



OPTIMIZATION OF SIMULATION VARIABLES OF POWDER BED FUSION FOR 17-PH STEEL

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ABSTRACT

This research aims to carry out an optimization process through the new simulation tool in additive manufacturing, specifically the powder bed fusion process. It begins by defining those values to reduce costs and production times for parts. Subsequently, a 17-4PH material tension specimen is simulated to determine the improvements in this manufacturing process using the Additive Manufacture library of ANSYS. This software guarantees the optimal and fast printing of the workpiece and helps to predict distortion, produced residual stress, thermal deformation; automatic supports generation, and scanning patterns. In addition, results at the microstructure level, such as the material's porosity and the machine's parameters, can be predicted.

Keywords: additive manufacturing, porosity simulation, thermal deformation simulation, distortion simulation.

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INTRODUCTION

Technological innovation provides excellent solutions to manufacture parts and products with complex and unique requirements, where AM plays an essential role in its manufacturing flexibility. Also, AM process has a promising future in maintenance because it is betting on digital storage parts, representing an expense reduction in stock parts warehouses and reducing delivery time [1]. Furthermore, with the COVID-19 pandemic, the AM was vital in generating design solutions to reduce time, cost, and material in constructing scarce supplies necessary for personal protection, medical equipment, and patient transport [2]. However, to apply this technology widely, some limitations must be reduced, such as the difficulty in studying the process parameters to obtain the required as-built component quality [3] and the cost of production [4] associated with both the high costs to implement it and the few available materials. AM also brings challenges, such as product redesign, necessary skills, new commercial proposals, and industry changes [5].

Optimization in the Additive manufacturing (AM) process includes many stages where variables are changed to improve the mechanical, physical, and finished requirements. Usually, practical experiments are carried out to determine the parameters influencing the as-built component quality that covers the following stages:

First, some variables are adjusted using computer-aided design (CAD). Second, the experiment design is planned to cover different variable levels, and the specimens' tensile tests are printed using the predetermined values, which iterate according to the experimental design. Next, mechanical tests are carried out to analyze the properties obtained in each case, and in agreement with the results, the best value for the process variable is defined. This optimization technique is costly due to the resources involved: time of specialized personnel, printing machine, printing time, amount of required material for specimens and its remaining waste,

and mechanical and metallurgical tests [4]. In addition, it requires the researcher's time to be spent on planning the trial and subsequent statistical analysis of the results. The impact that manufacturing has on the environment must also be taken into account because this sector is the largest consumer of energy and materials. It is vital to reduce energy and materials consumption in the manufacturing process [6].

Variables of the most common AM processes include laser power, layer thickness, laser scanning speed, and scanning pattern. These variables influence physical characteristics and properties such as density, roughness, mechanical properties, and defect formation. Determining the appropriate parameter values solve more important manufacturing-related problems such as porosity, residual stress, and distortion. Incomplete melt powder, large granulometric distribution powder sizes, and laser power frequently cause porosity. It causes geometry, mechanical properties, density, thermal insulation, and permeability challenges. Bearing in mind the porosity importance, determining its quantity through simulation be a tremendous potential contribution to AM since it allows planning in manufacturing [7]. Residual stress is produced due to thermal gradients during fabrication, which causes uneven expansion and contraction in the material and consequent states of compressive or tensile stresses. Distortion is generated when the residual stresses exceed the elastic limit of materials, producing plastic deformation. Defects affect functionality, required tolerances, flatness, or even crack presence on the component [8].

Also, with the implementation of computer-aided engineering (CAE) could be minimized the number of specimens to be printed, the energy and material spent, and therefore, it is possible to reduce the share of the cost of resources associated with some stages [1]. The main contribution of this research is to analyze an optimization method for the powder bed fusion (PBF) process using



simulation by a recently manufactured additive package on the ANSYS software [2]. This research determines the best parameters to improve densification and decrease thermal deformation and distortion during manufacturing 17-4PH specimens for a tensile test through an additive manufacturing simulation. Furthermore, it demonstrates the advantages of computer-assisted simulation in improving the AM process by reducing: time, costs, and material consumption. This program guarantees the workpiece's optimal and fast printing by predicting distortion, porosity, residual stress, and thermal deformation and generating automatic support and scanning patterns.

