THE SEQUENCE OF PHASES IN THE PROCESS OF TRANSFORMING A USUAL CNC INTO A HYBRID CNC MACHINE FOR 3D ADDITIVE MANUFACTURING

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Abstract: *This research paper contains the steps which are necessary to transform a CNC milling machine into a hybrid CNC 3D printer machine.*
For this research were used a 5-axis CNC milling machine, TMA-AL-550, which belongs to the University of Oradea, equipped with a FANUC 310i-A5 series numerical control, and to make it possible to connect a printer head, was made some changes in the PLC (Programmable Logic Controller) of CNC machine. Also, mechanically and electrically were designed a printer head, which later was connected to the CNC machine, after a few subsequent modifications proved to be functional. Obviously, for the NC program, we used parameterized programming, with logical conditions, and Matlab.
Keywords: *CNC milling machine, hybrid CNC, 3D printer CNC machine, Fanuc, printer head, MATLAB, G code.*

1. INTRODUCTION

Today, a new industrial revolution [1] makes its mark in the field of parts construction, namely, 3D printing [2], the method that uses different types of printing technologies [3], and as materials using printing are printed materials such as polymers, metals, metals-ceramics polymers, polymers photocurable resins, hybrids, paper, metals ceramics [4–6], each material having its printing technology (Fig. 1.).

Also to streamline the production process [7], hybrid machines are being built, and companies like DMG Mori, Hurco [8,9], and others companies that build machines and robots build such hybrid machines that provide the ability to print and then milling the part which was printing from metals (Fig. 2.), and plastic material (Fig. 3.) [10].

Fig. 2. Lasertec 65 DED hybrid [8]**.**
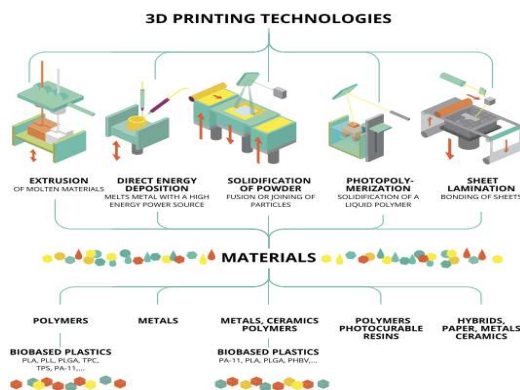
The part presented in figure 2 was obtained by Laser Metal Deposition (LMD) deposition and the tools used are: a laser melting head, a tank from which the metal/non-metal powder is

Fig. 1. 3D printing technology process [4].

evacuated, and the finishing of the obtained parts is used milling tools like spherical cutters, profiled, drills.

The examples in figure 2 and figure 3 represent additive processing equipment that makes it possible to obtain parts of very high precision shape and complexity, only in terms of roughness and dimensional accuracy, parts obtained by laser fusion, loaded by laser welding, FDM (Fused Deposition Modeling) printing does not correspond thus requiring further finishing operations by cutting, [11].
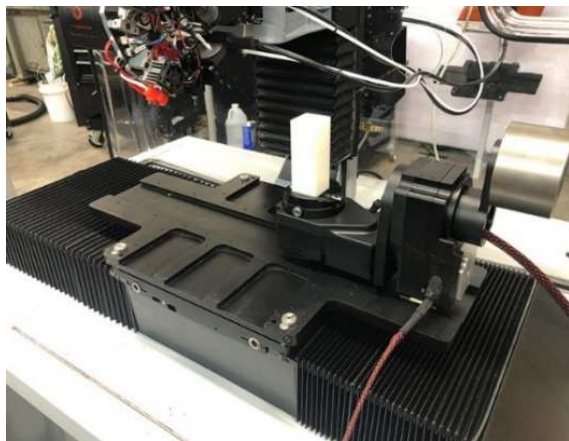

Fig. 3. 3D printer machine Herdon [11].

