text{ mm}$

Consequently: $H_r = 20 \text{ mm}$

The preliminary riser geometry is therefore:

- $D_r = 20 \text{ mm}$
- $H_r = 20 \text{ mm}$

The riser volume is:

$$V_r = \frac{\pi \times 20^2 \times 20}{4}$$

$$V_r \approx 6283 \text{ mm}^3$$

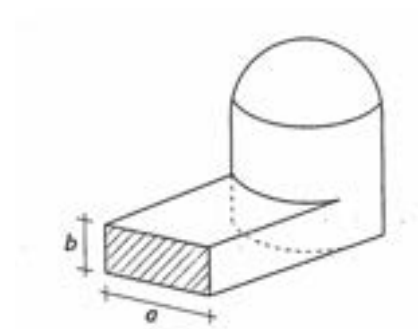
The riser therefore has a solidification modulus equal to: $M_r = 20/5 = 4 \text{ mm}$ and satisfies the previously defined design requirement.

Collar Dimensioning

The next step is the definition of the collar dimensions.

Considering that the maximum available width is approximately 15 mm, the following dimensions are adopted:

- $a = 15 \text{ mm}$
- $b = 10 \text{ mm}$



The collar solidification modulus is:

$$M_c = 15 \cdot 10 / 2 \cdot 15 + 10$$

$$M_c = 150 / 40$$

$$M_c = 3,75 \text{ mm}$$

The obtained value satisfies the required condition:

$$M_g < M_c < M_r$$

Indeed:

$$3,16 < 3,75 < 4$$

This sequence of solidification moduli promotes directional solidification:

Casting $\rightarrow$ Collar $\rightarrow$ Riser

The final collar geometry is therefore:

- **$a = 15 \text{ mm}$**
- **$b = 10 \text{ mm}$**
- **$L = 6 \text{ mm}$**

The collar volume is:

$$V_c = 15 \cdot 10 \cdot 6 = 900 \text{ mm}^3$$



For the preliminary configuration, a vertical sprue with a circular cross-section, slightly tapered towards the bottom, was selected. The reduction in cross-sectional area allows the acceleration of the molten metal during its downward flow to be properly accommodated, limiting the formation of incompletely filled regions inside the channel.

The sprue is connected to the lower part of the component, on the opposite side with respect to the riser, through a rectangular ingate.

The selected dimensions are:

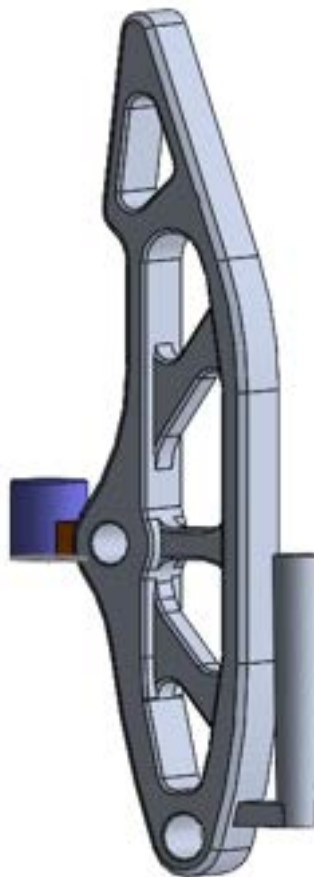
Element	Dimension
Sprue height	70 mm

Upper sprue diameter	12 mm
Lower sprue diameter	10 mm
Rectangular ingate	10 x 6 mm
Gate length	15 mm
Fillet radii	2-3 mm
Riser	diameter 20 x 20 mm

The ingate cross-sectional area is:

$$A_g = 10 \cdot 6 = 60 \text{ mm}^2$$

The transition between the sprue and the ingate must be properly filleted, avoiding sudden changes in cross-section and sharp edges that could generate turbulence or flow separation.



6.7.4. Calculation of total mass and pouring time

Once the geometric modeling of the component and the entire gating system was completed, the total volume of metal required for the production of the casting was determined using SolidWorks.

The considered volume includes:

- the brake pedal lever;
- the sprue;
- the rectangular ingate;
- the riser;
- the connecting collar.

From the CAD model, the total volume was obtained:

$$V_{\text{tot}} = 98837,14 \text{ mm}^3$$

Converting the value into cubic centimeters:

$$V_{\text{tot}} = 98,84 \text{ cm}^3$$

Assuming a density for the AlSi7Mg alloy equal to:

$$\rho = 2.68 \text{ g/cm}^3$$

The total mass of molten metal required for pouring is calculated using the following relationship:

$$m_{\text{tot}} = \rho V_{\text{tot}}$$

Substituting the values:

$$m_{\text{tot}} = 2,68 \cdot 98,84 = 264, 88 \text{ g}$$

Therefore:

$$m_{\text{tot}} = 0,265 \text{ kg}$$

The calculated mass includes both the component and all the elements of the gating system, which will subsequently be removed during the cutting-off and finishing operations.

Pouring Time Calculation

To estimate the theoretical time required for the complete filling of the mold cavity, the following empirical relationship was used:

$$t_c = 3.2 \times G$$

where:

- t_c = pouring time, expressed in seconds
- G = total mass of poured metal, expressed in kilograms

Substituting the previously calculated value:

$$G = 0.265 \text{ kg}$$

The pouring time is:

$$t_c = 3.2 \times 0.265$$

$$t_c = 1.65 \text{ s}$$

To account for unavoidable pressure losses and the approximations introduced by the empirical model, a slightly higher design pouring time can be adopted:

$$t_c = 1.7 \text{ s}$$

This value will subsequently be compared with the filling time obtained from the Inspire Cast simulation.

The volumetric flow rate required to fill the system within the established time is calculated as:

$$Q = V_{\text{tot}} / t_c$$

Substituting the values:

$$Q = 98837.14 / 1.7$$

$$Q = 58139 \text{ mm}^3/\text{s}$$

Converting the value into the International System of Units:

$$Q = 5.81 \times 10^{-5} \text{ m}^3/\text{s}$$

The obtained value represents the minimum theoretical flow rate that the gating system must ensure in order to achieve complete mold cavity filling within the expected time.

6.7.5. Choke section sizing and fluid-dynamic verification

The choke area represents the minimum cross-sectional area of the gating system and controls the molten metal flow rate.

The theoretical velocity of the molten metal at the base of the sprue can be estimated using Torricelli's law:

$$v = C_d \sqrt{2gh}$$

where:

- C_d = discharge coefficient
- $g = 9.81 \text{ m/s}^2$
- h = metallostatic head, corresponding to the sprue height
- v = theoretical velocity of the molten metal

The following values are assumed:

$$C_d = 0.7$$

$$h = 70 \text{ mm} = 0.07 \text{ m}$$

Therefore:

$$v = 0,7 \sqrt{2 \cdot 9,81 \cdot 0,07}$$

$$v = 0.82 \text{ m/s}$$

The minimum cross-sectional area required to ensure the required flow rate is determined using the continuity equation:

$$Q = A_c \times v$$

Therefore:

$$A_c = Q / v$$

Substituting the values:

$$A_c = (5.81 \times 10^{-5}) / 0.82$$

$$A_c = 71 \text{ mm}^2$$

The equivalent circular diameter is:

$$d_c = \sqrt{4A_c \div \pi}$$

$$d_c = \sqrt{(4 \cdot 71) \div \pi}$$

$$d_c = 9,5 \text{ mm}$$

The lower sprue diameter, assumed equal to 10 mm, is therefore consistent with the calculated value.

The actual cross-sectional area is:

$$A_s = (\pi \times 10^2) / 4$$

$$A_s = 78.54 \text{ mm}^2$$

This value is slightly higher than the theoretical minimum area and provides a sufficient safety margin considering the approximations introduced during the calculation.

Rectangular Ingate Dimensioning

The ingate connects the base of the sprue to the lower region of the component. Its geometry was selected as rectangular in order to adapt to the available surface on the lever and to distribute the molten metal flow over a wider area compared with a circular ingate.

The adopted dimensions are:

$$10 \times 6 \text{ mm}$$

with a length of:

$$L = 15 \text{ mm}$$

The length of 15 mm is required to maintain a sufficient distance between the sprue and the component, avoiding geometric interferences with the lever profile and its fillet radii.

The ingate cross-sectional area is:

$$A_g = 10 \times 6 = 60 \text{ mm}^2$$

The lower sprue cross-sectional area is instead:

$$A_s = (\pi \times 10^2) / 4$$

$$A_s = 78.54 \text{ mm}^2$$

Since:

$$A_g < A_s$$

the actual minimum cross-sectional area of the gating system is represented by the ingate. Therefore, the ingate acts as the real choke area of the system.

The adopted choke area is therefore:

$$A_c = 60 \text{ mm}^2$$

Gate Velocity Verification

Using the previously calculated volumetric flow rate, the average velocity required in the ingate to achieve a pouring time of 1.7 s would be:

$$v_g = Q / A_g$$

Substituting the values:

$$v_g = 58139 / 60$$

$$v_g = 968.98 \text{ mm/s}$$

Therefore:

$$v_g = 0.97 \text{ m/s}$$

This value is higher than the theoretical velocity previously estimated at the base of the sprue, equal to approximately 0.82 m/s. This indicates that, with a metallostatic head of 70 mm and an ingate section of 10 × 6 mm, the actual pouring time will be slightly higher than the initial value of 1.7 s.

The effective flow rate achievable through the ingate can be estimated as:

$$Q_{\text{eff}} = A_g v$$

where:

- $A_g = 60 \text{ mm}^2$
- $v = 0.82 \text{ m/s} = 820 \text{ mm/s}$

Therefore:

$$Q_{\text{eff}} = 60 \times 820 = 49200 \text{ mm}^3/\text{s}$$

The corresponding filling time is:

$$t_{\text{eff}} = V_{\text{tot}} / Q_{\text{eff}} = 98837,14 / 49200 = 2,01 \text{ s}$$

For the final geometric configuration, a theoretical pouring time equal to:

$$t_c = 2.0 \text{ s}$$

is therefore adopted.

Sprue Velocity Verification

The average velocity in the lower section of the sprue is calculated using the previously determined effective volumetric flow rate:

$$v_s = Q_{\text{eff}} / A_s$$

Substituting the values:

$$v_s = 49200 / 78.54$$

$$v_s = 626.4 \text{ mm/s}$$

Therefore:

$$v_s = 0.63 \text{ m/s}$$

The velocity therefore increases when passing from the sprue to the ingate, since the cross-sectional area decreases from:

$$A_s = 78.54 \text{ mm}^2$$

to:

$$A_g = 60 \text{ mm}^2$$

This behavior is consistent with the continuity equation, according to which a reduction in flow area results in an increase in molten metal velocity, while maintaining the same volumetric flow rate.

Fluid-Dynamic Flow Verification

To verify the correct sizing of the gating system, the volumetric flow rate of the molten metal was first calculated using the following relationship:

$$Q = V / t$$

where:

- $V = 98837.14 \text{ mm}^3$ represents the total volume of the gating system;
- $t = 1.7 \text{ s}$ represents the pouring time assumed during the design phase.

Therefore:

$$Q = 98837.14 / 1.7 = 58139.5 \text{ mm}^3/\text{s}$$

By applying the continuity equation:

$$Q = A \times v$$

the average velocity of the molten metal through the choke area of the gating system can be determined.

Considering the rectangular ingate with dimensions $10 \times 6 \text{ mm}$, corresponding to an area of:

$$A = 60 \text{ mm}^2$$

the velocity is:

$$v = Q / A$$

$$v = 58139.5 / 60 = 968.99 \text{ mm/s}$$

Therefore:

$$v = 0.97 \text{ m/s}$$

The obtained value is consistent with the velocity theoretically estimated using Torricelli's law, confirming that the gating system is capable of ensuring complete mold cavity filling within the expected time.

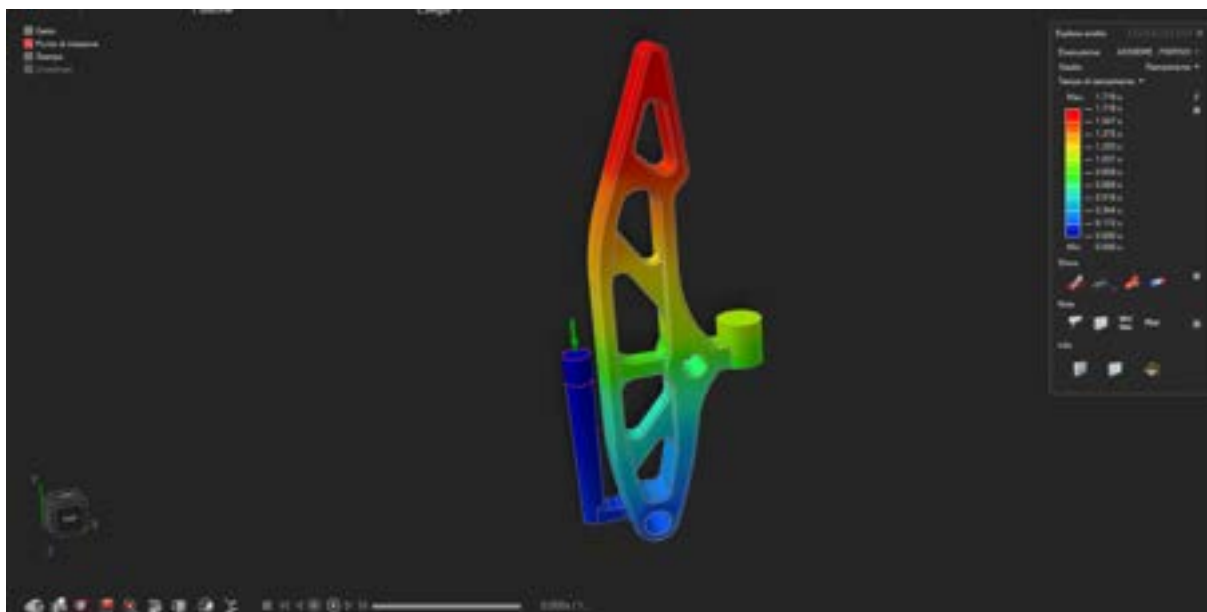
From a fluid-dynamic point of view, the geometry was designed by avoiding sudden changes in cross-section and by appropriately filleting the connections between the sprue, ingate, and component, in order to limit the formation of vortices, air entrapment, and oxidation of the molten metal.