METHODOLOGY

This research was supported by the specialized package Additive of the ANSYS software, used in the labor and academic field. The different process variables were investigated using this software to find the best conditions. Computer Aided Engineer (CAE) performed a standard stress specimen by iterating variables such as base plate temperature, layer angle, laser beam diameter, laser power (W), scanning speed (mm/s), layer thickness (μm), slice width (mm), minimum height support (mm), safety factor, wall thickness (μm), distance to the wall (μm) and anisotropic stress coefficients [9] and simulating the additive process (PBF) to determine which values obtained the minor porosity, distortion, and thermal deformation and reduction of cost and time.

Computer Features

A high-capacity computer is needed, and a processor can be from an Intel i5 onwards, with a solid disk more significant than 8 Gb of RAM (it is recommended to be 16 Gb) of the latest generation ideal. The computer used for the simulations was an 8th generation Intel i5, a Tera SSD, and 8 Gb RAM.

Software Programming

First, a straightforward approach to the Ansys Additive software environment was made. It shows four icons that are used to program the additive manufacturing process. The first (Figure-1a) shows the materials used for the simulations; some materials come by default as 316L (Beta), Al357, AlSi10Mg, CoCr, IN625, IN718, Ti64, and 17-4PH. Different materials can be loaded from other databases, such as ANSYS GRANTA. This investigation used a default material, 17-4PH stainless steel.

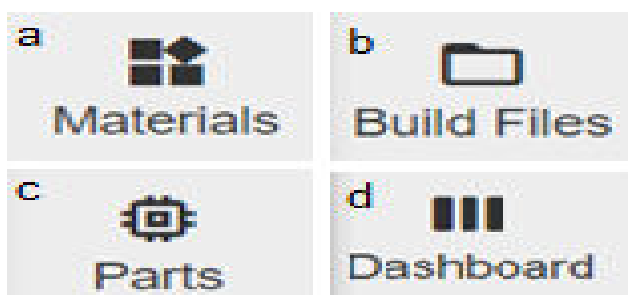


Figure-1. Basic icons.

The second icon (Figure-1b), "Build Files" enables the creation or importing of files with a machine extension file or a single-part geometry file (.stl). The part and support geometries must match the scan patterns' size, orientation, and position in the machine instruction file. Additive Industries, Eosprint (EOS), Renishaw, or SLM extension are the software used to change the machine parameters. The third icon (Figure-1c) "Parts" is where the parts of the component are imported to be simulated, and the total volume is calculated. The last one, the dashboard icon (Figure-1d) is where the simulation for the MA is carried out. It helps minimize thermal deformation, ensures high-quality parts, checks distortion and stress, avoids a nozzle crash, reduces impression time, and provides a fast and detailed thermal analysis.

Ansys Additive software is designed to determine the optimal parameters of metallic materials and the machine. It can simulate two properties, porosity and grain size. Porosity indicates the number of spaces or pores in the material. The grain size affects the material's mechanical properties; for example, a small grain size confers higher hardness and tensile strength than one coarse.

For a simulation where the porosity and grain size are defined previously, the parameters that must be considered are the type of material, the temperature of the bed, the laser's power, and the dimension of the geometry. Ansys Additive Print can simulate three essential variables to guarantee the part's quality: thermal stress, scanning pattern, and the assumed deformation. Thermal stress is generated when a temperature difference occurs in the material, producing internal deformation gradients, even fracturing it when it is enormous. This variable depends on two factors, material properties and geometry. The material's mechanical and thermal properties must be considered: modulus of elasticity, elastic limit (yield strength), Poisson's ratio, the anisotropic coefficients, and thermal expansion coefficient. The geometry is associated with its dimensions and the type of supports used. For carrying out the simulation, the software can set parameters such as base temperature ($^{\circ}\text{C}$), plate thickness (μm), the angle of the initial layer, the angle of the laser, the width of the cutting strip (mm), beam diameter laser (μm), laser power and scanning speed (mm/s). Material properties are included when the material is chosen. The scan pattern is how the scanning vectors are oriented to fill each layer. On the software can be fixed the plate's thickness (μm), the initial layer angle, and the laser angle to define this variable. Finally, the assumed deformation depends on the selected geometry, support, and material properties.

Porosity Simulation

This simulation option obtains the porosity levels in the material produced by a lack of fusion. The scanning pattern, geometry configuration, and the piece's dimensions must be considered for the machine's configuration.



Thermal Stresses

The simulation predicts the thermal cycle that affects the part with the deformation accumulation. Any time the part is heated above the melting temperature, thermal stress occurs. The thermal stress simulation must consider both the type of material and a good mesh resolution, which implies its size, geometry, and node number. Thermal stresses require less computational time compared to porosity ones. Other parameters required are base plate temperature, laser power, and scan speed.

