

# Finite Element Modeling of Additive Manufacturing in Case of Metal Parts

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## Abstract

Metal Additive Manufacturing has grown from 3D metal printing; this technology leads to manufacturing parts using various metallic materials.

Additive Manufacturing technology uses the same principle of slicing a solid model into multiple layers and creating a tool path for each layer, then uploading this data to the printing machine and building the part up layer by layer following the sliced model data using a heat source (laser, electron beam, electric arc, or ultrasonic energy, etc.) and feedstock (metal powder, wire or thin metal sheet, etc.).

The Additive Manufacturing process starts with designing the prototype, continues with printer pre-processing, then with printing the prototype, and finally with post-processing to get the final part, followed by testing. This sequence has to be repeated till achieving the desired prototype. This method costs money and time. In this paper, the Simufact Additive Manufacturing software makes a virtual simulation to save time and money. In this virtual modelling, different types of materials can be used. Different approaches can be tested, such as building orientations with various parameters, changing supporting structures, and cutting and support removal to achieve a usable process, which is free from damaging effects on the first time that goes through the build. This paper deals with three types of metal alloys (TiAl6V4, AlSi10Mg, and 316L). Different types of machines, thermal analysis, mechanical calibration, thermal and thermomechanical calibration, were applied to find the set parameters such as laser power, inherent strains, exposure energy fraction, and volumetric expansion factor.

## Keywords

Additive Manufacturing, inherent strain, 3D printing, Simufact Additive, residual stress

## 1 Introduction

The AM process starts with selecting the part and determining the part requirements. Once this is accomplished, the design process begins with creating the CAD file called STL (Standard Tessellation Language), which is widely used in rapid prototyping and computer-aided manufacturing, and then the CAM toolpath for the AM equipment. At the other end of the process, suitable build material (powder or wire form) is identified, given property requirements for the part. Next, appropriate AM process parameters are selected, and data is uploaded to the machine. Then, the part is built up layer by layer, creating one layer at a time (Dutta and Froes, 2015; Froes and Dutta, 2014). After the process is completed, the part is cleaned, stress relieved or heat-treated according to the part specification. Finally, the platform and support structures are removed, then the part is finish machined as per

drawing specifications, inspected for compliance, and ready for use and Fig. 1 illustrates the AM general process flow (Rani et al., 2017).

Additive Manufacturing (AM), or as it is known 3D printing, is considered an emerging manufacturing technology. AM technology is a technology that realizes the direct transfer of digital data to a physical product. The Additive Manufacturing process chain may look very simple and short: drawing a physical object using Computer-Aided Design (CAD) software. Then, transferring the digital data to a particular 3D printer that directly produces the part (Györi and Ficzer, 2017).

Nowadays, there are a variety of printing technologies available. However, they commonly build 3D objects by adding material layer by layer. The diversity of printing processes depends on materials (solid or liquid plastics,

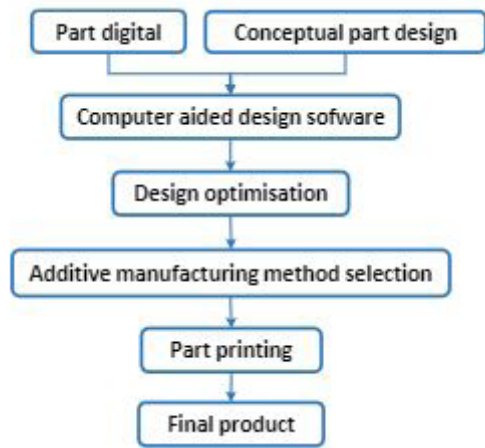


Fig. 1 Additive manufacturing general process flow (Rani et al., 2017:p.465, Fig. 3)

sand, numerous metals) and other techniques for building the layers (e.g., electron beam or lasers for fusing/melting/sintering metal powder) (Alsardia et al., 2021).