The final verification of the flow behavior will be carried out through the numerical simulation in Inspire Cast, which will allow the evaluation of mold filling, velocity distribution, and the possible occurrence of casting defects.

6.8. Casting and solidification simulation

To verify the validity of the designed gating system, a numerical simulation was performed using Altair Inspire Cast software. The simulation was set up considering a gravity investment casting process (Lost Wax), using an AlSi7Mg aluminum alloy and a ceramic mold.

The analysis was divided into two main phases: cavity filling and subsequent casting solidification. The obtained results made it possible to evaluate the behavior of the molten metal during the casting process and to compare the simulation outcomes with the theoretical sizing developed in the previous sections.



The simulation highlights a progressive filling of the cavity starting from the sprue and the ingate, with a regular advancement of the molten metal front towards the component extremities.

No flow interruptions or areas apparently affected by incomplete filling are observed. The total filling time obtained from the simulation is:

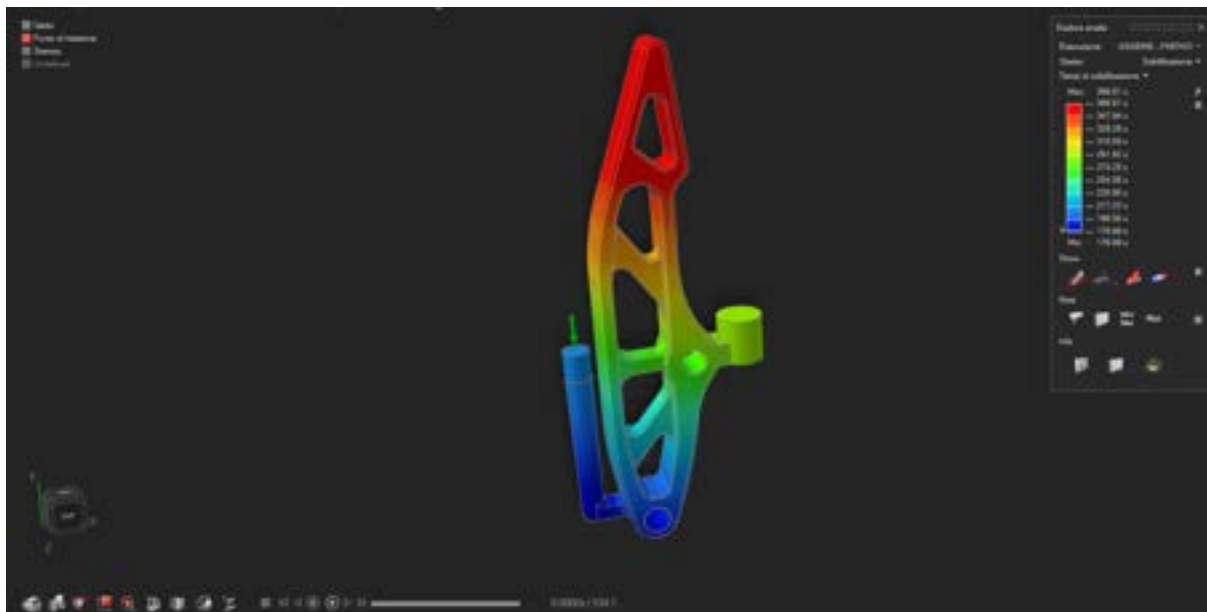
$$t = 1.719 \text{ s}$$

This value is in excellent agreement with the theoretical design time:

$$t = 1.7 \text{ s}$$

calculated during the sizing of the gating system.

This result confirms the consistency between the developed theoretical model and the numerical simulation.



The solidification analysis showed a gradual distribution of cooling times, with longer solidification times in the regions characterized by higher material accumulation.

The interpretation of the results also indicates that the distribution of solidification times could be further optimized through a refinement of the feeding system geometry, particularly the riser and its connecting region, in order to promote a more pronounced directional solidification.

However, the performed simulation did not highlight any anomalies during cavity filling and represents a valid preliminary verification of the adopted design choices.

6.9. Time and cost analysis

6.9.1. Timing

Operating Times

The following active processing times were considered:

- CAD model preparation and print file generation: 10 min
- Removal, washing, and cleaning of the resin pattern: 15 min
- Assembly of the pattern on the gating system: 10 min
- Ceramic shell formation: 30 min
- Furnace loading and burnout preparation: 10 min
- Alloy preparation and casting operation: 20 min
- Ceramic shell removal, cutting of the channels, and deburring: 20 min
- Loading and unloading for heat treatment: 10 min
- Final visual and dimensional inspection: 10 min

Total operating time: 135 min

Idle Times

The following inactive processing times were considered:

- 3D printing of the castable resin pattern: 3 h
- Drying and post-curing of the resin pattern: 30 min
- Drying of the subsequent ceramic shell layers: 24 h
- Pattern burnout and ceramic shell preheating: 2 h 30 min
- Casting cooling: 1 h 30 min
- T6 heat treatment: 10 h

Total idle time: 41.5 h

Therefore, the total production time required is:

Total production time = 43 h 45 min

6.9.2. Costs

Material Cost

The following material costs were considered:

- Aluminum alloy: €1.06
(assuming an average cost of AlSi7Mg alloy equal to €4/kg)
- Castable resin: €10.88
(assuming an indicative cost of castable resin equal to €100/kg)
- Ceramic shell and consumable materials: €8.50
(including refractory slurry, ceramic sand, materials for subsequent coating layers, abrasives, and finishing tools)

Total material cost: €20.44

Labor Cost

For the calculation of the labor cost, an hourly cost for a skilled operator was assumed:

$$C_{op} = €30/h$$

The labor cost is applied exclusively to the active operating time:

$$C_{labor} = t_{op} \times C_{op}$$

Considering the total operating time:

$$t_{op} = 135 \text{ min} = 2.25 \text{ h}$$

the labor cost is:

$$C_{labor} = 2.25 \times 30 = €67.50$$

$$\textbf{Total production cost} = \textbf{€20.44} + \textbf{€67.50} = \textbf{€87.94}$$

The analysis shows that the cost of the metal alloy has a limited impact on the overall component cost. The most significant cost items are associated with the production of the castable resin sacrificial pattern and the labor required for ceramic shell preparation, casting operations, and finishing processes.

The overall production time is instead mainly influenced by the inactive phases, particularly the drying of the ceramic shell, burnout process, and heat treatment.

Attached are the images of the prototype manufactured through PLA 3D printing, produced for demonstrative purposes in order to represent the geometry of the component originally designed to be manufactured using a different manufacturing technology.



7. Component introduction: adjustment gear

The component under study is an adjustment gear.

Its main function is to enable fine adjustment, ensuring precision, repeatability, and operational reliability.

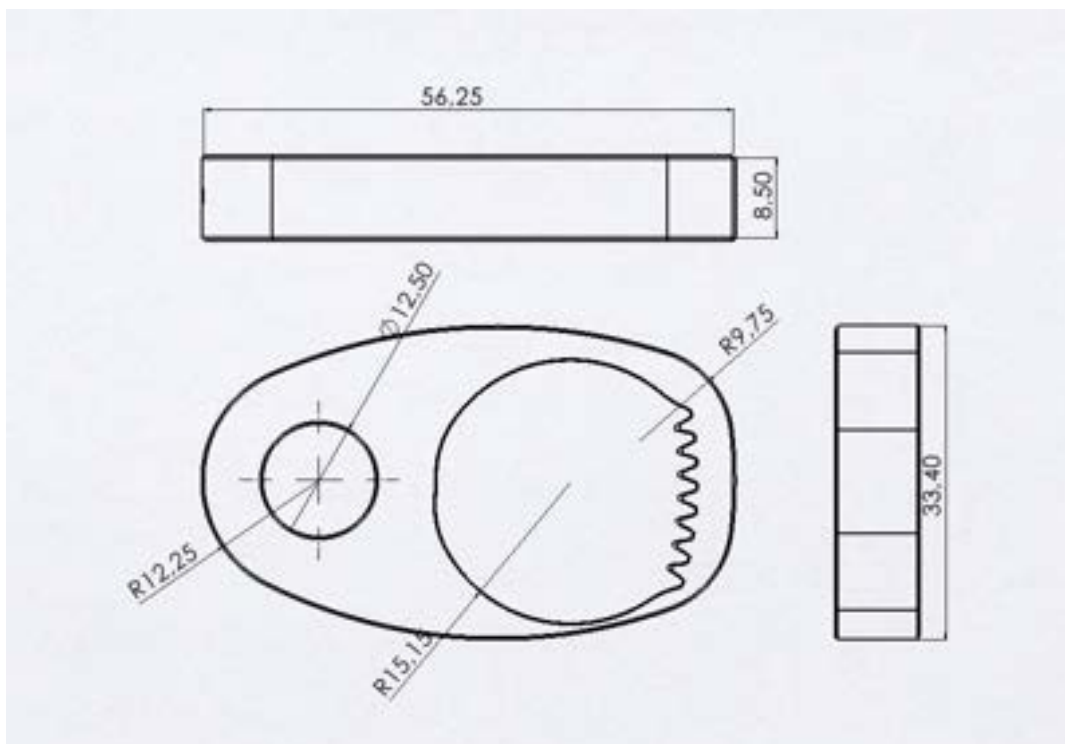
From a functional point of view, the component:

- Transmits rotational motion;
- Enables controlled adjustment;
- Operates in combination with other mechanical elements.

Since it is part of a critical system such as the braking system, it is subjected to:

- Moderate but repeated mechanical loads;
- Vibrations;
- Possible thermal variations;
- The need for good wear resistance.

However, as it is an adjustment element rather than a primary force-transmission component, its structural requirements are less demanding compared with components directly involved in generating the braking torque.



7.1. Material selection

The selected material for the component is **ABS (Acrylonitrile Butadiene Styrene)**.

ABS provides adequate mechanical strength for components subjected to non-extreme loads and offers good toughness, making it suitable for applications involving impacts and vibrations without the risk of brittle failure.

The main material properties are reported in the following table:

Shrinkage	Medium-high
Print speed	30 - 60 mm/s
Density	1,04 g/cm ³
Hardness (Rockwell)	R95 – R110
Tensile strength	35 – 50 MPa
Modulus of elasticity (E)	1.8 – 2.3 GPa
Elongation at break	10 – 50%

7.2. Manufacturing process selection: 3D printing

The manufacturing technology selected for the production of the component is **FDM 3D printing (Fused Deposition Modeling)**, which consists of the layer-by-layer deposition of molten thermoplastic material until the desired geometry is completed.

This choice is particularly consistent with the Formula Student context, where rapid development and the possibility of quickly iterating the design represent fundamental aspects.

From a design perspective, it is necessary to consider the specific characteristics of the FDM process. In particular, the mechanical strength of the component is anisotropic, with lower resistance along the layering

direction. For this reason, the printing orientation must be selected in order to align the deposited layers with the main load directions, reducing the risk of delamination.

Printing parameters also play a crucial role: a high infill percentage and an adequate number of perimeters contribute to increasing the overall strength of the component, while a reduced layer height improves geometric accuracy, which is particularly important for a gear.

7.3. 3D printer selection

For the production of the adjustment gear, a mid-to-high range FDM 3D printer was selected, specifically the **Bambu Lab P2S**.

The choice of this printer is based on the need for a fully enclosed printing environment, which is particularly important when processing technical materials such as ABS. The enclosed configuration helps maintain a stable chamber temperature, reducing the risk of warping and improving dimensional accuracy during the printing process.