Scan Pattern

The scan pattern simulation assumes that stress is generated in the scan direction. In addition, the anisotropic strain coefficient of the material and machine parameters, such as layer thickness (μm), initial layer angle, and layer rotation angle must be considered.

- Anisotropic stress coefficient: The anisotropic stress coefficient determines the strain behavior in the coordinate system defined during the build. There are three conditions in which this coefficient assumes different values. First, when the stress is generated longitudinally, the predicted strain in the direction of the laser scanning the main fill pixels will be multiplied by 1.5. So the anisotropic strain coefficient (\parallel) = 1.5. In contrast, if the stress is transverse, the predicted strain is orthogonal to the direction in which the laser scans the main fill; in this case, the anisotropic strain coefficient is (\perp) = 0.5. If the stress is generated by depth, the predicted strain in the Z direction will be multiplied by 1; then, the anisotropic strain coefficient (z) = 1.
- Machine parameters for a scan pattern simulation: The software uses an internal division of the component in a function called "slicing," which assumes a contoured rotating fringe scanning pattern; it divides the piece to generate each layer circularly. The required parameters are the layer's thickness, the angle of the initial layer, and the layer's rotation angle. The simulation predicts the thermal cycle that affects the part with the deformation accumulation. Any time the part is heated above the melting temperature, thermal stress occurs. The thermal stress simulation must consider both the type of material and a good mesh resolution, which implies its size, geometry, and node number. Thermal stresses require less computational time compared to porosity ones. Other parameters required are base plate temperature, laser power, and scan speed.

Residual or Assumed Strain

Residual strain is one of the most complex drawbacks in the Power Bed Fusion manufacturing process, so its determination is crucial to understanding the limitations [10].

The assumed strain simulation is the fastest compared to thermal stress and porosity level ones. This deformation occurs within the piece during its manufacturing. This strain is equal to the Stress Scale

Factor (SSF) multiplied by the elastic limit divided by the elastic modulus, as can be observed in equation (1) [11].

$$\varepsilon = SSF * \frac{\sigma_{yield}}{E} \quad (1)$$

The SSF value is determined experimentally depending on the variables machine, deformation, stress mode and material kind, and it quantifies the fabrication machine variables.

Setting up an Assumed Stress simulation

The number of cores: For the optimal simulation in ANSYS, Additive allows specifying the multiple processor cores numbers up to 12; the default value is 4.

- Voxel size: A voxel is a hexahedral (cubic) element used in the meshing of finite element method; when combined, they define the geometry domain. The minimum voxel size depends on the computer capacity; also, their size must ensure a safe simulation run. The software calculates its size automatically when the part is imported. The default voxel size is 0.5mm.
- Voxel Sampling Rate: The voxelization function divides the geometry domain into sub-voxels, representing the best geometry, particularly for edges and curves. Sometimes, more voxels may be required to adequately capture thin supports and part features than the five default ones.
- Use of automatic supports: ANSYS Additive application creates automatic support for the as-built component. The software simulates the build process with an initial set of supports based solely on geometry considerations; then, it generates two new sets of optimized supports from the results.
- Minimum overhang angle: This angle is measured from the powder bed surface (horizontal = 0 degrees) to the component surface. Any point on the part surface with an angle less than 45° is accepted.
- Essential parameters to create solid support are wall thickness, laser power, scanning speed, angles of each layer, layer thickness, shading spacing, and base temperature. Each one is explained as follows.
- Minimum and maximum wall thickness (μm): The minimum wall thickness is the thinnest possible support that the machine can build. Typically, it specifies the thickness of a single bead scan. The default software value is 100 microns. The thickness of the supporting walls does not exceed the maximum wall thickness, and its range is from 20 to 500 microns.
- Laser power (W): The laser power on the machine should be between 50 and 700 Watts; the default settings is 195 Watts.
- Scan speed (mm/sec): The laser speed used to melt the powder, excluding jump, up, and down speeds. It must be between 350 and 2500 mm/sec. The set value is 1000 mm/sec.
- Laser beam diameter (μm): The laser width on the powder surface depends on the machine's



characteristics. The software considers a diameter between 20 and 140 μm . The set value is 100 μm .