### 1.1 Part building technology

There are four processing methods for metal Additive Manufacturing (AM): directed energy deposition (DED), powder bed fusion (PBF), sheet lamination, and binder jetting. Table 1 shows the layer thickness for each process.

### 1.2 Modeling approach in Simufact

The Simufact is a finite element analysis software for simulation of metal Additive Manufacturing focusing on powder bed fusion processes (Simufact Engineering GmbH). The difficulties in metal powder bed fusion Additive Manufacturing (PBF AM) can be addressed and analyzed by simulation.

As shown in Fig. 2, the Additive Manufacturing workflow has been one of the traditional manufacturing processes. The revision for AM goes through those parts to find the best solution according to design parameters, build orientation, support structure, removal cutting, etc.

After that, the software starts to build a simulation of the part, and then the building goes ahead and performs an inspection. If any defects are observed, the component

**Table 1** Layer thickness for metal AM process (Source: made by Alzyod, H. based on the site of Additive Manufacturing Research Group, Loughborough University)

Processing	Layer thickness (mm)
Directed energy deposition (DED)	0.089–0.203
Powder bed fusion (PBF)	0.08–0.15
Sheet lamination	0.1–0.19
Binder jetting	0.089–0.203

goes through a trial-and-error process to achieve the desired part (Simufact Engineering GmbH).

Alternatively, as shown in Fig. 3, a virtual model can be built to reduce the number of required physical builds in the AM simulation workflow. In this virtual model, different approaches can be applied like build orientation, various parameters, changing supporting structures, and keeping treatment cutting and support removal to achieve a usable and free from adverse effects of the process on the first time that goes through the actual build. The significant benefit is that some of these parts may cost thousands of dollars for a single shape, or the trial-and-error approach is quite undesirable.

## 2 Design methodology and simulation

There are many factors on which Additive Manufacturing depends in order to determine the set parameter to get the desired part, like laser power, exposure energy fraction, and volumetric expansion factor. So, experimental tests should be done to get these parameters.

### 2.1 Sample selection

As shown in Fig. 4 for the simulation, an aircraft component was chosen because of the complexity of the geometry and the importance of AM in aerospace, like increased asset uptime, reduced cost, lighter parts, more durability, and improved customer satisfaction.

### 2.2 Material selection

Three types of materials (TiAl6V4, AlSi10Mg, and 316L) were chosen with different properties for building the sample to investigate the effect of each material on the surface (shape) deviation.

### 2.3 Machine selection

Different types of 3D printing machines are available in the software; two kinds of Electro-Optical Systems (EOS) have been used, M280 and M400. Each one has a different size and different power.

### 2.4 Thermal analysis

The laser power has to be adjusted. The printing temperature must be greater than the melting point and less than the boiling point for each material.

### 2.5 Mechanical calibration

The purely mechanical, macro-scale analysis approach of Simufact Additive requires the input of the so-called

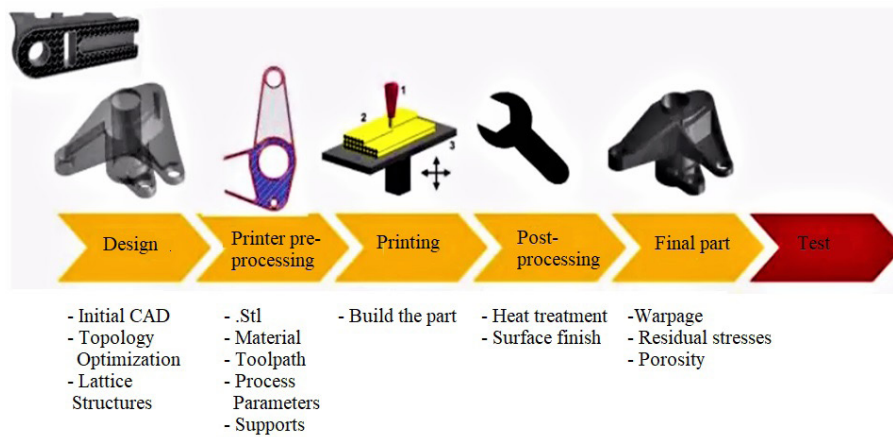


Fig. 2 Additive Manufacturing workflow (Reprinted with permission from © Simufact Engineering GmbH, 2017)