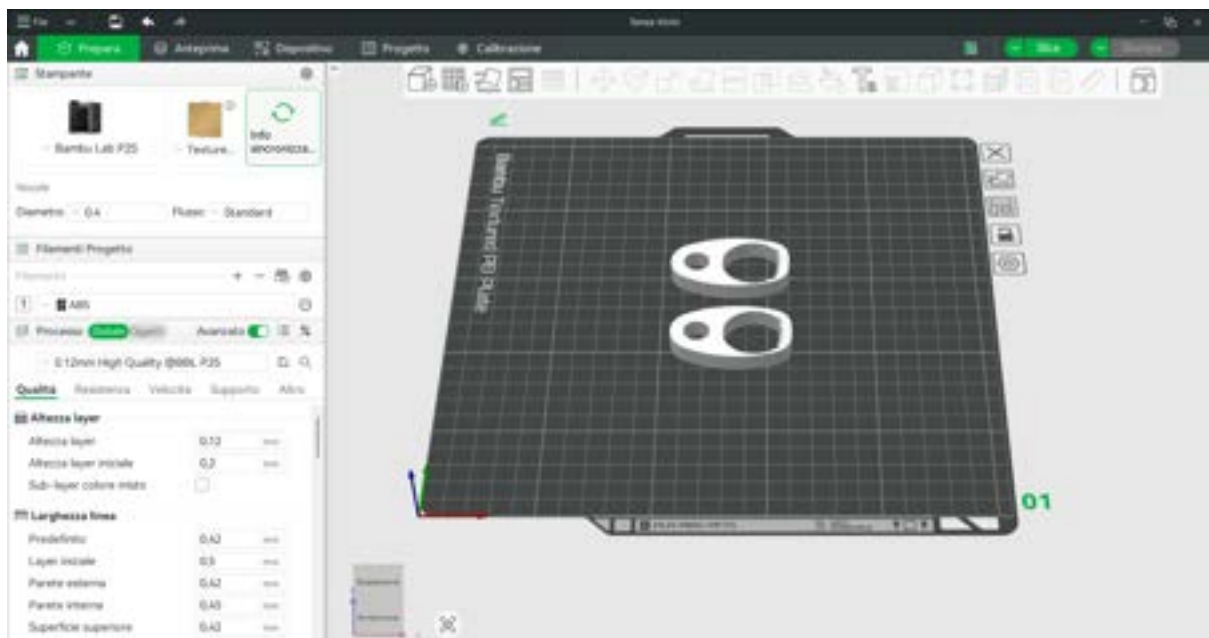


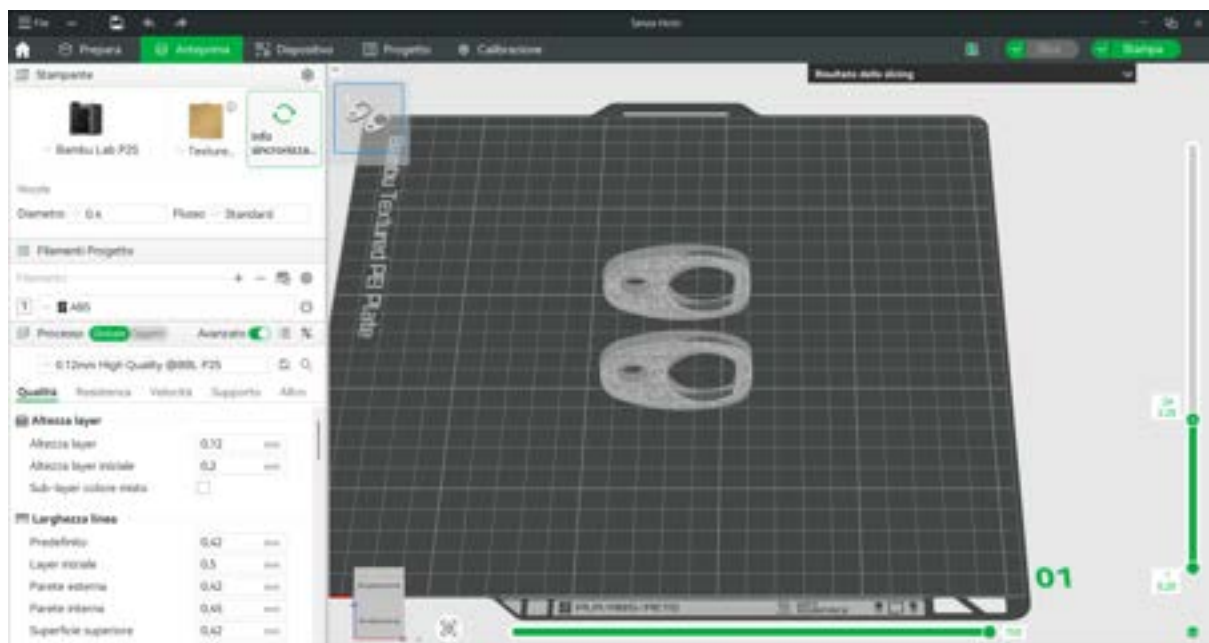
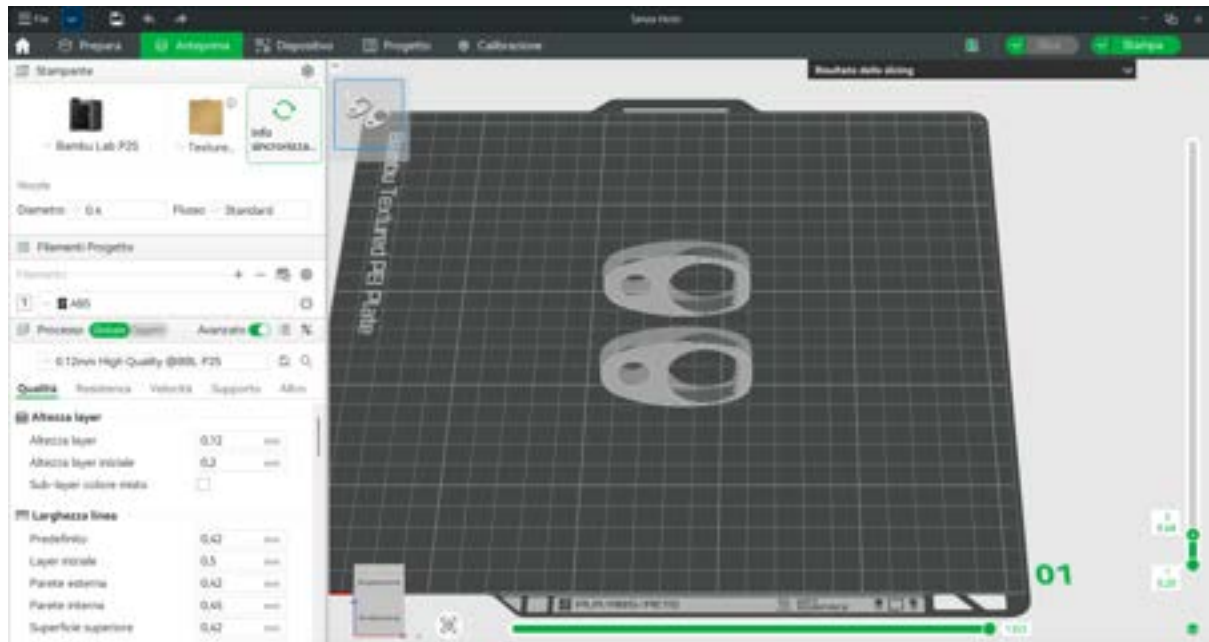
Technical Specifications

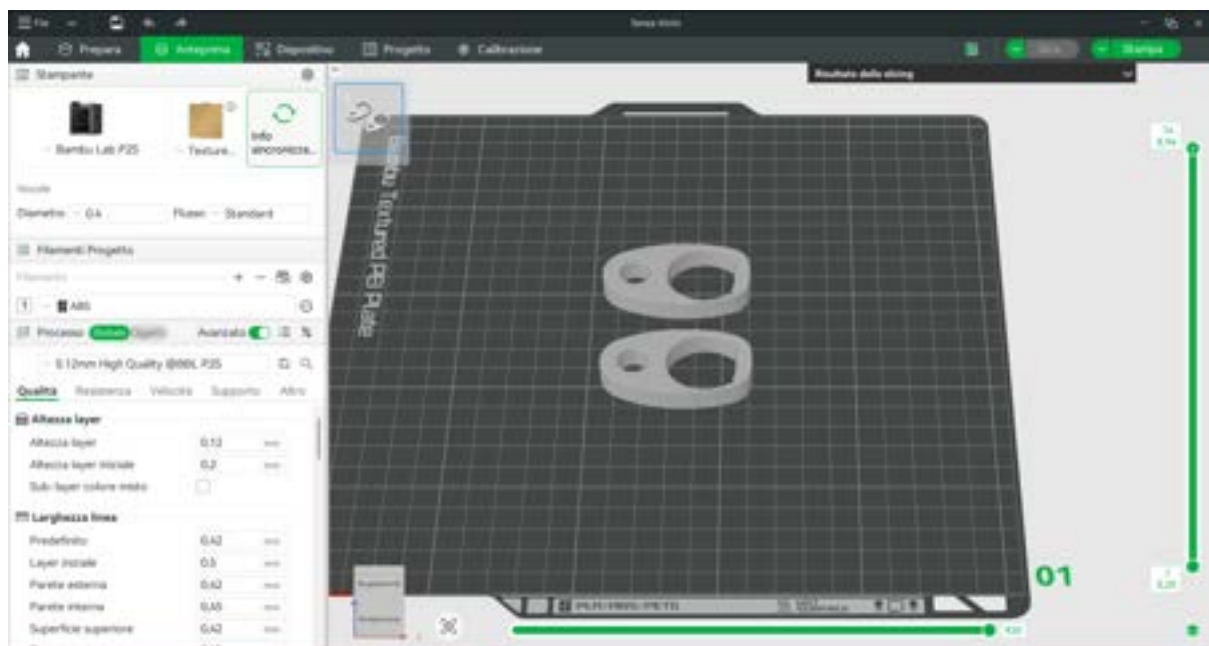
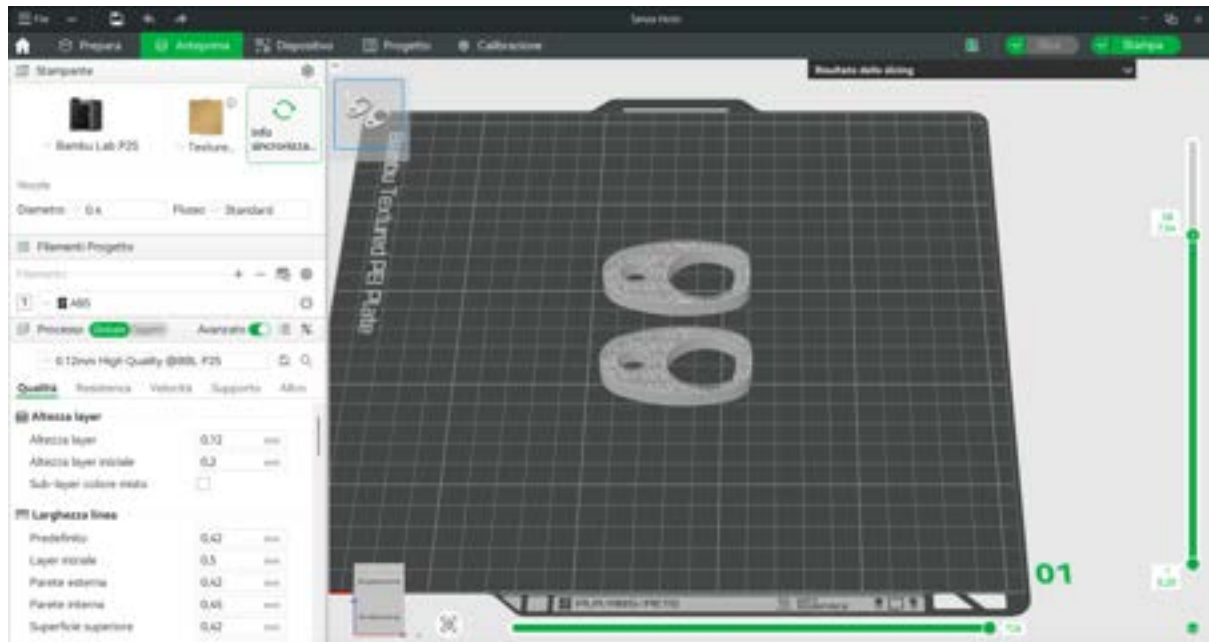
Article		Specifications
Printing Technology		Fused Deposition Modeling
Body	Construction Volume (WxDxH)	256*256*256 mm ³
	Frame	Plastic and Steel
	Outer Frame	Plastic and Glass
Physical Dimensions	Physical Dimensions	392*406*478mm ³ Packaging Dimensions: 490*490*560mm ³
	Weight	P2S Net weight: 15.0kg Gross weight: 18.58kg
		P2S Combo (AMS 2 pro included) Net weight: 16.4kg gross weight: 21.33kg
Tool head	Extruder gear	Hardened steel
	Nozzle	Hardened steel
	Maximum Nozzle Temperature	300 °C
	Nozzle Diameter Included	0.4 mm
	Nozzle Diameter Supported	0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm
	Filament Cutter	Included
	Filament Diameter	1.75 mm
	Extruder Motor	High precision permanent magnet synchronous motor Bambu Lab
Heatbed	Print Plate Material	Flexible Steel Plate

7.4. Printing simulation

The printing process is now analyzed in chronological order using the **Bambu Studio** software:







7.5. Production time and cost calculation

The calculation of production times and costs was also carried out using the Bambu Studio software.