Hybrid machines also combine the advantages of additive manufacturing with those of removal processes (chipping manufacturing) [12] and the surface quality of the cut surfaces has a very good roughness [13].

2. CONNECT THE PRINTHEAD TO THE CNC

2.1 Physical connection between equipment components

Starting from the idea presented above, namely CNC hybrid machines, it was designed using CAD software [14], electric [15], and printhead and the assembly of the electrical components together with the mechanical ones, led to the realization of a functional printhead, extrusion head for plastic materials (figure 4), head that is connected to a horizontal CNC milling cutter, in 5 axes TMA-AL-550 (figure 5) [16].

The equipment shown in figure 4 and 5 show the two versions (2nd and 3rd respectively) that

have been tested to optimize printing with this mixing machine, which at the University of Oradea is located and equipped with a numerical control from the FANUC 310i-A5 series, FANUC drives and motors, also having 5 continuous axes X, Y, Z, B, C.

Fig. 4. Print head - V2[16].

The equipment shown in figure 4 and 5 show the two versions (2nd and 3rd respectively) that have been tested to optimize printing with this mixing machine, which at the University of Oradea is located and equipped with a numerical control from the FANUC 310i-A5 series, FANUC drives and motors, also having 5 continuous axes X, Y, Z, B, C. The machine is equipped with an internal storage unit having a capacity of 34 tools and a tool change system consisting of a mechanical catch device.

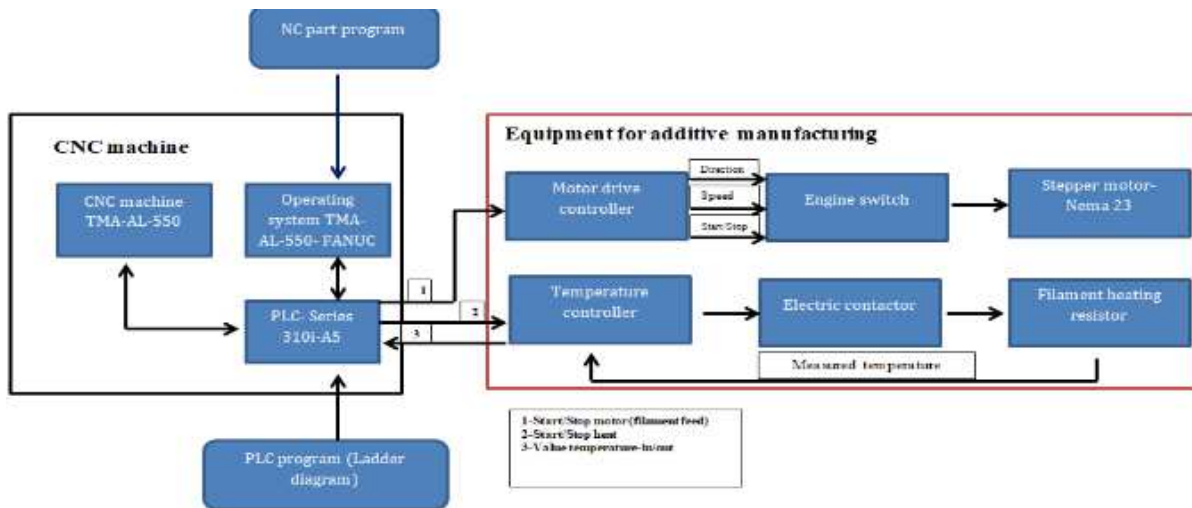**Fig. 5.** CNC TMA-AL-550 3D-view -V3[16].

Fig. 6. The steps of printing.

At the basis of this concept of control of the extrusion head, according to the sketch in figure 6, in addition to the mechanical and electrical assembly of the print head, this head was connected to the CNC, the control printing parameters being controlled based on the M codes for the head, and the movements necessary for printing using the G codes.

