

# MACHINE SIMULATION OF ADDITIVE MANUFACTURING TOOL PATH

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**Abstract:** Additive technology (AT) has emerged as a key enabling technology, with its ability to shorten product design and development time. The paper presents the programming and program verification using machine simulation of additive manufacturing tool path in CAD/CAM and Vericut environment. A procedure for configuring and preparing of a virtual machine for several additive process simulations has been proposed. The paper analyses the available programming software for generating G code from the STL file as well as the possibility of simulating the virtual machine when working according to the generated program.

**Keywords:** additive manufacturing, machine simulation, CAD/CAM

## INTRODUCTION

Industry 4.0 has an initiative that aims to digitalize industrial manufacturing via the exploitation of innovative technologies [1]. In this regard, this paper will present the possibilities of applying the machine simulation of additive manufacturing processes in the era of Industry 4.0. The machine simulation of the additive manufacturing tool path aims to configure the digital twin of the machine for additive processes and simulate its work. Whatever happens on screen during simulation, will also occur identically on the real machine for additive processes.

Additive technology (AT) has emerged as a key enabling technology, with its ability to shorten product design and development time. AT is used for quick fabrication of physical models, functional prototypes and small series of parts directly from CAD models [2,3]. Rapid prototyping is used in a variety of industries to fast fabrication of parts, and representation before final realization or commercialization [4]. The main advantage of rapid prototyping technologies is that almost any shape can be produced.

The application of new additive technologies is based on models STL models of prototypes that will be build. This paper discusses two additive technologies: Fused Deposition Modeling – FDM and Laser Metal Directed Energy Deposition – Laser DED in terms of program preparation and its verification by simulation of material addition, i.e. machine simulation for these procedures. Simulation is a key technology for program verification. Machine simulation and digital twin are the primary simulation-based approaches in the context of the Industry 4.0.

## OUTLINE OF CONSIDERED ADDITIVE MANUFACTURING PROCESSES

Within this paper, the machine simulation of additive manufacturing machines based on the FDM (Fused Deposition Modelling) and Laser DED (Direct Energy Deposition) methods will be considered.

### — Fused Deposition Modeling – FDM

Fused deposition modeling (FDM) is one of the most widely used additive fabrication technologies. FDM is the same as fused filament fabrication (FFF), but the term “Fused deposition modeling” and the abbreviated “FDM” were trademarked by Stratasys in 1991, creating the need for a second name [5].

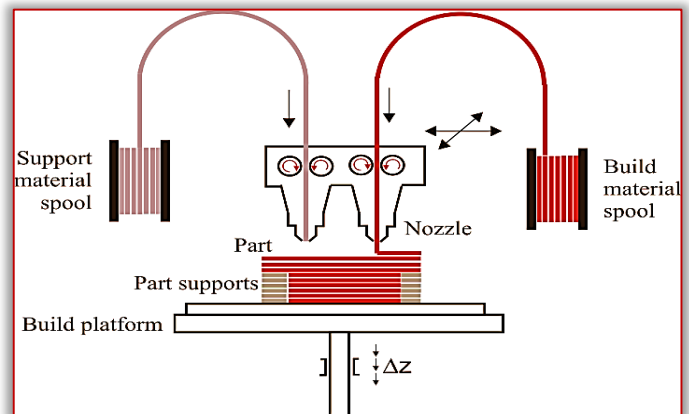


Figure 1. Schematic of FDM system

A plastic filament is unwound from a coil and supplied as a material to an extrusion nozzle, which moves along the programmed path of material addition. The possible movements of the nozzle are defined by the machine’s own kinematic configuration. The nozzle is heated to melt the plastic, has closed-loop temperature control and is coupled with a mechanism which allows the deposition of the melted plastic to be turned on and off. As the nozzle is moved over the table in the active layer, following the

programmed path, it deposits extruded plastic, thus forming each layer. FDM approach demands fully controlled extrusion of material through a nozzle. Two extrusion heads are often used so that support structures can be fabricated from a different material to facilitate part clean-up and removal, Figure 1.