In this case, support structures were not required, since the component was directly positioned on the build plate.

The 3D printer used for the manufacturing process, the Bambu Lab P2S, has an approximate purchase cost of:

$$C_{\text{printer}} = \text{€}519.00$$

Since it is necessary to manufacture two identical components, different production strategies were evaluated in order to identify the most efficient solution. The analysis showed that the optimal approach is to print both components simultaneously on the same build plate, rather than performing two separate printing operations.

This solution allows a saving of 9 minutes and 9 seconds of printer operating time and a cost reduction of €0.01, while the amount of filament used remains unchanged.

In addition to these directly quantifiable benefits, further time savings are achieved during process management. Between two consecutive prints, it is necessary to wait for the build plate cooling phase before removing the component and starting a new operation. Furthermore, operator involvement is reduced, since only one printing job needs to be prepared and started instead of two.

Therefore, the overall production times and costs for the selected solution are:

- **Printer setup time:** approximately 5 min
- **File upload time to the PC:** approximately 30 s
- **Printing time:** 53 min 10 s
- **Component removal from the build plate:** approximately 20 s
- **Filament consumption:** 7.80 g
- **Total production cost:** €0.19

Filament Cost

The assumed ABS filament cost is:

$$C_{\text{filament}} = \text{€}18/\text{kg}$$

The material cost is therefore:

$$C_{\text{material}} = 0.0078 \times 18 = \text{€}0.14$$

Printer Cost Allocation

The 3D printer used for manufacturing the components is a shared capital asset within the Formula Student team and is employed for the production of multiple components and prototypes.

For this reason, the purchase cost of the printer was not fully assigned to the components analyzed in this work, but was allocated through an hourly depreciation criterion based on machine usage.

The following assumptions were considered:

- Purchase cost: €519
- Useful life: 10 years
- Average utilization: 15 hours/day
- Operating days per year: 300 days/year

The total expected operating time is therefore:

$$\text{Total operating hours} = 10 \times 300 \times 15 = 45000 \text{ h}$$

The hourly depreciation cost is:

$$\text{Hourly depreciation cost} = 519 / 45000 = 0.0115 \text{ €/h}$$

Considering the printing time:

$$t = 53 \text{ min } 10 \text{ s} = 0.886 \text{ h}$$

the printer depreciation cost is:

$$C_{\text{printer}} = 0.0115 \times 0.886 = 0.01 \text{ €}$$

Therefore, the total production cost, including both material and machine depreciation, is approximately:

$$C_{\text{total}} = \text{€}0.19$$

The analysis confirms that material consumption represents the main cost contribution, while the machine depreciation cost has a negligible impact due to the high expected utilization of the equipment.

Risultato dello slicing		
Schema Colore ~ Filamento		
Filamento	Modello	
■ 1	3,12 m	7,80 g
Tempi cambio filamento: 0		
Costo: 0,19		
Tempo stimato		
Tempo di preparazione:		7m2s
Tempo di stampa del modello:		46m8s
Tempo totale:		53m10s
Opzioni	Mostra	
☒ Spostamento	☐	
☒ Retrazione	☐	
☒ De-retrazione	☐	
☒ Pulizia	☐	
☒ Cuciture	☒	

Attached are the images of the manufactured component:





8. Component introduction: Sensor gear

The component under consideration is a sensor gear that, during pedal actuation, transmits the pedal's angular rotation to the rotary sensor by meshing with a mating gear, enabling the sensor to accurately detect the pedal position.



8.1. Selection of the Manufacturing Process

Machining was identified as the most suitable manufacturing process for this component based on the following considerations:

- **Part Geometry**
The component is predominantly a rotationally symmetric part. The flanges and cylindrical hub are axisymmetric features that can be efficiently produced by turning. The gear teeth and the special profile of the central bore, however, require milling operations. Therefore, a combination of turning and milling represents the most appropriate manufacturing solution for this component.
- **Required Precision**
The component must ensure accurate mating with the shaft and maintain a constant gear tooth pitch to guarantee proper meshing with the mating gear. These requirements can be readily achieved through turning and milling operations, which are capable of producing tolerances on the order of hundredths of a millimeter.

8.2. Number of Parts to Be Produced

The component is present in two units within the braking system. In addition, spare parts are required to ensure the vehicle's operational continuity throughout the racing season. Therefore, a total production quantity of 6 parts is planned: 2 units installed on the vehicle and 4 spare units, which are considered sufficient to cover the entire racing season, including testing sessions.

The spare quantity has been determined by considering the component's low wear rate and the possibility of manufacturing additional parts within a short timeframe if required.

8.3. Material Selection

The gear will be manufactured from **6082-T6 aluminium alloy**. The choice of this material is based on an evaluation of the actual functional requirements of the component within the specific competition environment.

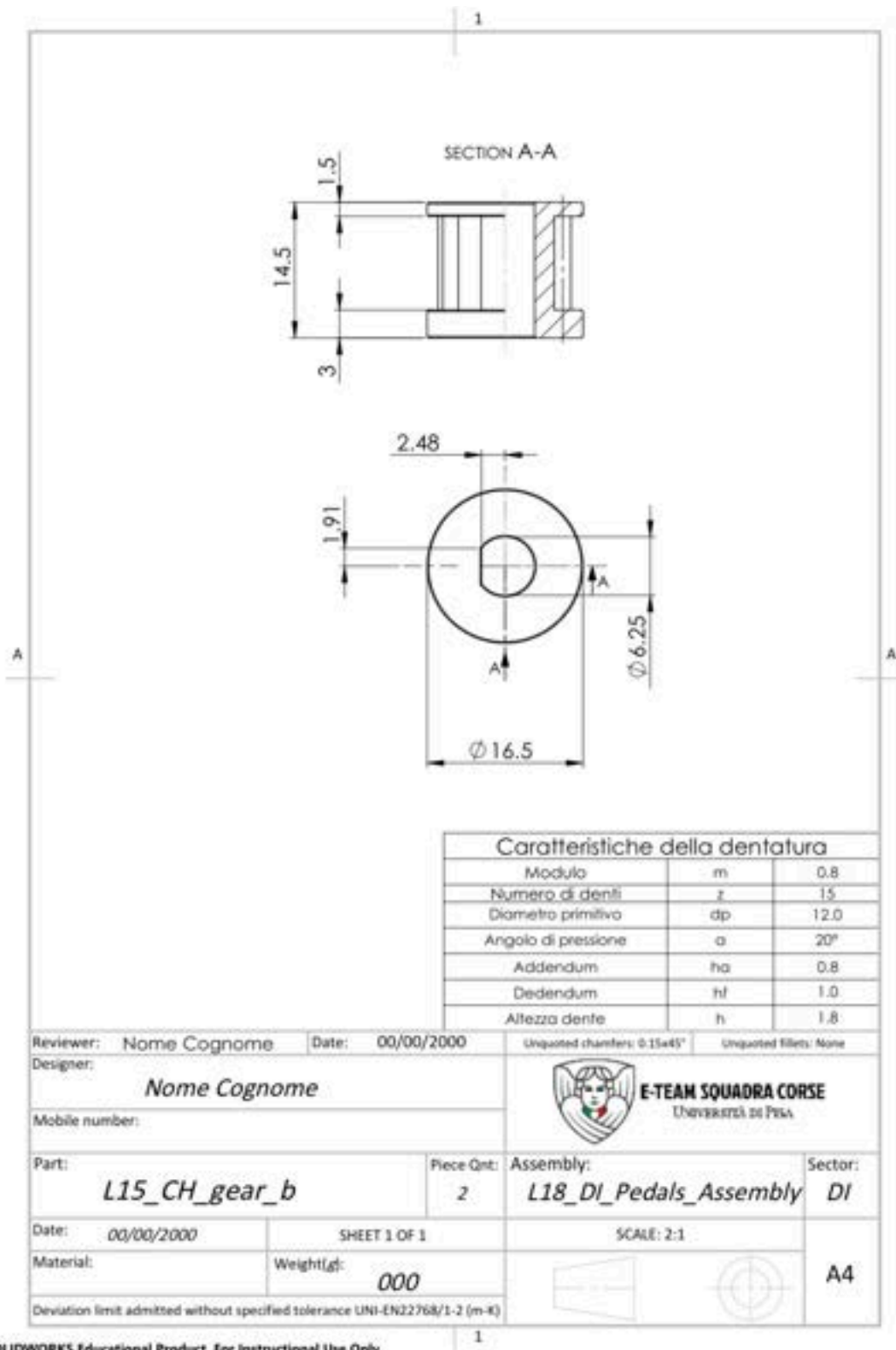
This part is not a structural component and is subjected to relatively low loads, as its sole purpose is to transmit motion to the rotary sensor.

The material offers the following properties:

- **Sufficient mechanical strength** for the applied loads (yield strength ≈ 260 MPa)
- **Low weight**, with a density of 2.70 g/cm^3 , contributing to the reduction of the system's rotating mass
- **High machinability**, making it particularly suitable for manufacturing using conventional machine tools
- **Corrosion resistance**, which is important to ensure long-term component durability

For the production of the 6-unit batch, the procurement of a single 20 mm diameter, 150 mm long Anticorodal aluminium alloy bar is planned, with a total cost of €5.17.

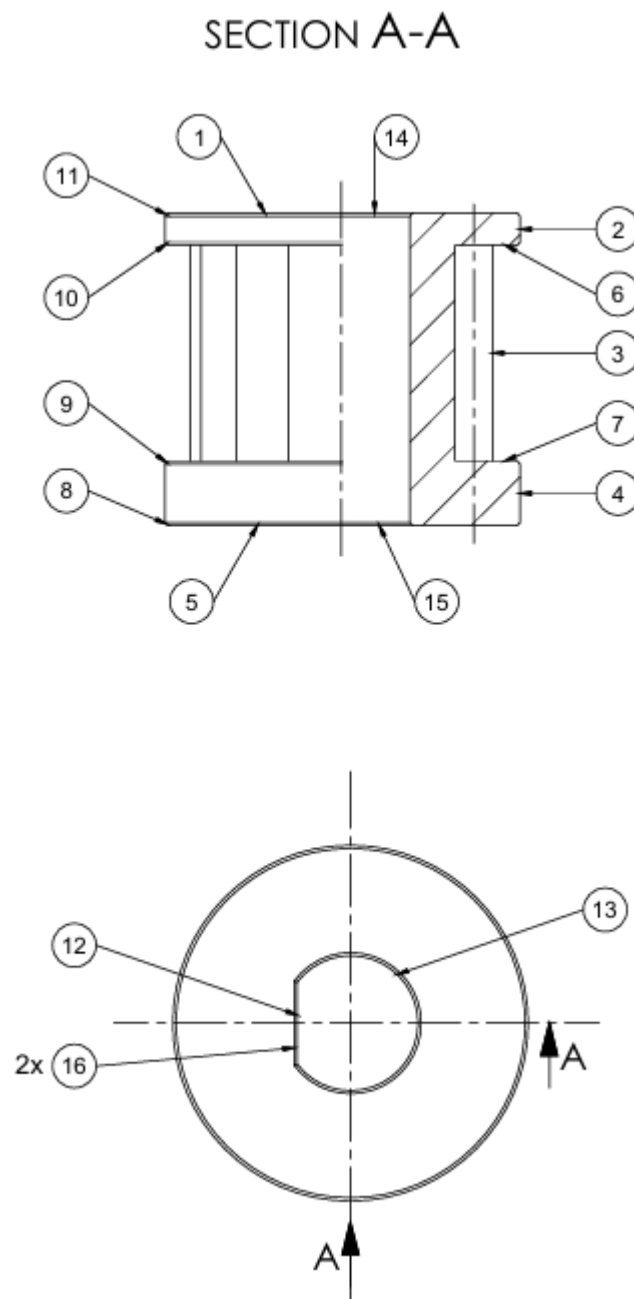
8.4. Technical Drawing



SOLIDWORKS Educational Product. For Instructional Use Only.

8.5. Machining Process Sequence

8.5.1. Surface Analysis



8.5.2. Process Analysis

n. sup	tipologia	processi possibili
2, 4	Cilindriche esterne coassiali	Tornitura
3	Cilindrica esterna coassiale	Tornitura, Fresatura
1, 5, 6, 7	Piane ortogonali all'asse	Tornitura
13	Cilindrica interna coassiale	Foratura, Fresatura
12	Piana interna	Foratura, Fresatura
8, 9, 10, 11	Conica esterna	Tornitura
14, 15	Conica interna	Aggiustaggio, Fresatura
16	Piana inclinata	Aggiustaggio, Fresatura

8.5.3. Operation Grouping

n. sup.	processo
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	Tornitura
(12, 13)	Foratura
3, 12, 13	Fresatura
14, 15, 16	Aggiustaggio

8.5.4. Precedence Constraints

- Milling and drilling operations must be performed after the machining of the external surfaces by turning, due to the need to establish accurate references with respect to the part axis.
- The rough drilling operation must be carried out before milling the "D" profile, as it acts as a pilot hole for the entry of the end mill.
- The turning operation of the external diameter (surface 3) must be completed before gear tooth milling, as it defines the reference surface for the subsequent operation.
- All machine tool operations must be completed before bench fitting, as the latter represents the final stage for burr removal and the finishing of microscopic details (chamfers 14, 15, and 16).