- Initial layer angle: It is the orientation of the filler on the first layer printed. It is measured on X-axis, and its value must be between 0 and 180°. Zero degrees mean parallel to the X-axis. The default setting is 57°.
- Layer rotation angle: It is the angle of scan orientation that changes from layer to layer. It must be between 0 and 180°, set at 67°.
- Layer thickness (μm): The filler material thickness evolved in each laser pass. Each machine and material has a specific thickness; so it is recommended to use this value. Generally, it is between 10 and 100 microns. The default setting is 50 microns.
- Hatch spacing (μm): This is the scan distance when the laser moves from one side to another. The hatch spacing should allow for a slight overlap of the scan vector so that some of the material is re-melted to ensure complete coverage of the solid material. It should be between 10 and 1000 microns. The set value is 100 microns.
- Base plate *temperature* ($^{\circ}\text{C}$): It must be between 20° and 500°C. The default value is 80 $^{\circ}\text{C}$.

Other Parameters

The following parameters are less relevant to generating the simulation but help with the accuracy of the results. On the list can be observed the default values.

- Cutting line width (mm): 1 to 100
- Voxel size (mm): 0.02 to 10
- Voxel Sampling Rate: 1 to 10
- Mesh resolution factor: 1 to 12
- Minimum Overhang Angle: 1 to 89
- Minimum support height (mm): 0 to 25
- Support yield strength ratio: 0.01 to 1
- Support Safety Factor: 0.1 to 10
- Maximum distance to the wall (μm): 0 to 10000
- Minimum wall thickness (μm): 0 to 10000
- Maximum Wall Thickness (μm): 0 to 10000
- Distance to the wall (μm): 0 to 10000

Geometry configuration

- Width, X (mm): 1 to 10
- Length, Y (mm): 1 to 10

- Height, Z (mm): 1 to 10
- Cord length (mm): 1 to 10

RESULT AND DISCUSSIONS

Six simulations were conducted to determine the best parameters to improve densification and decrease thermal deformation and distortion. The material used for the simulation was 17-4PH steel. Cubic geometry mesh was applied with 3 mm on each side. Table-1 shows the parameters used for the simulation of the specimen.

Table-1. Simulation parameters.

Baseplate temperature	80°C
Laser power	195W
Scan speed	1000mm/s
Layer thickness	50 μm
Laser beam diameter	100 μm
Initial layer angle	57th
Layer rotation angle	67th
Hatch spacing	0.1mm
Cutting Bandwidth	10mm
Volume	3266.08mm ³
Size (x,y,z)	95.00mm 15.00mm 3.00mm
Triangle count	1,292 _
Voxel size	0.5mm
Voxel Sampling Rate	5
Elastic limit	760MPa
Elastic module	196GPa
Poisson ratio	0.272
Support type	Automatic
Minimum overhang angle	45°
Safety coefficient support factor	1
Support performance strength ratio	0.4375
Maximum distance to the wall	1600 μm
Minimum support height	5mm
Minimum wall thickness	100 μm
Maximum wall thickness	1000 μm

Standard Specimen Simulation

Five simulations were performed, varying both the power and laser diameter. Iterating values were:

- 300W power and 80 μm diameter



- 50W power and 100 μm diameter
- 100W power and 100 μm diameter
- 195 W power and 100 μm diameter
- 500W power and 100 μm diameter

So, the obtained optimal values were laser power of 195 W and laser diameter of 100 μm ; the lowest stress and distortion were also obtained. Table-2 shows the parameters used for porosity simulation.

Table-2. Porosity data simulation parameters.

Geometry height (mm),	3
Geometry length (mm),	3
Geometry width (mm),	3
Initial layer angle (degrees),	57
Layer rotation angle (degrees),	67
Laser power (W),	195
Scan speed (mm/s)	1000
Layer thickness (mm)	0.05
Hatch spacing (mm)	0.1
Cutting strip width (mm)	10
void ratio	0
dust ratio	0.0016
strong relationship	0.9984

The simulation evaluates the different parameters of the piece, obtaining, as a result, the parameter with the

greatest influence, which is the power of the laser, and also other parameters listed below.

- Bed temperature
- The diameter of the laser beam
- Scanning speed
- Layer thickness

Microstructural, porosity, thermal deformation and stress simulations can also be generated to optimize a part before printing it. For porosity simulation with automatic software parameters, it takes approximately 5 hours to generate results; on the other hand, the printing of this specimen can take more than two weeks of continuous work, due to its low layer thickness. Distortion and thermal deformation simulations using the automatic parameters take about 1 hour, but changing these values extends the simulation to 5 hours. Additionally, by changing parameter values such as bed temperature, laser diameter, laser power, scan speed, layer thickness, and slice width, such simulations can take up to 12 days.