FDM 3D additive machine is a type of a CNC machine that has 3 axes of movement and usually implements Cartesian (serial) or DELTA (parallel) mechanisms, although machines with hybrid kinematics are also possible. This paper considers Velleman Vertex K8400 additive manufacturing machine – 3D printer with 3-axis Cartesian serial kinematics.

#### — Laser Metal Directed Energy Deposition (DED)

Directed energy deposition (DED) is a group of AM processes that adds material alongside the heat input simultaneously. The heat input can either be a laser, electron beam, or plasma arc, while the material feedstock is either metal powder or wire [6]. This paper discusses laser and powder DED processes. A schematic of the laser powder DED process is shown in Figure 2.

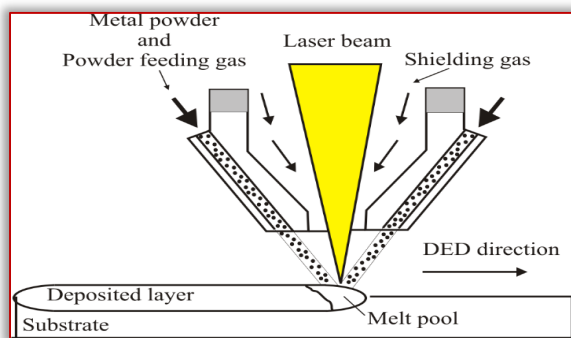


Figure 2. Schematic of a Laser powder DED process

Powder DED machines often have powder-feeding gas blown together with the powder from the nozzles, thereby sheathing the melted region, and reducing the oxidization rate. Powder DED systems can use single or multiple nozzles to eject the metal powders [6].

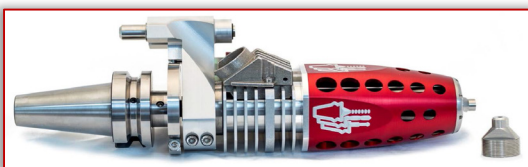
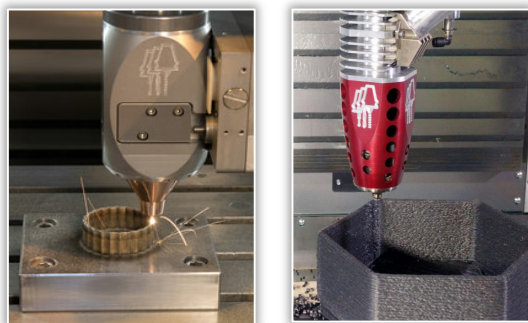


Figure 3. Laser DED extruder in a testing setup in a Haas VF series CNC machine [8]

Phillips has taken the innovative laser metal deposition technology of Meltio, and integrated it with the Haas CNC vertical machining centres, bringing the best value of additive hybrid machines to the market [7]. Supported Haas Machine Models are Haas VF Series, Haas UMC Series and Haas TM series. These machines can combine benefits from both additive and subtractive technologies. In this regard, the real challenge is the simulation of their work, which can be realized in the Vericut environment.

This opens the access to hybrid manufacturing processes that include additive and subtractive operations. Additive processes allow increased design flexibility, customization and part complexity, while subtractive processes enable higher production speeds, improved accuracy and surface finish [8]. Figure 3 shows a metal powder directed energy deposition (DED) process which can be combined with a multi-axis CNC milling process.

#### CONFIGURING VIRTUAL MACHINES FOR ADDITIVE MANUFACTURING

The simulation of additive manufacturing machines and processes, in the era of Industry 4.0, is one of the most important verification steps prior to the actual production. This section will show procedures and examples of configuring virtual machines for additive manufacturing using available software environments (PTC Creo and Vericut).