8.5.5. Possible Manufacturing Process Routes

Route A

fase	operazioni	macchina
10	Troncatura	Sega a nastro
20	Tornitura 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 Foratura	Tornio parallelo
30	Fresatura 3, 12, 13	Fresatrice
40	Aggiustaggio 14, 15, 16	Banco da lavoro

Route B

fase	operazioni	macchina
10	Troncatura	Sega a nastro
20	Tornitura 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	Tornio parallelo
30	Foratura Fresatura 3, 12, 13	Fresatrice
40	Aggiustaggio 14, 15, 16	Banco da lavoro

Cycle A – Pilot Hole Drilling on the Lathe

Advantages:

- **Guaranteed concentricity** with the external surfaces
- **Immediate centering** thanks to the lathe chuck

Disadvantages:

- **Risk of misalignment:** Transferring the part from the lathe to the milling machine introduces a possible repositioning error, which may compromise the concentricity between the pilot hole and the “D” profile.

Cycle B – Pilot Hole Drilling on the Milling Machine

Advantages:

- **No transfer-related errors** between machines

- **Repeatability:** Once the first part has been centered, the same setup can be reused for the following parts without repeating the entire operation

Disadvantages:

- **Initial centering difficulty:** Finding the exact center of a cylindrical part on a manual milling machine requires more time and accuracy compared with using a lathe.

Cycle B is selected to ensure maximum geometric accuracy. Although the initial centering operation on the manual milling machine requires a longer setup time, performing both the pilot hole drilling and the “D” profile milling in a single setup eliminates the repositioning errors typically associated with transferring the part between machines. This ensures the correct alignment of the gear–shaft coupling without requiring complex manual centering procedures.

8.5.6. Machining Process Sequence

Fase	Operazione	Macchina	Attrezzatura
10	Troncatura	Sega a nastro	Morsa
20 a	Sfacciatura 1 Cilindratura esterna (sgrossatura) 2 Cilindratura esterna (sgrossatura) 3 Cilindratura esterna (finitura) 2 Sfacciatura 6 Cilindratura esterna (finitura) 3 Smussatura 10, 11	Tornio parallelo	Mandrino autocentrante a 3 griffe
20 b	Sfacciatura 5 Cilindratura esterna (sgrossatura) 4 Cilindratura esterna (finitura) 4 Sfacciatura 7 Smussatura 8, 9		Mandrino autocentrante a 3 griffe con bussola spaccata a gradino in rame o ottone
30	Centratura 1 Foratura Fresatura interna 12, 13 Dentatura (sgrossatura) 3 Dentatura (finitura) 3	Trapano fresatrice	Divisore universale, mandrino autocentrante a 3 griffe
40 a	Smussatura 14, 16	Banco da lavoro	Morsa da banco
40 b	Smussatura 15, 16		

8.6. Selection of Machine Tools and Cutting Tools

8.6.1. Band Saw — Optimum SP 11V



Dotazione:

- Nastro bimetallico
- Limite arresto materiale

Listino	767,00€
Risparmio	- 20%
Prezzo	659,95€
In Promo	613,75€
	748,78€ iva inclusa

Technical Data

- **Band speed:** 30–80 m/min
- **Blade dimensions:** 1335 × 13 × 0.65 mm
- **Motor power:** 850 W
- **Price:** €613.75

Cutting capacity

	
Taglio 0°	105 mm
Taglio 45°	65 mm

Blade

- **Grade:** Bi-M42
- **Overall length:** 1335 mm
- **Thickness:** 0.65 mm
- **Width:** 13 mm
- **Tooth pitch:** 8/12
- **Price:** €13.18



8.6.2. Centre Lathe — Optimum TU 2807 V



Dotazione:

- Autocentrante a tre griffe Ø 125 mm
- Contropunte fisse CM 2 - CM 4
- Parete paraspruzzi
- Vasca raccogli-trucioli
- Utensili da tornio HSS
- Brida
- Portautensili a 4 scomparti
- Set ingranaggi cambio
- Chiavi di servizio

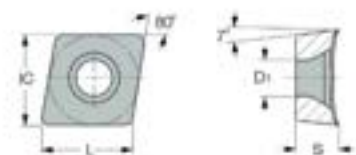
Technical Data

- **Centre height:** 140 mm
- **Distance between centres:** 700 mm
- **Maximum turning diameter over bed:** 266 mm
- **Spindle speed range:** 30–4,000 rpm
- **Bar capacity:** Ø 26 mm
- **Upper slide travel:** 60 mm
- **Cross slide travel:** 160 mm
- **Longitudinal feed rate:** 0.07–0.4 mm/rev
- **Maximum tool height for four-way tool post:** 13.5 mm
- **Motor power:** 1500 W
- **Price:** €4,768.99

8.6.3. Turning Inserts and Tool Holders

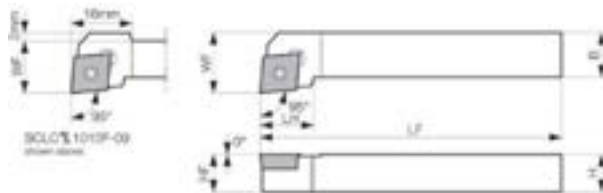
Insert (CCGT 060204-AS IC20 – Hoffmann Group Catalogue)

- **Insert nose radius (RE):** 0.4 mm
- **Cutting edge length (L):** 6.4 mm
- **Maximum depth of cut (APMX):** 2 mm
- **Inscribed circle diameter (IC):** 6.35 mm
- **Insert thickness (S):** 2.38 mm
- **Maximum turning feed rate:** 0.25 mm/rev
- **Minimum depth of cut:** 0.5 mm
- **Minimum turning feed rate:** 0.1 mm/rev
- **Price:** €13.90



Tool Holder (SCLCR1010F-06 – Hoffmann Group Catalogue)

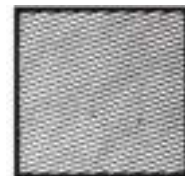
- **Shank size (CZCMS):** 1010
- **Cutting direction (HAND):** R (Right-hand)
- **Overall length (OAL):** 120 mm
- **Insert size:** 06
- **Shank height (H):** 10 mm
- **Shank width (B):** 10 mm
- **Functional height (HF):** 10 mm
- **Functional width (WF):** 12 mm
- **Functional length (LF):** 80 mm
- **Price:** €69.78



8.6.4. Hand Tools

Precision Needle File (Code 527230 5 – Hoffmann Group Catalogue)

- **Shape:** Square
- **Cut type:** Double cut (for finer finishing)
- **Grade:** 2 (Semi-smooth)
- **Minimum hardness:** HRC 65
- **Maximum hardness:** HRC 66
- **Width:** 2.2 mm
- **Height:** 2.2 mm
- **Overall length:** 140 mm
- **Price:** €10.10



8.6.5. Milling and Drilling Machine — Optimum MB 4



In dotazione compreso nel prezzo

- Adattatore CM 4-CM3
- Chiavi di servizio
- Asta di trazione M16

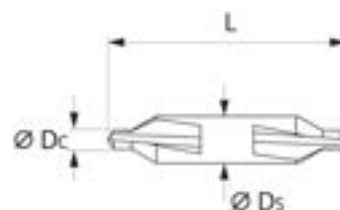
Technical Data

- **Motor power:** 1100/1500 W
- **Maximum end mill diameter:** $\varnothing$ 28 mm
- **Quill travel:** 120 mm
- **Head inclination:** $\pm 60^\circ$
- **Spindle speed range:** 95–3,200 rpm
- **Cross table dimensions:** 800 × 240 mm
- **X-Y-Z axis travel:** 450 / 195 / 430 mm
- **Price:** €3,544.12

8.6.6. Milling Tools

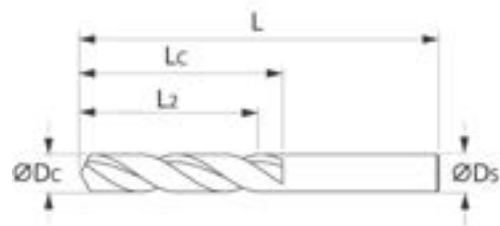
Centre Drill (Code 111050 1.6 – Hoffmann Group Catalogue)

- **Coating:** Uncoated
- **Cutting material:** HSS-E
- **Number of cutting edges (Z):** 2
- **Nominal diameter (Dc):** 1.6 mm
- **Shank diameter (Ds):** 4 mm
- **Usable length:** 4.56 mm
- **Overall length (L):** 35 mm
- **Price:** €6.41



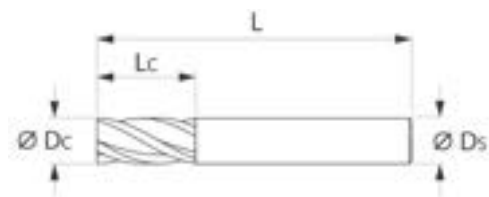
Twist Drill (Code 113150 4.5 – Hoffmann Group Catalogue)

- **Coating:** Uncoated
- **Cutting material:** HSS-E
- **Number of cutting edges (Z):** 2
- **Nominal diameter (DC):** 4.5 mm
- **Shank diameter (Ds):** 4.5 mm
- **Recommended maximum drilling depth (L2):** 18 mm
- **Chip flute length (Lc):** 24 mm
- **Overall length (L):** 46 mm
- **Price:** €6.22



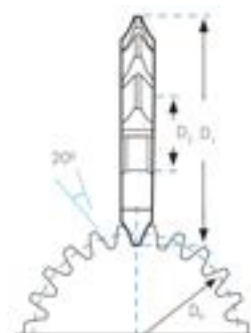
End Mill (Code DJ2F 4 – MJ CNC Automation Catalogue)

- **Cutting material:** HSS-E
- **Number of cutting edges:** 2
- **Nominal diameter (D):** 4 mm
- **Shank diameter (d):** 4 mm
- **Cutting edge length (Lc):** 17 mm
- **Overall length (L):** 40 mm
- **Price:** €10.00



Gear Milling Cutter (Code 811002 – Blue Master Catalogue)

- **Cutting material:** HSS
- **Module:** 0.8 mm
- **Cutter number:** 2
- **Outside diameter (d1):** 40 mm
- **Bore diameter (d2):** 16 mm
- **Price:** €131.56



8.6.7. Dimensional Inspection

After the machining operations, a dimensional inspection phase is carried out to ensure that the pinion complies with the geometric and surface finish requirements specified by the **UNI-EN 22768/1-2 (m-K)** standard. The following measuring instruments will be used:

Vernier caliper: used for the quick inspection of less critical external linear dimensions, such as flange thickness and the overall length of the pinion body. For these dimensions, the medium tolerance class (m) allows a deviation of 0.1 mm or 0.2 mm, which is fully covered by the caliper resolution.



Optical profile projector: specifically used for the inspection of the internal “D”-shaped bore. Since the bore dimensions present significant accessibility limitations for caliper jaws, optical profile inspection or the use of a custom-shaped gauge ensures geometric conformity without damaging the component.



Electronic surface roughness tester: used to measure the surface roughness on the pinion tooth flanks and inside the mating bore. Surface finish control is crucial to minimize sliding friction, prevent premature wear, and ensure the correct kinematic operation of the gear.



Dial Indicator (with Magnetic Base): required to verify the general geometric tolerances of class K. It is used to measure the radial circular run-out error (maximum allowable limit of 0.2 mm) of the external flange with respect to the bore axis.