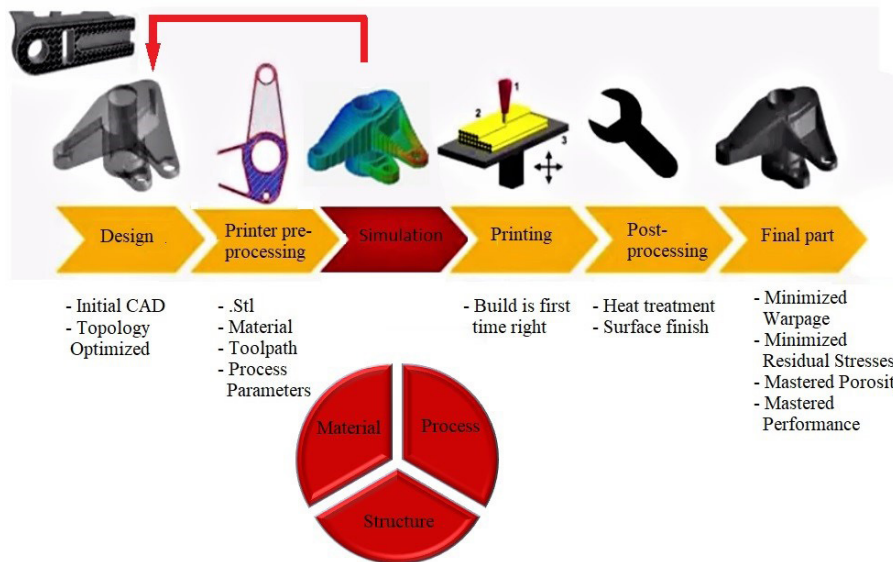


Fig. 3 AM simulation workflow (Reprinted with permission from © Simufact Engineering GmbH, 2017)

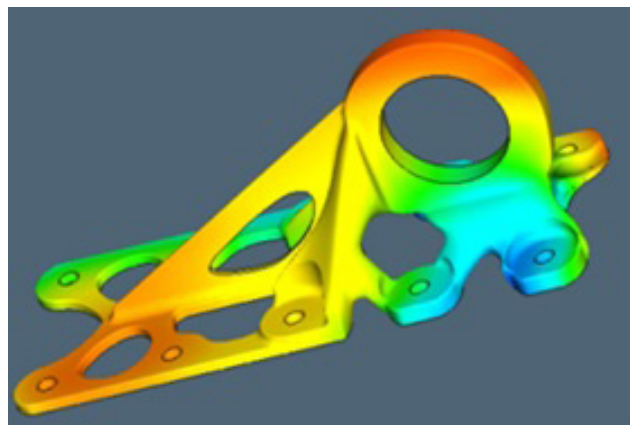


Fig. 4 Aircraft component (Reprinted with permission from © Simufact Engineering GmbH, 2018:p.59)

inherent strain values before the simulation. As shown in Fig. 5, the inherent strains are produced in the building process by plastic strains, thermal strains, and phase transformation (Simufact Engineering GmbH, 2018).

These strains can be calibrated from experiments (e.g., by measuring the distortion after cutting a printed cantilever beam with dimensions of 72 mm length, 12 mm width, and 9 mm height, and running simulations to match