#### — PTC Creo

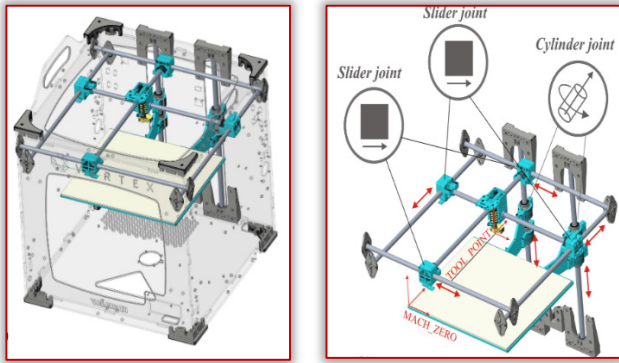
Most CAD/CAM systems are used for the simulation of the subtractive technologies, simulating virtual machine tool along a given tool path, while offering no similar alternatives for additive manufacturing.

In contrast, CAD /CAM system PTC Creo has a module for Additive Manufacturing, but it must be used in an indirect way, by configuring the machine for additive manufacturing as an equivalent milling machine with the same kinematics [9].

This paper presents the configuration of an additive manufacturing machine Velleman Vertex K8400 [10,11]. The configured virtual machine offers a virtual prototype with graphic structural elements that move as a rigid body system, aiming to be used in the simulation of the tool path [12]. All kinematic connections between structural elements of the virtual prototype must be defined in accordance with the real machine. The required kinematic connections for the considered 3-axis Velleman Vertex K8400 are three translations with slider and/or cylinder connection type, Figure 4.

During configuring of the complete virtual model of the machine, based on the available machine components [11], it is necessary to define the kinematic connections for all the moving parts. Next, need connect the coordinate systems of the workpiece, the tool with coordinate systems on virtual machine within the used PTC Creo 8.0. On virtual machine tool need to define the coordinate

system MACH\_ZERO, on the machine table and TOOL\_POINT on top of the nozzle (Figure 4b). Also, workpiece and tool have the same coordinate systems. By matching the appropriate coordinate systems of tool and workpiece with coordinate systems on virtual machine is prepare a set-up for simulation [12,16]. The virtual machine prepared in this way is ready for the needs of simulation according to the programmed tool path within the layer, which will be specified in section 5.



a) b)  
Figure 4. Virtual machine Velleman Vertex K8400 with defined kinematic connections and coordinate systems

#### — Vericut

Vericut provides CNC machine simulation according to a given program, program verification and process visualization. Vericut now offers the Additive module that provides CNC machine simulation for directed energy deposition (DED), laser sintering, 3D printer and powder bed layups from their build files, wire-fed additives, thermo-plastic composite additives, welding, and other layup processes that add material [13].

A very important advantage of the simulation is collision detection between the expensive machine elements and the additive part being built [13].

Vericut uses G-code as one of its basic inputs, so to simulate an additive technology operation, one of the existing machines from the Vericut library that supports additive technologies can be selected, or a new machine can be configured.

To configure a new virtual machine in the Vericut environment, it is necessary to define the machine's kinematics – type and order of joints/axes according to the structural formula. For example, the Haas VF3 machine has a kinematic structure (X'Y'OZ), Figure 5.

The basic structure of the machine tool in Vericut consists of a BASE, TOOL, and STOCK. The configuration of the virtual machine starts from the base (O), as a fixed component. The vertical translational axis Z (Z Linear) was first added to the base, on the tool side. The horizontal translational axis Y '(Y Linear) was first added to the base in order, and then the horizontal translational axis X' (X Linear) was added to it, on the workpiece side.

On the spindle that moves along the Z-axis, there is the main spindle (Spindle) and a tool (Tool), which completes

the kinematic structure of the machine. The hierarchical tree structure of the Haas VF3 machine is shown in Figure 5. The machine has the name *haas\_vf3\_tc20* with control *haascnc*. This machine supports additive technologies and will be used as an example for simulation of additive technology in section 5.2.