8.6.8. Cutting Parameters

Parting-off

- $v = 80 \text{ m/min}$
- $f = \text{manual feed}$

Turning

- $D = \frac{Df + Di}{2} \rightarrow \text{Diametro medio di lavorazione (mm)}$
- $a_p \rightarrow \text{Profondità di passata (mm)}$
- $v \rightarrow \text{Velocità di taglio (m/min)}$
- $Ra = \frac{f^2}{32 \cdot RE} \cdot 1000 \rightarrow \text{Rugosità teorica (\mu m)}$
- $RE \rightarrow \text{Raggio di punta dell'inserto (mm)}$
- $f \rightarrow \text{Avanzamento al giro (mm/giro)}$
- $n = \frac{v \cdot 1000}{\pi D} \rightarrow \text{Numero di giri al minuto del mandrino (giro/min)}$
- $1/n \rightarrow \text{Costante di Kronenberg}$
- $P_s \rightarrow \text{Pressione specifica di taglio (N/mm}^2\text{)}$
- $S = f \cdot a_p \rightarrow \text{Sezione del truciolo (mm}^2\text{)}$

- $P_t = P_s \cdot S^{\frac{-1}{n}} \rightarrow$ Pressione di taglio (N/mm^2)
- $F_t = P_t \cdot S \rightarrow$ Forza di taglio (N)
- $W = \frac{F_t \cdot v}{1000 \cdot 60} \rightarrow$ Potenza di taglio (kW)
- $\eta \rightarrow$ Rendimento
- $P_m = \frac{W}{\eta} \rightarrow$ Potenza della macchina (kW)

Facing of surfaces 1 and 5

- | | | |
|-----------------------------------|-------------------------------|---------------------------------|
| • $D = 10 \text{ mm}$ | • $f = 0,1 \text{ mm/giro}$ | • $S = 0,10 \text{ mm}^2$ |
| • $D_i = 20 \text{ mm}$ | • $n = 2500 \text{ giro/min}$ | • $P_t = 631,48 \text{ N/mm}^2$ |
| • $D_f = 0 \text{ mm}$ | • $1/n = 0,060$ | • $F_t = 63,15 \text{ N}$ |
| • $a_p = 1,0 \text{ mm}$ | • $W = 0,083 \text{ kW}$ | • $P_m = 0,103 \text{ kW}$ |
| • $v = 78,54 \text{ m/min}$ | • $P_s = 550 \text{ N/mm}^2$ | • $\eta = 0,8$ |
| • $Ra = 0,78 \text{ }\mu\text{m}$ | • $RE = 0,4 \text{ mm}$ | |

Rough turning of surfaces 2 and 4

- | | | |
|-----------------------------|-------------------------------|---------------------------------|
| • $D = 18,75 \text{ mm}$ | • $f = 0,2 \text{ mm/giro}$ | • $S = 0,25 \text{ mm}^2$ |
| • $D_i = 20 \text{ mm}$ | • $n = 1500 \text{ giro/min}$ | • $P_t = 597,70 \text{ N/mm}^2$ |
| • $D_f = 17,5 \text{ mm}$ | • $1/n = 0,060$ | • $F_t = 149,43 \text{ N}$ |
| • $a_p = 1,25 \text{ mm}$ | • $W = 0,220 \text{ kW}$ | • $P_m = 0,275 \text{ kW}$ |
| • $v = 88,31 \text{ m/min}$ | • $P_s = 550 \text{ N/mm}^2$ | • $\eta = 0,8$ |
| • $RE = 0,4 \text{ mm}$ | | |

Finishing turning of surfaces 2 and 4

- | | | |
|-----------------------------------|-------------------------------|---------------------------------|
| • $D = 17 \text{ mm}$ | • $f = 0,1 \text{ mm/giro}$ | • $S = 0,05 \text{ mm}^2$ |
| • $D_i = 17,5 \text{ mm}$ | • $n = 2500 \text{ giro/min}$ | • $P_t = 658,30 \text{ N/mm}^2$ |
| • $D_f = 16,5 \text{ mm}$ | • $1/n = 0,060$ | • $F_t = 32,92 \text{ N}$ |
| • $a_p = 0,5 \text{ mm}$ | • $W = 0,073 \text{ kW}$ | • $P_m = 0,092 \text{ kW}$ |
| • $v = 133,45 \text{ m/min}$ | • $P_s = 550 \text{ N/mm}^2$ | • $\eta = 0,8$ |
| • $Ra = 0,78 \text{ }\mu\text{m}$ | • $RE = 0,4 \text{ mm}$ | |

Rough turning of surface 3

- | | | |
|-----------------------------|-------------------------------|---------------------------------|
| • $D = 16,05 \text{ mm}$ | • $f = 0,2 \text{ mm/giro}$ | • $S = 0,29 \text{ mm}^2$ |
| • $D_i = 17,5 \text{ mm}$ | • $n = 1500 \text{ giro/min}$ | • $P_t = 592,41 \text{ N/mm}^2$ |
| • $D_f = 14,6 \text{ mm}$ | • $1/n = 0,060$ | • $F_t = 171,80 \text{ N}$ |
| • $a_p = 1,45 \text{ mm}$ | • $W = 0,216 \text{ kW}$ | • $P_m = 0,271 \text{ kW}$ |
| • $v = 75,60 \text{ m/min}$ | • $P_s = 550 \text{ N/mm}^2$ | • $\eta = 0,8$ |
| • $RE = 0,4 \text{ mm}$ | | |

Finishing turning of surface 3

- $D = 14,1 \text{ mm}$
- $D_i = 14,6 \text{ mm}$
- $D_f = 13,6 \text{ mm}$
- $a_p = 0,5 \text{ mm}$
- $v = 110,69 \text{ m/min}$
- $Ra = 0,78 \text{ }\mu\text{m}$
- $f = 0,1 \text{ mm/giro}$
- $n = 2500 \text{ giro/min}$
- $1/n = 0,060$
- $W = 0,073 \text{ kW}$
- $P_s = 550 \text{ N/mm}^2$
- $RE = 0,4 \text{ mm}$
- $S = 0,05 \text{ mm}^2$
- $P_t = 658,30 \text{ N/mm}^2$
- $F_t = 32,92 \text{ N}$
- $P_m = 0,092 \text{ kW}$
- $\eta = 0,8$

Facing of surfaces 6 and 7

- $D = 15,05 \text{ mm}$
- $D_i = 16,5 \text{ mm}$
- $D_f = 13,6 \text{ mm}$
- $a_p = 0,5 \text{ mm}$
- $v = 118,14 \text{ m/min}$
- $Ra = 0,78 \text{ }\mu\text{m}$
- $f = 0,1 \text{ mm/giro}$
- $n = 2500 \text{ giro/min}$
- $1/n = 0,060$
- $W = 0,073 \text{ kW}$
- $P_s = 550 \text{ N/mm}^2$
- $RE = 0,4 \text{ mm}$
- $S = 0,05 \text{ mm}^2$
- $P_t = 658,30 \text{ N/mm}^2$
- $F_t = 32,92 \text{ N}$
- $P_m = 0,092 \text{ kW}$
- $\eta = 0,8$

Chamfering of surfaces 8, 9, 10 and 11

- $D_i = 16,5 \text{ mm}$
- $D_f = 16,20 \text{ mm}$
- $f = \text{manuale}$
- $n_R = 500 \text{ giro/min}$

Drilling

- $D \rightarrow$ Diametro nominale (mm)
- $a_p \rightarrow$ Profondità di passata (mm)
- $v \rightarrow$ Velocità di taglio (m/min)
- $f \rightarrow$ Avanzamento al giro (mm/giro)
- $n = \frac{v \cdot 1000}{\pi D} \rightarrow$ Numero di giri al minuto del mandrino (giro/min)
- $1/n \rightarrow$ Costante di Kronenberg
- $P_s \rightarrow$ Pressione specifica di taglio (N/mm^2)
- $S = \frac{f \cdot D}{4} \rightarrow$ Sezione del truciolo (mm^2)
- $P_t = P_s \cdot S^{\frac{-1}{n}} \rightarrow$ Pressione di taglio (N/mm^2)
- $C = \frac{f \cdot D^2}{8000} p_t \rightarrow$ Coppia di taglio (Nm)
- $F_t = P_t \cdot S \rightarrow$ Forza di taglio (N)
- $W = \frac{2\pi \cdot nR}{1000 \cdot 60} C \rightarrow$ Potenza di taglio (kW)
- $\eta \rightarrow$ Rendimento
- $P_m = \frac{W}{\eta} \rightarrow$ Potenza della macchina (kW)

Center Drilling of surface 1

- $D = 1,6 \text{ mm}$
- $a_p = 0,8 \text{ mm}$
- $v = 12,56 \text{ m/min}$
- $F_t = 7,25 \text{ N}$
- $P_s = 550 \text{ N/mm}^2$
- $f = 0,02 \text{ mm/giro}$
- $n = 2500 \text{ giro/min}$
- $1/n = 0,060$
- $W = 0,001 \text{ kW}$
- $\eta = 0,8$
- $S = 0,01 \text{ mm}^2$
- $P_t = 725 \text{ N/mm}^2$
- $C = 0,005 \text{ Nm}$
- $P_m = 0,001 \text{ kW}$

Drilling

- $D = 4,5 \text{ mm}$
- $a_p = 3,0 \text{ mm}$
- $v = 31,09 \text{ m/min}$
- $F_t = 69,07 \text{ N}$
- $P_s = 550 \text{ N/mm}^2$
- $f = 0,1 \text{ mm/giro}$
- $n = 2200 \text{ giro/min}$
- $1/n = 0,060$
- $W = 0,037 \text{ kW}$
- $\eta = 0,8$
- $S = 0,11 \text{ mm}^2$
- $P_t = 627,9 \text{ N/mm}^2$
- $C = 0,159 \text{ Nm}$
- $P_m = 0,046 \text{ kW}$

Milling

- $D \rightarrow$ Diametro nominale (mm)
- $Z \rightarrow$ Numero di taglienti della fresa
- $a_p \rightarrow$ Profondità di passata (mm)
- $v \rightarrow$ Velocità di taglio (m/min)
- $Ra = \frac{f_z^2}{16 \cdot D} \cdot 1000 \rightarrow$ Rugosità teorica (μm)
- $f_z \rightarrow$ Avanzamento per dente (mm/min)
- $V_a = f_z \cdot n \cdot Z \rightarrow$ Velocità di avanzamento della tavola (mm/min)
- $n = \frac{v \cdot 1000}{\pi D} \rightarrow$ Numero di giri al minuto del mandrino (giro/min)
- $1/n \rightarrow$ Costante di Kronenberg
- $P_s \rightarrow$ Pressione specifica di taglio (N/mm^2)
- $S_{\max} = \frac{2V_a}{n \cdot Z} \sqrt{\frac{ap}{D}}$ Spessore massimo del truciolo (mm)
- $S_{\max} = s_{\max} \cdot l \rightarrow$ Sezione massima del truciolo (mm^2)
- $P_t = P_s \cdot S_{\max}^{-\frac{1}{n}} \rightarrow$ Pressione di taglio (N/mm^2)
- $T_{\max} = P_t \cdot S_{\max} \rightarrow$ Forza di taglio massima (N)
- $W_{\max} = \frac{T_{\max} \cdot v}{1000 \cdot 60} \rightarrow$ Potenza di taglio (kW)
- $\eta \rightarrow$ Rendimento
- $P_m = \frac{W_{\max}}{\eta} \rightarrow$ Potenza della macchina (kW)

Machining of surfaces 12 and 13

- $D = 4 \text{ mm}$
- $Z = 2$
- $V_a = 128 \text{ mm/min}$
- $a_p = 1,2 \text{ mm}$
- $v = 40,19 \text{ m/min}$
- $f_z = 0,02 \text{ mm/giro}$
- $n = 3200 \text{ giro/min}$
- $1/n = 0,060$
- $S_{\max} = 0,022 \text{ mm}$
- $P_s = 550 \text{ N/mm}^2$
- $S_{\max} = 0,026 \text{ mm}^2$
- $P_t = 684,65 \text{ N/mm}^2$
- $T_{\max} = 17,8 \text{ N}$
- $W_{\max} = 0,012 \text{ kW}$
- $\eta = 0,8$

- $Ra = 0,006 \mu m$
- $P_m = 0,015 kW$

Rough gear cutting of surface 3

- $D = 40 mm$
- $Z = 12$
- $V_a = 240 mm/min$
- $a_p = 1,4 mm$
- $v = 62,8 m/min$
- $P_m = 0,019 kW$
- $f_z = 0,04 mm/giro$
- $n = 500 giro/min$
- $1/n = 0,060$
- $s_{max} = 0,015 mm$
- $P_s = 550 N/mm^2$
- $S_{max} = 0,021 mm^2$
- $P_t = 693,47 N/mm^2$
- $T_{max} = 14,56 N$
- $W_{max} = 0,015 kW$
- $\eta = 0,8$

Finishing gear cutting of surface 3

- $D = 40 mm$
- $Z = 12$
- $V_a = 150 mm/min$
- $a_p = 0,4 mm$
- $v = 62,8 m/min$
- $Ra = 0,001 \mu m$
- $f_z = 0,025 mm/giro$
- $n = 500 giro/min$
- $1/n = 0,060$
- $s_{max} = 0,005 mm$
- $P_s = 550 N/mm^2$
- $P_m = 0,002 kW$
- $S_{max} = 0,002 mm^2$
- $P_t = 798,55 N/mm^2$
- $T_{max} = 1,6 N$
- $W_{max} = 0,002 kW$
- $\eta = 0,8$

8.7. Production Times

Parting-off

$$t = \frac{D + e}{V_a}$$

Parametri tempi attivi	Valore
Diametro (mm)	20
Extracorsa (mm)	3
Velocità di avanzamento (mm/min)	90
Tempo per singolo taglio (min)	0,26

Tempi di preparazione	Tempo unitario (min)
Piazzamento pezzo	0,15
Regolazione guidalame	0,4
Impostazione parametri	0,15

Regolazione battuta	0,5
Taglio di intestazione	0,26
Spostamenti a vuoto arco	0,16
Smontaggio pezzo	0,05
Misurazione	0,3
Totale	1,97

Tempi passivi	Tempo unitario (min)
Avanzamento barra a battuta	0,2
Spostamenti a vuoto arco	0,16
Totale	0,36