Figure-2 shows the displacement stress that the specimen supports when being manufactured, where the highest stress is 110.8 μm , and the lowest is 0 μm and can be seen with the blue color; that is to say, the forces generated are few and are produced in the corners of the piece. In manufacturing the test piece, a displacement is generated between each layer with a value greater than 375.68 μm and a value less than 4.122 μm , as seen in Figure-3.

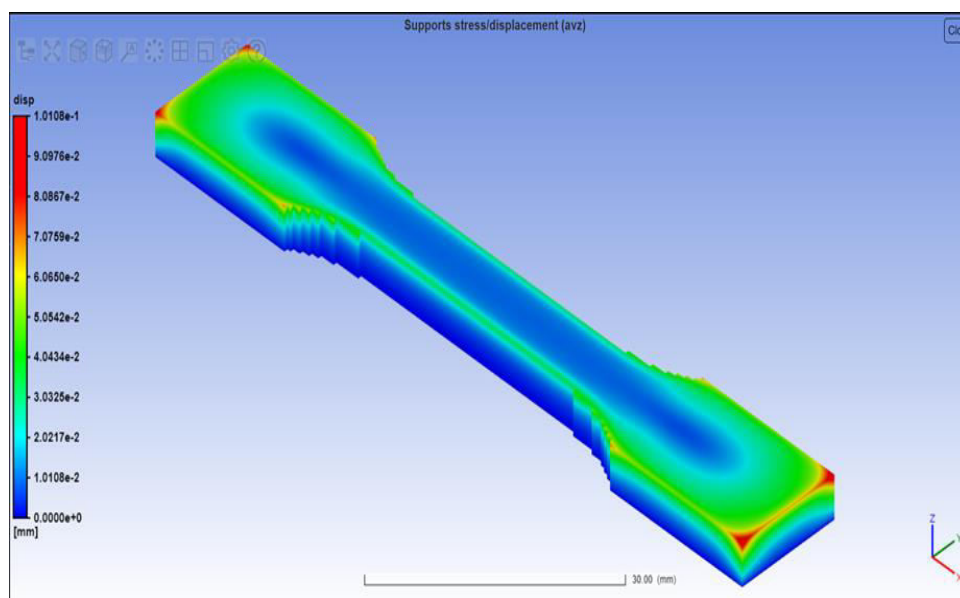


Figure-2. Supports stress/displacement.
Source: self made.

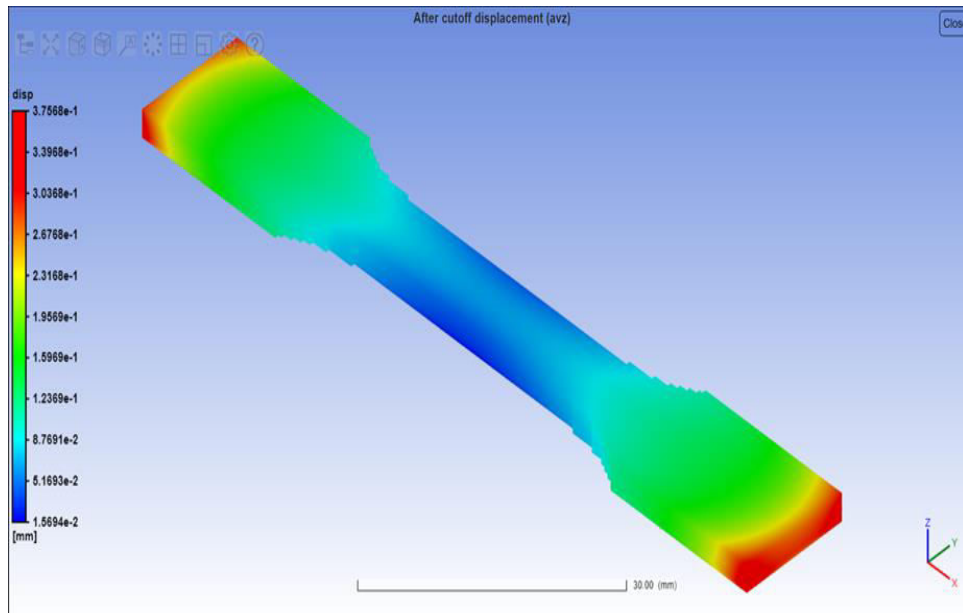


Figure-3. After shear displacement.
 Source: self made.

As seen in Figures 4 and 5, additive manufacturing simulations can be generated for powder bed, where the manufacturing parameters are controlled to have an optimal part before printing. Figures 4 and 5 show distortion geometry before and after cutting, the most significant distortion before is 107.59 μm and after 359.22 μm . Also, this distortion occurs at the specimen edges.