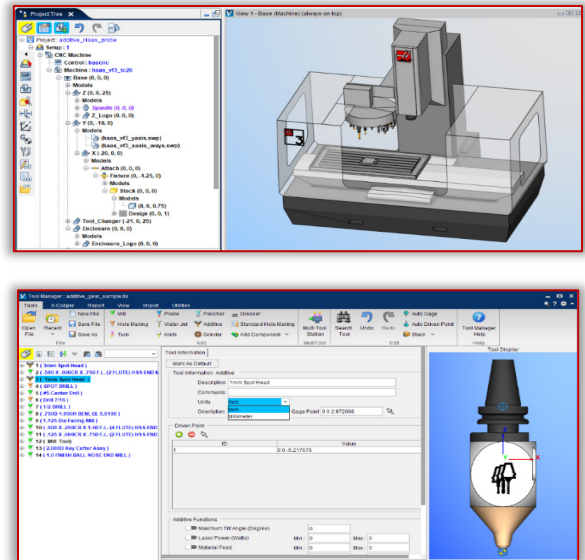


Figure 5. Selected virtual machine Haas vF3 and Laser DED extruder

### PROGRAMMING OF MACHINES FOR ADDITIVE MANUFACTURING

Programming of machines for additive manufacturing can be realized using various specialized software, such as Slic3r, Replicator G, Catalyst EX, Repetier-Host, and others. These programs represent an interface for communication with additive manufacturing machines. The input into these programs is a 3D model file, upon which we prepare additive layers and the required paths for material addition. Such programs usually allow [10]: (i) 3D model display; (ii) model scaling to the desired size; (iii) model orientation in the workspace; (iv) automatic or manual basing of the model when several parts are produced at once; (v) slicing and forming of additive layers; (vi) layer addition simulation and display of each layer; (vii) G-code generation for the specified machine.

In this paper, the Slic3r software was tested as a programming software of the considered machines for additive processes. Slic3r translates digital 3D models into instructions that are understood by a 3D printer (G-code). It slices the model into horizontal layers and generates suitable paths to fill them. Slic3r accepts the following 3D model files types: STL (Stereo Lithography), OBJ, Additive Manufacturing File Format (AMF), while 3MF is an XML-based file format, similar to AMF [14].

A typical procedure for additive manufacturing includes the following stages: (1) obtain the model in STL format, (2) load model into software, (3) set the parameters for 3D additive manufacturing (print, filament, printer), (4)

export to G-code (5) simulate 3D additive manufacturing, (6) build prototype on the machine.

The first example for programming additive processes was tested on the example of the Champions League Cup model in pendant form, given in STL format, Figure 6.

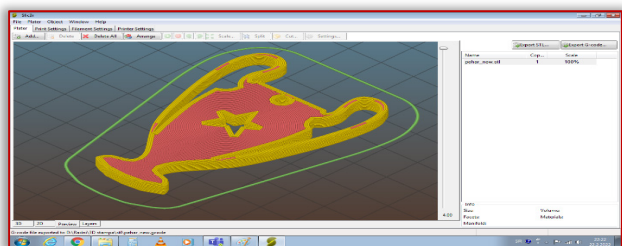


Figure 6. The example of the Champions League Cup in pendant form in slic3r environment

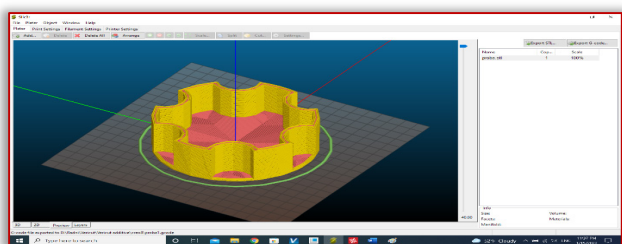


Figure 7. The second example of CNC machine simulation for laser directed energy deposition

For this example, machine simulation was prepared in CAD/CAM system PTC Creo (section 5.1), and finally this part was made on Velleman Vertex K8400 machine for additive manufacturing using FDM. Model for the first example is prepared in PTC Creo 8.0 and exported in the STL format that was loaded into Slic3r, where G-code is obtained for additive manufacturing. Prior to generating the G-code – print, filament and printer settings are adjusted. After generating the G-code, options are available for simulating the addition of material with the possibility of displaying toolpath for each individual layer. The second example of programming additive processes, utilizing laser directed energy deposition (DED), is prepared for CNC machine simulation, Figure 7. Here also, the model is produced in PTC Creo, exported in STL and loaded into Slic3r, where the G-code is obtained for additive manufacturing. This example was checked in Vericut environment.