Turning

$$t = \frac{L + e}{f \cdot n}$$

Parametri tempi attivi	Sfa. 1-5	Sgr. 2	Sgr. 4	Fin. 2	Fin. 4	Sgr. 3	Fin. 3	Sfa. 6-7	Smu. 8-9-10- 11
Lunghezza (mm)	10	1,5	3	1,5	3	10	10	1,45	-
Extracorsa (mm)	2	3	3	1,5	1,5	2	1	1	-
Avanzamento (mm/giro)	0,1	0,2	0,2	0,1	0,1	0,2	0,1	0,1	manua le
Velocità del mandrino (giri/min)	2500	1500	1500	2500	2500	1500	2500	2500	500
N. passate	1	1	1	1	1	1	1	1	1
Tempo per singola	0,048	0,015	0,02	0,012	0,018	0,04	0,044	0,0098	0,025

passata (min)									
Tempo totale (min)	0,096	0,015	0,02	0,012	0,018	0,04	0,044	0,0196	0,1
Totale	0,37								

Tempi di preparazione	Tempo unitario (min)
Montaggio piattaforma autocentrante	0,6
Regolazione apertura griffe	0,1
Montaggio portautensili	0,1
Regolazione altezza portautensili	0,2
Impostazione parametri	0,15
Adattamento attrezzatura	3
Totale	4,5

Tempi passivi	Tempo unitario (min)	Frequenza	Tempo totale (min)
Piazzamento pezzo	0,4	2	0,8
Avviamento e arresto	0,05	16	0,8
Spostamenti a vuoto carro	0,2	10	2
Spostamenti a vuoto utensile manuale	0,1	2	0,2
Modifica parametri	0,15	6	0,9
Misurazione	0,3	5	1,5
Smontaggio pezzo	0,4	2	0,8

Totale	7
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Drilling

$$t = \frac{L + e}{f \cdot n}$$

Parametri tempi attivi	Centatura 1	Foratura
Profondità (mm)	0,8	3
Extracorsa (mm)	2	4,35
Avanzamento (mm/giro)	0,02	0,1
Velocità del mandrino (giri/min)	2500	2200
N. passate	1	5
Tempo per singola passata (min)	0,056	0,033
Tempo totale (min)	0,056	0,167
Totale	0,22	

Milling

$$t = \frac{L' + e}{V_a}$$

Parametri tempi attivi	Esecuzione 12-13	Sgrossatura 3	Finitura 3
Corsa dell'asse della fresa (mm)	19,37	17,35	18,29
Extracorsa (mm)	0	2	2
Velocità di avanzamento (mm/min)	128	240	150
N. passate	13	1	1
Tempo per singola passata (min)	0,15	0,08	0,135
Tempo totale (min)	1,95	0,08	0,14
Totale	2,17		

Tempi di preparazione	Tempo unitario (min)
Montaggio divisore universale	3
Allineamento divisore universale	2,5
Montaggio piattaforma autocentrante	0,6
Regolazione corsa verticale	0,2
Regolazione apertura griffe	0,1
Montaggio mandrini portautensili	1,5
Impostazione parametri	0,15
Totale	8,05

Tempi passivi	Tempo unitario (min)	Frequenza	Tempo totale (min)
Piazzamento pezzo	0,4	1	0,4
Avviamento e arresto	0,05	10	0,5
Spostamenti a vuoto tavola	0,3	45	13,5
Cambi mandrini portautensili	1,5	1	1,5
Cambi utensile	1	4	4
Modifica parametri	0,15	4	0,6
Riposizionamento divisore	0,15	30	4,5
Misurazione	0,3	3	0,9
Smontaggio pezzo	0,4	1	0,4
Totale	26,3		

Workbench

Tempi attivi	Tempo unitario (min)	Frequenza	Tempo totale (min)
Smussatura	0,2	2	0,4

Tempi di preparazione	Tempo unitario (min)
Adattamento attrezzatura	0,5
Totale	0,5

Tempi passivi	Tempo unitario (min)	Frequenza	Tempo totale (min)
Piazzamento pezzo	0,15	2	0,3
Spostamenti a vuoto	0,1	2	0,2
Smontaggio pezzo	0,15	2	0,3
Totale	0,8		

The time required to manufacture a single component is approximately 40.38 minutes. Therefore, the production of the entire batch of 6 components requires a total time of approximately 4 hours.

8.8. Production Costs

Labour Cost

It is assumed that the operator's hourly rate is €30/h, resulting in a total labour cost of €120 for the production of the entire batch.

Depreciation Costs

Considering a useful life of 10 years with an annual utilization of 2000 hours, the hourly depreciation rates of the individual machines are calculated. By multiplying these rates by the total occupation time

recorded for each workstation, the total depreciation costs allocated to the entire batch are:

Band saw $\rightarrow \text{€}613.75 / (10 \times 2000 \text{ h}) \times 0.087 \text{ h} = \text{€}0.0026$

Lathe $\rightarrow \text{€}4768.99 / (10 \times 2000 \text{ h}) \times 0.812 \text{ h} = \text{€}0.195$

Milling machine $\rightarrow \text{€}3544.12 / (10 \times 2000 \text{ h}) \times 3.003 \text{ h} = \text{€}0.541$

Total = €0.74

Power Consumption Cost

Assuming an electricity cost of €0.25/kWh, the electrical energy cost consumed during machining by each machine is:

Band saw $\rightarrow 0.85 \text{ kW} \times 0.0217 \text{ h} \times 0.25 \text{ €/kWh} \times 0.7 = \text{€}0.0032$

Lathe $\rightarrow 1.5 \text{ kW} \times 0.037 \text{ h} \times 0.25 \text{ €/kWh} \times 0.7 = \text{€}0.0097$

Milling machine $\rightarrow 1.5 \text{ kW} \times 0.217 \text{ h} \times 0.25 \text{ €/kWh} \times 0.7 = \text{€}0.057$

$\rightarrow 1.1 \text{ kW} \times 0.022 \text{ h} \times 0.25 \text{ €/kWh} \times 0.7 = \text{€}0.0042$

Total = €0.074

Raw Material Cost

For the entire batch, a single material bar will be purchased at a cost of €5.17.

Maintenance Cost

The cost of routine maintenance and lubricants is calculated by applying a fixed coefficient of 15% to the total depreciation cost of the batch:

$C_{\text{man}} = 0.74 \times 0.15 = \text{€}0.11$

Tooling Cost

The cost is calculated by considering the cutting edge wear contribution based on the specific tool life cycle. For integral tools (band saw blades, drills, and milling cutters), the number of possible operations before resharpening is estimated. For disposable interchangeable tools (turning insert), the useful cutting time before replacement at the end of tool life is considered.

Band saw blade $\rightarrow \text{€}13.18 / 1000 \text{ cuts} \times 6 \text{ cuts} = \text{€}0.078$

Turning insert CCGT 060204-AS IC20 $\rightarrow \text{€}13.90 / 15 \text{ min} \times 2.22 \text{ min} = \text{€}1.03$

Centre drill 111050 1.6 → €6.41 / 500 holes × 6 holes = €0.077

Twist drill 113150 4.5 → €6.22 / 500 holes × 6 holes = €0.074

End mill DJ2F 4 → €10.00 / 30 min × 11.7 min = €3.90

Gear milling cutter 811002 → €131.56 / 60 min × 1.32 min = €2.89

Total = €8.05

Allocated Share of General Company Expenses

General workshop management costs are calculated by applying a fixed overhead rate of 40% to the sum of depreciation, labour, and power consumption costs.

$$0.74 + 120.00 + 0.074 = €120.81$$

$$Csp = 120.81 \times 0.40 = €48.32$$

The total cost for manufacturing the entire batch is therefore €182.46, which corresponds to a unit production cost of €30.41 per component.

Attached are the images of the prototype manufactured through PLA 3D printing, produced for demonstrative purposes in order to represent the geometry of the component originally designed to be manufactured using a different manufacturing technology.



9. Component Introduction: Accelerator Pedal Plate

The component under consideration is the **accelerator pedal support plate**. This element represents the direct ergonomic interface between the driver and the vehicle actuation systems. Consequently, the component must meet both structural and functional requirements: it must provide high bending and torsional stiffness to prevent elastic deformation under driver-applied loads, ensure a high-grip surface under all environmental conditions, and maintain an extremely low mass in order to reduce the overall inertia of the assembly.



9.1. Material Selection

The material selection for the accelerator pedal plate was driven by the objective of maximizing the stiffness-to-weight ratio, while simultaneously ensuring excellent manufacturability through laser cutting and bending operations. For this component, 5754-H111 aluminium alloy (Peraluman) was selected.

The H111 temper provides excellent suitability for cold plastic deformation, preventing the risk of microcracks along bending radii while exploiting local work hardening to increase the pedal's yield strength under driver-applied loads.

9.2. Number of Parts to Be Produced

The production of this component is planned for extremely low volumes, typical of the motorsport and prototype racing sectors, with a limited batch of only 2 parts for the entire racing season (including the component installed on the vehicle and one safety spare part).

9.3. Selection of the Manufacturing Process

The selected manufacturing process for the accelerator pedal plate consists of a sequential combination of CNC laser cutting followed by manual cold bending.

This choice is motivated by a logical evaluation of the limited seasonal production volume (one primary component and one spare part), which excludes the use of mass plastic deformation processes or industrial

blanking operations, as the tooling costs for dedicated dies would be economically unsustainable.

The adopted process is characterized by the following features:

Geometric flexibility and millimetric precision: The laser cutting process allows the perimeter profile and the mounting holes to be produced simultaneously directly from the flat sheet, ensuring optimal tolerances for the subsequent mechanical fastening using screws to the rear tabs.

Structural optimization: Manual segmented bending allows the creation of the inclined flanges and the lateral safety wall. This approach geometrically stiffens the 2 mm thick structure by exploiting local material work hardening, increasing bending strength without adding unnecessary mass.

Economic efficiency: The entire process minimizes material waste and eliminates investments in dedicated tooling, making the production fully compatible with the racing team's budget and available resources.

9.4. Machine Selection

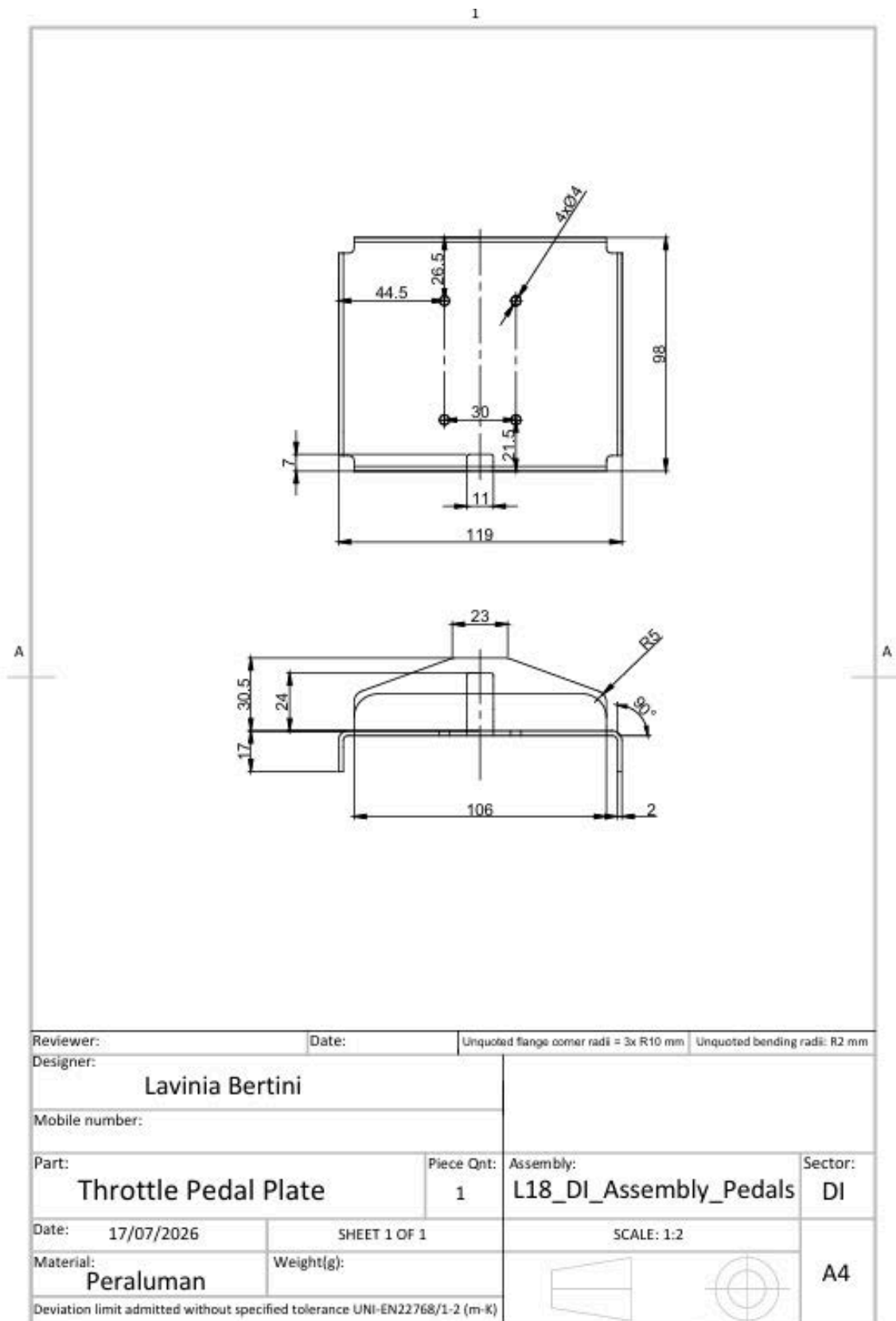
Sheet Metal Bending Machine — Bernardo TBS 1020