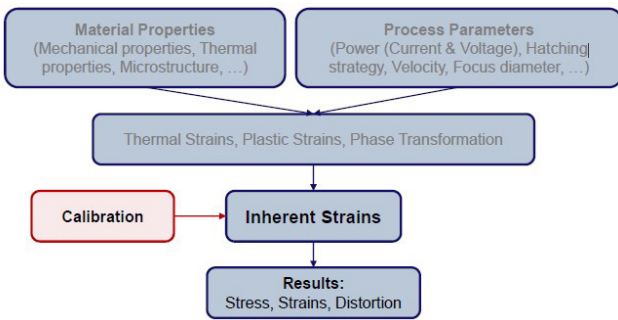


Fig. 5 The inherent strains (Reprinted with permission from © Simufact Engineering GmbH, 2018:p.64)

the experimental distortion values that should be less than 3%) or estimated based on the process. In this paper, the empirical calibration was used by printing two cantilevers on X-axis and Y-axis, as shown in Fig. 6 and by cutting them in the middle of the teeth. So, a particular part of them remains on the base plate. Then the maximum observed Z-distortion was measured, as shown in Fig. 7.

Three values of strains are input in the build stage dialogue ( $\epsilon_{xx}$ ,  $\epsilon_{yy}$ ,  $\epsilon_{zz}$ ). These values are dimensionless and are defined in three directions (X, Y, and Z). Default values will be shown in the dialogue: ( $\epsilon_{xx} = -0.008$ ,  $\epsilon_{yy} = -0.003$ ,  $\epsilon_{zz} = -0.030$ ) (Simufact Engineering GmbH, 2018).

The mechanical calibration was done for the three materials (TiAl6V4, AlSi10Mg, and 316L) to get the inherent strains.

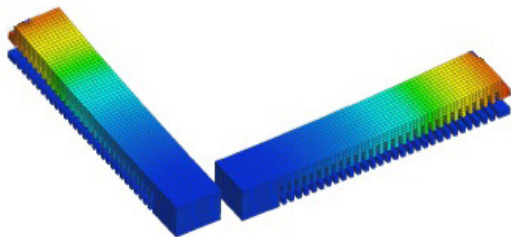


Fig. 6 Printing two cantilevers (Reprinted with permission from © Simufact Engineering GmbH, 2018:p.69)

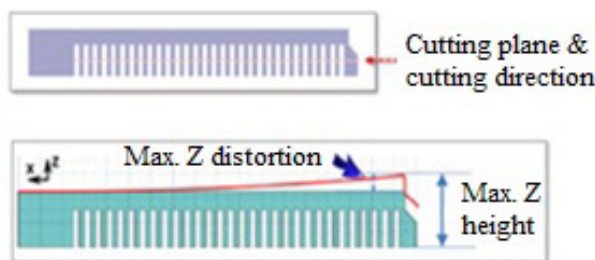


Fig. 7 Measuring the Z-distortion (Reprinted with permission from © Simufact Engineering GmbH, 2018:p.124)

## 2.6 Thermomechanical calibration

The thermo-mechanical analysis requires the exposure energy fraction and volumetric expansion factor values before starting the simulation. These values depend on material properties and machine parameters. Therefore, they need to be carefully calibrated and done experimentally.

## 2.7 Exposure energy fraction

Exposure energy fraction is a term responsible for the process's peak temperature. During the exposure time, the energy mainly (but not only) melts the powder. The rest of the power will (re-heat) the solid material after the exposure time.

For thermomechanical calibration, it is recommended to do the thermal calibration first to get the optimized exposure energy and then get into the thermomechanical calibration with the optimized exposure energy fraction to calibrate the volumetric expansion factor.

The calibration was done using a cantilever specimen. The peak temperature has to be measured during the process, and the maximum Z-distortion after cutting, as shown in Fig. 8. The measured point was chosen on the upper surface because the upper surface has the highest temperature, and the average will be in the middle.

Thermal calibration for the three materials (TiAl6V4, AlSi10Mg, and 316L) was done to get the exposure energy fraction, and Fig. 9 shows the thermal calibration for TiAl6V4.