**MACHINE SIMULATION AND TOOL PATH VERIFICATION**

This section presents a machine simulation of additive manufacturing for two considered methods: FDM and DED in two different environments (PTC Creo and Vericut).

**— Machine Simulation of Additive Manufacturing in Creo**

An example of programming additive processes for FDM was tested on the example of the Champions League Cup in pendant form and printed on Velleman Vertex K8400. CAD/CAM system PTC Creo can simulate additive manufacturing in an indirect way. The configuration of the considered additive machine Velleman Vertex K8400 is

shown in section 3.1. The configured machine can move along the tool path for each individual layer. The simulation of the last layer was chosen for the illustration. To obtain the toolpath (nozzle path) in additive processes, it is necessary to convert the nozzle path into G code, using appropriate software, Slic3r in this case, Figure 8. Obtained G-code can be converted into DXF file using CIMCO software. After that, the DXF is loaded into PTC Creo, where it is saved as a part, including nozzle path as a curve. This part is used in the CAM Manufacturing module (CAM-MFG), where the nozzle path serves to generate tool paths for simulation. During the simulation, the CAD model of the complete virtual machine can be loaded in PTC Creo environment, as shown in Figure 8, and Figure 9.

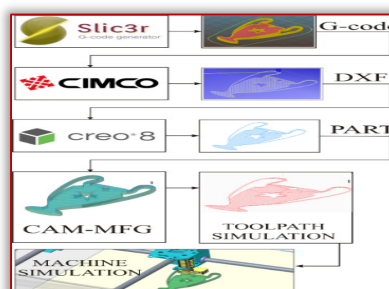


Figure 8. Procedure for indirect machine simulation of additive tool path on each layer

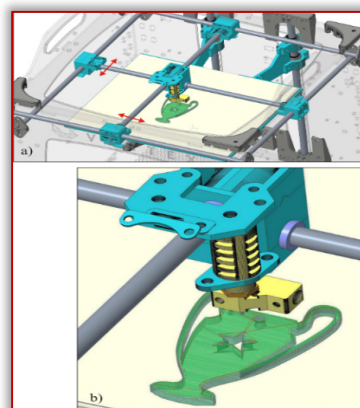


Figure 9. Machine simulation according to the given tool path within the last layer in PTC Creo environment

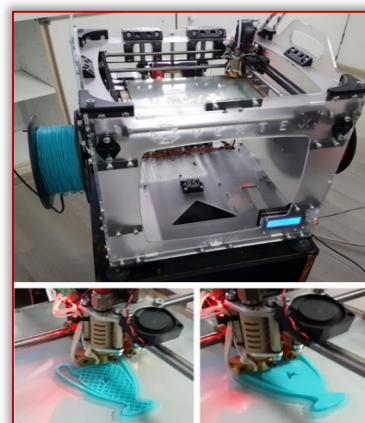


Figure 10. Velleman Vertex K84000 during the printing of model champion league cup in pendant form in STL format

An illustration of the work done on Velleman Vertex K8400 during 3D printing of the first example is shown in Figure 10.

— **Machine Simulation of Additive Manufacturing in Vericut**  
Simulation of the virtual machine tool in the VERICUT environment, according to the given program, allows the simulation of the operation of the machine based on G-code [15]. Virtual machines can be loaded from the available library or configured from scratch by the user, as explained in Section 3.2. The following is a procedure for additive technology simulation based on G-code with an example of adding material by directed energy deposition (DED). The project hierarchical tree of Vericut has already been discussed in the description of the virtual machine configuration, and now the other parts it contains are presented, referring to the basic tools needed to prepare a simulation project according to the given program, Figure 11, with specifics that are characteristic for additive technology.

At the beginning, it is necessary to choose the control system and the virtual machine to perform the simulation. For example, in this paper, the chosen machine is haas\_vf3\_tc20 with its control haascnc.