According to the developed simulation, the porosity due to lack of fusion is identified with solids proportion values below 1; the result of the porosity simulation gave a value of 0.9984, which means that the specimen has a very small porosity of 0.16%

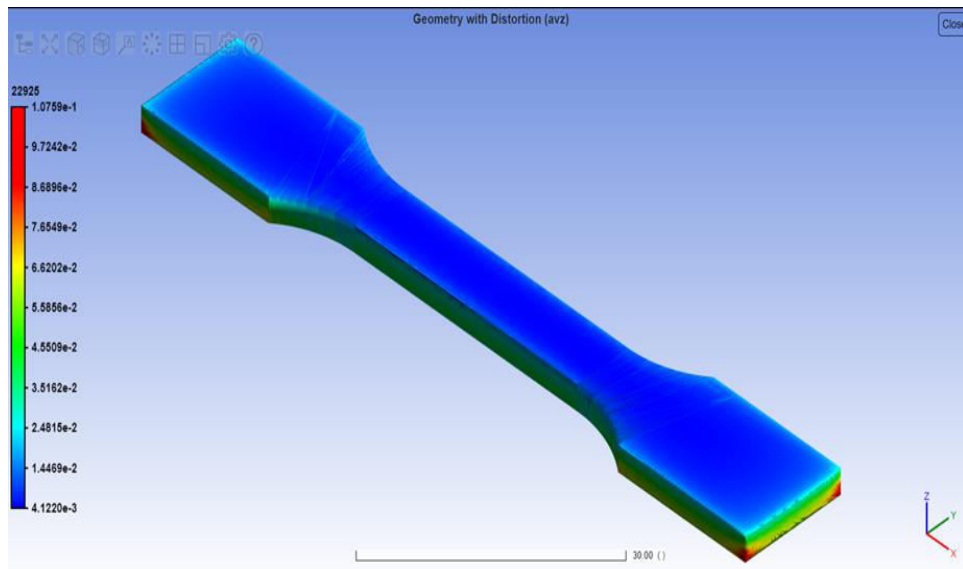


Figure-4. Geometry with distortion.
 Source: self made.

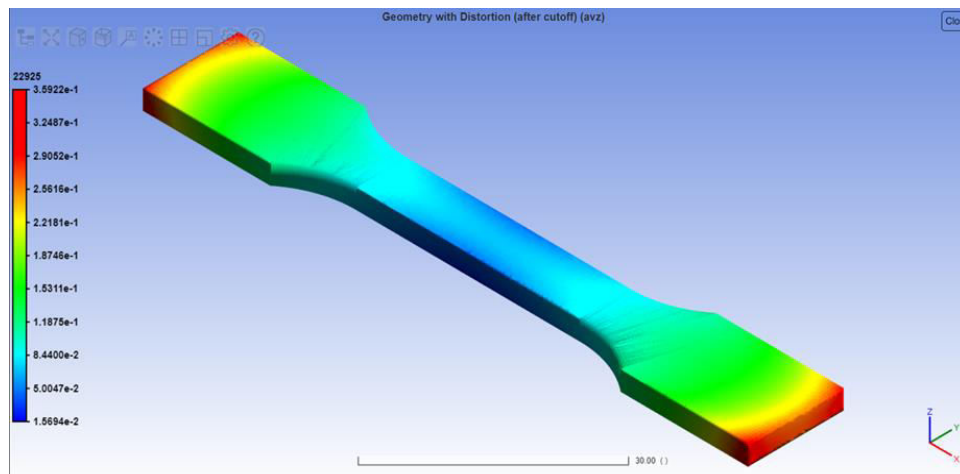


Figure-5. Geometry with distortion (after cutting).
 Source: self made.

4. CONCLUSIONS

This program allows the evaluation of different variables to guarantee the workpiece's optimal and fast printing. Similarly, it helps predict distortion, residual stress, thermal deformation, automatic support generation, and scanning pattern. If any of these values are not those required in the application of the part, they can be analyzed to make design, process, or material decisions before manufacturing the part. In addition, results at the microstructure level, such as material's porosity and machine's parameters, can be predicted.

Simulations can be generated to optimize the part before printing; therefore, a high computational resource is needed for the simulations.

Thermal deformation and distortion simulations find ideal parameter values to reduce stress and distortions on the specimen; therefore, the lower the laser power, the greater the distortion and stress in the component.

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