## 2.8 Volumetric expansion factor

The volumetric expansion is the change in the volume of a given mass with temperature. The volumetric expansion factor accounts for the thermal expansion and shrinkage

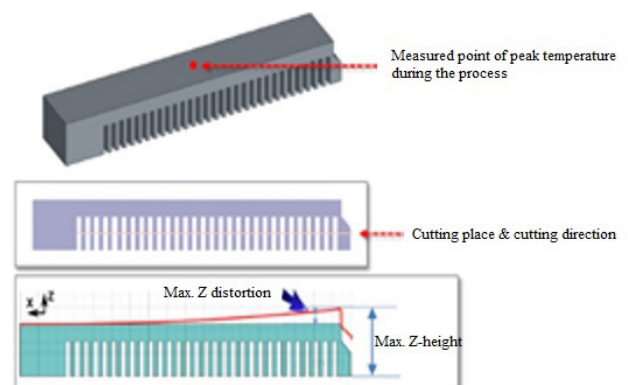


Fig. 8 Measuring the peak temperature (Reprinted with permission from © Simufact Engineering GmbH, 2018:p.73)



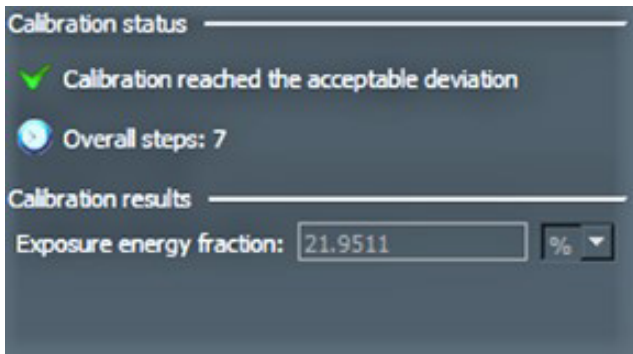


Fig. 9 Thermal calibration for TiAl6V4

effects caused by the modelling approach, combining multiple powder layers and repeated heating of the heat source in one element layer. It can be either set to isotropic for all directions or anisotropic for each order individually and scales the thermal expansion coefficient of the material.

Thermal expansion is the change in volume in three dimensions, as shown in Eq. (1):

$$V = 3\alpha V_o \times \Delta T \quad (1)$$

This equation is usually written as:

$$V = \beta V_o \times \Delta T,$$

where:

- $\beta (= 3\alpha)$  is the coefficient of volume expansion;
- $V_o$  is the original volume;
- $\Delta T$  is the change in the temperature.

### 3 Results

The aircraft component was printed with different machines and materials. Changing the machine did not affect the design of the sample and features, as shown in Table 2. When the printed aircraft component was compared with the simulations regarding the residual stresses using Stoney's equation, the effective stress in MSC Simufact was implemented. The effective stress was the same in both machines, M280 and M400. It was about 1260 MPa, 370 MPa, and 680 MPa for TiAl6V4,

Table 2 Machine and materials effects

Material used	Eos machine	Effective stress [MPa]	Surface deviation [mm]	
			Max	Min
TiAl6V4	M280	1262.03	0.17	-0.16
	M400	1288.13	0.88	-0.93
AlSi10Mg	M280	370.01	0.13	-0.12
	M400	370.02	0.36	0.26
316L	M280	683.19	0.17	-0.16
	M400	680.65	0.16	-0.15

AlSi10Mg, and 316L, respectively. The surface deviation, which indicates the difference between the designed sample and the printed one, had not changed in the three materials when the M280 machine was used. When the M400 machine was used, the surface deviation was different in each material.

One of the most critical parameters to be adjusted is the machine's laser power, responsible for fusing the powder. Therefore, the printing temperature, which is about twice the melting point, has to be more than the melting temperature and less than the boiling temperature. Table 3 shows the changes in laser power and the measured temperature for each one. For TiAl6V4, 200 W is a suitable power. The best power for AlSi10Mg and 316L is 100 W.

As shown in Fig. 9, mechanical calibration was done, illustrating the mechanical calibration for TiAl6V4 to find the inherent strains. Two points in the cantilever were selected with heights of 3.09 mm and 2.01 mm to measure the distortion in the beam. The simulation will printed the specimen many times until the acceptable distortion error was less than 3%. Fig. 10 shows that the sample was printed seven times to get an acceptable distortion.