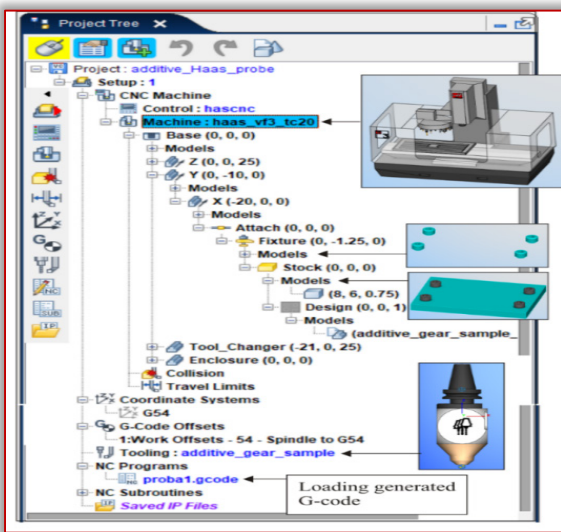


Figure 11. VERICUT project hierarchical tree, an example of for additive technology  
To continue with the definition of the simulation project, in this case, for additive technology, it is necessary to define: (i) stock as the platform on which the model will be based, and which is here connected to the worktable by means of a fixture; (ii) coordinate system (Program Zero Point), here G54, (iii) zero-point position adjustment on the virtual machine (G-code Offsets), (iv) tools which are used for additive technology (Laser DED extruder) and (v) G-code for additive technology.  
In order to connect the virtual machine to the zero point of the program, it is necessary to select the appropriate offset of the G-code. Work offset was chosen from Spindle to CSYS Origin-G54.

G-code is prepared in software for additive manufacturing (Slic3r), and loaded in Vericut environment for simulation. When all the previously mentioned stages for the preparation of the simulation project are completed, the G-code is loaded and the additive technology is simulated, Figure 12.

The simulation display of the virtual machine operation can be organized in several views, namely: Stock (workpiece)-view, where we can see the material being added layer by layer; Machine Base (Machine) – view, where the simulation of adding material can be followed on the virtual machine.

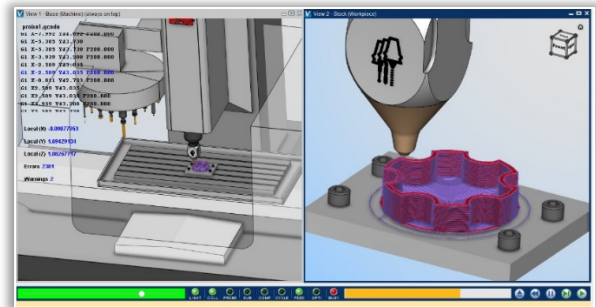


Figure 12. Machine simulation of Haas vF3 virtual vertical machining center operation on example of additive technology

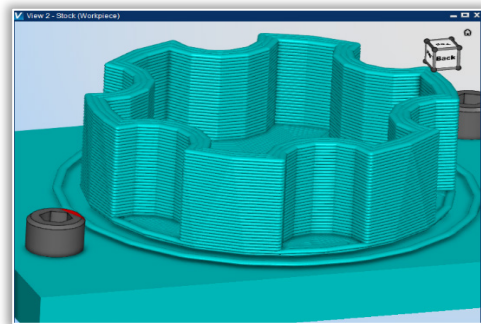


Figure 13. Finished simulation example of additive technology

During simulation, its speed can be controlled using the slider on the bottom-left of the screen. Also, the display of the G-code can be included, that also marks the line being executed. The final result of the simulation and the look of the obtained part is shown in Figure 13.

## CONCLUSIONS

This paper provides an overview of programming and program verification using machine simulation in two environments for additive technology. Two methods for rapid prototyping by adding material were considered: fused deposition modelling and laser direct energy deposition.

In the age of Industry 4.0, an important research direction is digitization and virtualization of processes, enabling better verification and process monitoring.

Currently, there is ongoing research in the field of adding metallic materials in combination with milling, the so-called hybrid manufacturing, uniting additive and subtractive technology.

The importance of machine simulation for additive processes refers to the detection of possible collisions of various extruders with machine parts or the part to be made, thus gaining a higher degree of safety for people and equipment.

Our further research relates to the configuration of new virtual machines that combine additive and subtractive technologies – virtual hybrid manufacturing.

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