Technical Data

- Working length: 1020 mm
- Maximum sheet thickness (400 N/mm²): 2.0 mm
- Maximum opening width: 54 mm
- Bending angle: 0°–135°
- Price: €1,980.07



9.5. Technical drawing



Study of Technological Parameters

Flat Sheet Metal Development Length

$$L = l_1 + l_2 + \pi \cdot \frac{\alpha}{180} \cdot (R_i + e \cdot \frac{s}{2})$$

$$13 + 111 + 4,18 = 128,18 \text{ mm}$$

$$28,5 + 90 + 4,18 = 122,68 \text{ mm}$$

$$13 + 90 + 4,18 = 107,18 \text{ mm}$$

Bend Allowance

$$BA = \pi \cdot \frac{\alpha}{180} \cdot (R_i + K \cdot s) = \pi \cdot \frac{90}{180} \cdot (2 + 0,33 \cdot 2) = 4,18 \text{ mm}$$

Springback

$$K_e = \frac{\alpha f}{\alpha i} \approx 1 - 3 \cdot \left(\frac{R_i \cdot \sigma s}{E \cdot s} \right) = 1 - 3 \cdot \left(\frac{2 \cdot 80}{70.000 \cdot 2} \right) = 1,0$$

Bending Force

$$F = \frac{C \cdot L \cdot s^2 \cdot \sigma r}{V}$$

$$\frac{1,3 \cdot 128,18 \cdot 4 \cdot 190}{16} = 7.915,12 \text{ N}$$

$$\frac{1,3 \cdot 122,68 \cdot 4 \cdot 190}{16} = 7.575,49 \text{ N}$$

$$\frac{1,3 \cdot 107,18 \cdot 4 \cdot 190}{16} = 6.618,37 \text{ N}$$

9.6. Cycle Time Calculation

Tempi attivi	Tempo unitario (min)	Frequenza	Tempo totale (min)
Deformazione	0,06	4	0,24

Tempi di preparazione	Tempo unitario (min)
Composizione segmenti	8
Regolazione registro	2,5
Taratura spessore	2
Totale	12,5

Tempi passivi	Tempo unitario (min)	Frequenza	Tempo totale (min)
Piazzamento pezzo	0,08	1	0,08
Riposizionamenti	0,08	3	0,24
Bloccaggi	0,025	4	0,1
Estrazione del pezzo	0,075	1	0,075
Totale	0,74		

The time required to manufacture a single component is approximately 7.23 minutes. Therefore, the production of the entire batch of 2 components requires a total time of approximately 14.46 minutes.

9.7. Production Costs

Labour Cost

It is assumed that the operator's hourly rate is €30/h, resulting in a total labour cost of €7.23 for the production of the entire batch.

Depreciation Cost

Considering a useful life of 10 years with an annual utilization of 2000 hours, the hourly depreciation rate of the machine is calculated. By multiplying this rate by the total recorded occupation time, the total depreciation cost allocated to the entire batch is:

$$€1,980.07 / (10 \times 2000 \text{ h}) \times 0.24 \text{ h} = €0.024$$

Raw Material Cost

For the entire batch, a single sheet of material will be purchased at a cost of €1.12.

Maintenance Cost

The routine maintenance cost is calculated by applying a fixed coefficient of 15% to the total depreciation cost of the batch:

$$C_{man} = 0.024 \times 0.15 = €0.0036$$

Allocated Share of General Company Expenses

General workshop management costs are calculated by applying a fixed overhead rate of 40% to the sum of depreciation and labour costs.

$$0.024 + 7.23 = €7.25$$

$$C_{sp} = 7.25 \times 0.40 = €2.90$$

The total cost for manufacturing the entire batch is therefore €11.28, which corresponds to a unit production cost of €5.64 per component.

Attached are the images of the prototype manufactured through PLA 3D printing, produced for demonstrative purposes in order to represent the geometry of the component originally designed to be manufactured using a different manufacturing technology.



10. Component introduction: brake pedal plate

The **pedal plate** represents the contact surface between the driver's foot and the brake pedal lever.

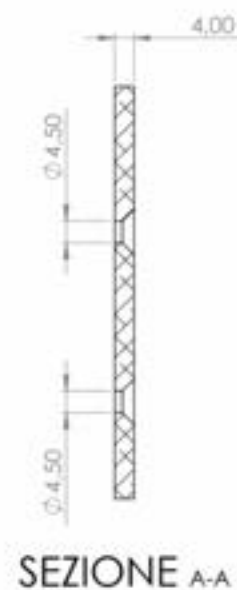
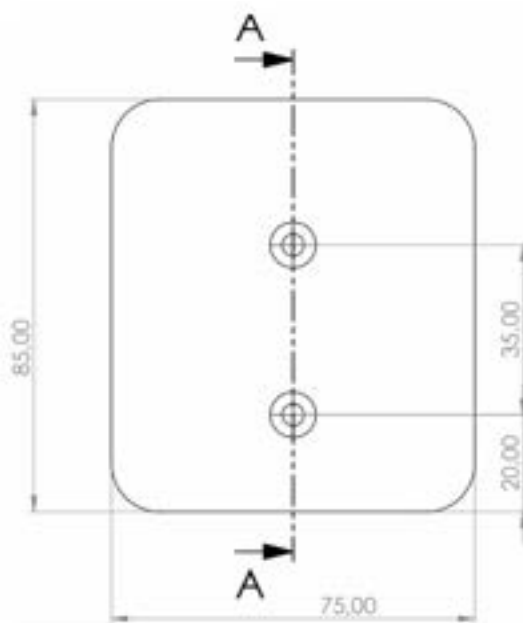
From a functional point of view, the component must ensure:

- Adequate grip during braking;
- Reduction of the overall weight;
- Good local stiffness;
- Resistance to surface wear;
- Reliable connection with the brake pedal lever.



In the actual configuration of the Formula Student car, the pedal plate is generally manufactured through ABS 3D printing and mechanically fastened using screws, allowing quick replacement of the component and ergonomic modifications during the vehicle development season.

However, in the present study, in order to analyze a welding joining technology, a different manufacturing configuration was considered. In this alternative configuration, the pedal plate is permanently connected to the brake pedal lever through a welded joint.



10.1. Material selection

For the manufacturing of the pedal plate, an **EN AW-6082 T6 aluminum alloy** was selected.

The choice was made considering the good weldability of the EN AW-6082 T6 alloy and the possibility of producing a joint with the AlSi7Mg alloy through the use of an appropriate filler material.

The use of an aluminum alloy also allows the overall mass of the braking system to be kept low, which is particularly important in the Formula Student context, where weight reduction contributes to improving the vehicle's dynamic performance.

Main Mechanical Properties:

- **Yield strength:** approximately 250 MPa
- **Tensile strength:** approximately 290 MPa
- **Density:** 2.70 g/cm³
- **Young's modulus:** approximately 70 GPa

From a production point of view, the material is readily available in sheet form and has costs compatible with the typical budget of a university Formula Student team.

10.2. Joining process selection: TIG welding

For the connection between the pedal plate in EN AW-6082 T6 and the brake pedal lever in AlSi7Mg, the TIG welding process (Tungsten Inert Gas) was selected.

This technology is particularly suitable for welding lightweight alloys due to the high quality of the resulting joint and the excellent control of heat input during the process.

In this specific case, an ER4043 filler material is used, as it is compatible with Al-Si alloys such as AlSi7Mg.

10.3. Welding machine selection

The selected welding machine is a **Fronius MagicWave 230i AC/DC TIG welder**.

Parametro	Valore
Corrente massima	230 A
Modalità AC/DC	Presente
Raffreddamento	Ad aria
Alimentazione	230 V
Costo indicativo	4500€
Polarità	AC

The machine was also selected because the **AC polarity** is required for **aluminum welding**, as it enables the removal of the surface oxide layer during the welding process.

This characteristic is essential when welding aluminum alloys, since the naturally occurring **aluminum oxide (Al_2O_3) layer** has a higher melting point than the base material and can negatively affect weld quality if not properly disrupted.

10.4. Welding parameters

The adopted welding parameters are:

Parametri	Valore
Corrente	90 A
Modalità	AC
Gas di protezione	Argon puro
Diametro elettrodo tungsteno	2.4 mm
Materiale d'apporto	ER4043
Velocità avanzamento	80 mm/min

The welding process is carried out according to the following steps:

1. Surface preparation through mechanical cleaning and degreasing;
2. Component positioning using a welding fixture;
3. Execution of tack welds to ensure correct positioning;
4. TIG welding execution;
5. Natural cooling of the welded assembly;

6. Visual inspection and non-destructive testing (NDT).

10.5. Welded joint inspection

To verify the quality of the welded joint, the following inspections are carried out:

- Visual inspection;
- Dimensional inspection;
- Liquid penetrant testing.

These inspections allow the detection of possible surface porosities, cracks, geometric defects, and lack of fusion in the welded joint.

10.6. Time and cost analysis

10.6.1. Production times

The following processing times were considered:

- Surface cleaning and degreasing: 5 min
- Component positioning and clamping: 5 min
- Preliminary tack welding: 2 min
- TIG welding execution: 8 min
- Natural cooling: 10 min
- Visual and dimensional inspection: 5 min
- Liquid penetrant testing: 10 min

The operating time, during which the presence of the operator is required, is:

$$t_{op} = 5 + 5 + 2 + 8 + 5 + 10$$

$$t_{op} = 35 \text{ min}$$

The natural cooling phase represents an inactive time equal to:

$$t_{in} = 10 \text{ min}$$

Therefore, the total processing time is:

$$t_{tot} = 35 + 10$$

ttot = 45 min

10.6.2. Costs

- Labor cost: assuming an operator cost of €30/h and an operating time of 35 minutes, the labor cost is:

$$Clabor = 30 \times (35/60) = \text{€}17.50$$

- Filler material: for the welded joint, a limited consumption of ER4043 filler rod was estimated. The corresponding cost is assumed equal to:

$$C_{\text{filler}} = \text{€}0.50$$

- Shielding gas: assuming an argon flow rate of approximately 10 L/min and a delivery time of 10 minutes, including welding and pre/post-gas:

$$Var = 10 \times 10 = 100 \text{ L}$$

Considering an indicative argon cost of €0.01/L:

$$CAr = 100 \times 0.01 = \text{€}1.00$$

- Electrical energy: considering the short operating time of the welding machine and an indicative average absorbed power of approximately 2.5 kW:

$$E = 2.5 \times (8/60) = 0.33 \text{ kWh}$$

Assuming an electricity cost of €0.30/kWh:

$$C_{\text{energy}} = 0.33 \times 0.30 = \text{€}0.10$$

- Welding machine depreciation: the welding machine, with an indicative purchase cost of €4500, is considered a shared capital asset. Its cost is therefore not fully assigned to the single component but distributed over the useful life of the machine.

Assuming:

- Useful life: 10 years
- Average utilization: 1000 h/year
- The total operating time is:

$$H = 10 \times 1000 = 10000 \text{ h}$$

The hourly depreciation cost is therefore:

$$C_{\text{amortization}} = 4500 / 10000 = \text{€}0.45/\text{h}$$

Considering the welding time:

$$t = 8 \text{ min} = 0.133 \text{ h}$$

The machine depreciation cost is:

$$C_{\text{machine}} = 0.45 \times 0.133 = \text{€}0.06$$

- Consumables and inspection materials: considering the wear of the tungsten electrode, gas nozzle, cleaning brushes, and the products used for liquid penetrant testing, a total cost is assumed equal to:

$$C_{\text{consumables}} = \text{€}1.50$$

- Total process cost:

$$C_{\text{total}} = 17.50 + 0.50 + 1.00 + 0.10 + 0.06 + 1.50$$

$$C_{\text{total}} = \text{€}20.66 \approx \text{€}21$$

Therefore, the total cost of the welding process is:

$$\mathbf{C_{\text{total}} = \text{€}21}$$

Attached are the images of the prototype manufactured through PLA 3D printing, produced for demonstrative purposes in order to represent the geometry of the component originally designed to be manufactured using a different manufacturing technology.



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4. EN AW-6082 T6 Datasheet
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APPENDIX

The images reported below document the actual braking system of the ET-18 Formula Student car developed by the E-Team Racing Team of the University of Pisa.

The opportunity to directly observe the component and the corresponding assembly during workshop activities made it possible to compare the CAD model with the system actually implemented on the vehicle, verifying its geometry, assembly methods, and construction features.

The photographic documentation therefore represents a useful support for the analyses developed in this report, showing the application context of the studied components and the main assembly phases of the braking system.





ACKNOWLEDGEMENTS

The authors would like to thank the **E-Team Racing Team of the University of Pisa** for making the Formula Student car braking system available and for allowing direct observation of the components during workshop activities, thereby contributing to the development of this work.