The same procedures were done for AlSi10Mg and 316L to find the inherent strains, and Table 4 shows the inherent strains for the three materials.

Table 3 Adjusting the power of the laser

Material used	Melting point (°C)	Laser power (W)	Printing temperature (°C)
TiAl6V4	1600	200	2650
		200	4220
AlSi10Mg	660	150	3098
		100	2084
316L	1400	200	4454
		150	3500
		100	2463

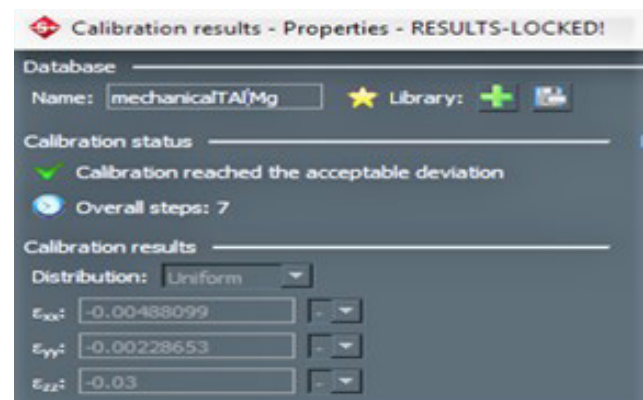


Fig. 10 Mechanical calibration for TiAl6V4

**Table 4** Inherent strains for TiAl6V4, AlSi10Mg, and 316L

Metal	$\epsilon_{xx}$	$\epsilon_{yy}$	$\epsilon_{zz}$	Number of Printing times
TiAl6V4	-0.00488099	-0.0022865	-0.3	7
AlSi10Mg	-0.00637062	-0.0016680	-0.3	18
316L	-0.0198353	-0.0025170	-0.3	3

The volumetric expansion factor is a crucial parameter in 3D printing. So, the simulation made the thermo-mechanical calibration to find the volumetric expansion factor. Fig. 11 illustrates the thermomechanical calibration for TiAl6V4.

The same principle was used to find the volumetric expansion factor for AlSi10Mg and 316L, as shown in Table 5.

#### 4 Conclusion

Additive Manufacturing (AM) technology was used to print an aircraft specimen with different materials by Simufact simulation to get the set parameter and virtual printing. The results showed that the laser power significantly impacts the printing temperature, as shown in Table 3, and it should be adjusted precisely.

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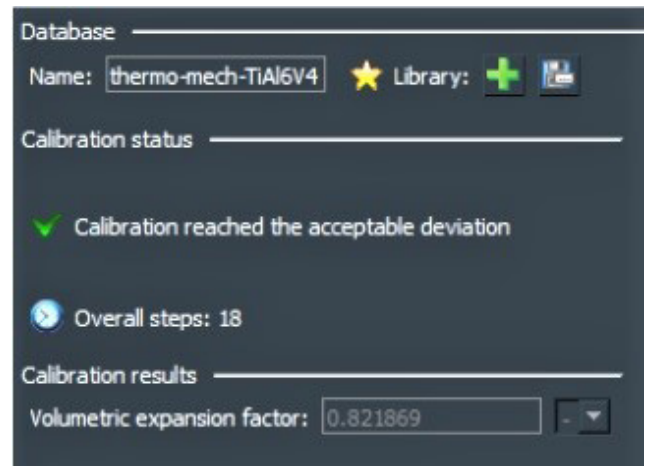
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**Fig. 11** Thermomechanical calibration for TiAl6V4

**Table 5** Volumetric expansion factor for TiAl6V4, AlSi10Mg, and 316L

Metal	Volumetric expansion factor	Number of steps
TiAl6V4	0.821869	18
AlSi10Mg	0.60999	2
316L	0.307238	24

Furthermore, calculating the inherent strains and volumetric expansion factor requires many printing times, as shown in Tables 4 and 5.

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