The listed codes in table 1 are M codes that allow the control of the print head on and off, codes that have been defined in the machine PLC. After dialling the code M27, the machine will provide an informative message "waiting for filament heating" (wait for the hot-end to heat up), and after the disappearance of that code, the CNC will perform the following steps, depending on the program.
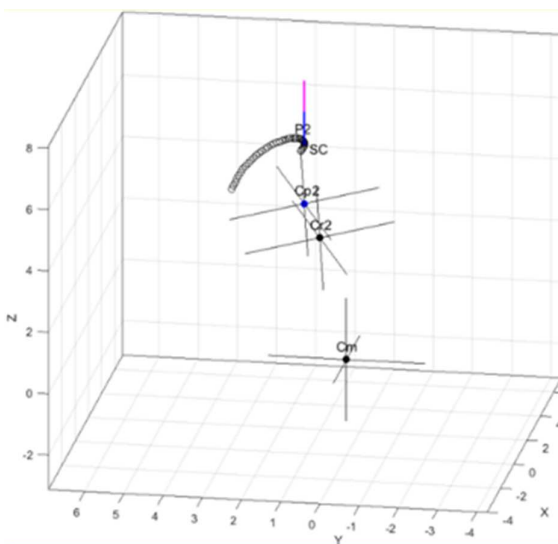
Fig. 7. Graphical simulation-Matlab.

Table 1.
M-Code list for the control of the head.

Nr. Crt.	Code command	Control load
1.	M23-M24	Start-stop Nema 23 stepper (filament)
2.	M27-M28	Start+Stop Controller (heating)
3.	M30	Stop program-Stop the printing process

2.2 Connection with MATLAB interface. Simulation of the obtained part, MATLAB program using

For the control of a CNC machine, G codes are used, codes that are written in the form of phrases in a program [17], followed by a digit or group of digits. In general, it is a code that tells the machine tool what type of action it needs to perform, such as fast movement (it takes the tool as fast as possible through space to the place where the cutting/cutting will take place) [18]. Also used for CNC programming are the codes M (M00, M01, M02, M30, M96, M97, M98, M99: program control codes, M03, M04, M05, M19: shaft rotation codes, M06: tool change code , M07, M08, M09: cooling use codes, from M11 to M18: shaft speed change codes). As well as codes such as S-speed, and F-feed.

The simulation shown in figure 7 and figure 8 was performed based on direct and inverse

kinematic analyses, on the one hand, to validate the obtained relationships and on the other hand to generate the part program sequence that achieves the desired trajectory.

Fig. 8. Physical simulation on CNC machine.

3. PRINT HEAD CONTROL BASED ON M AND G CODES

3.1 Using M and G codes in the parameterized part program

Although the codes of the programs from the 3D printers are similar and some even identical to those from the CNC, the NC programs from a 3D printer cannot be used on a CNC, only if they are modified manually so that no problems occur during their running. on CNC.

To control this extruder head via CNC based on G and M codes, several methods can be used, namely:

➢ Modifying a program provided by a printer programming software so that it is accepted by the CNC PLC.

This method, at first sight, seems simple and fast, only the program must be modified by a person with very good knowledge in the field of CNC programming, and on the other hand, it is very dangerous since a program offered by Cura has many phrases and if any phrase or code is omitted, which the CNC interprets as „OK" it can lead to the destruction of the extrusion head or injury to the operator.

➢ Programming the equipment „manual", i.e. gathering information using AutoCAD or other software or even manual calculation and then preparing such a program for deposition.

Such a program has few lines compared to a program obtained with the help of software, and CNC equipment allows various operations such as (scaling-G51), so the time to prepare such a program is much shorter and the occurrence of programming errors as presented in the first method being almost non-existent.

➢ Creating a postprocessor for additive deposition on CNC machines, which is the safest option. Postprocessors for mixed CNCs are not currently available for free.

Based on the second method, below (Fig. 9.) is described as a parameterized program that I wrote and successfully tested on CNC-TMA-AL-550.

```
%
O5110;-the name of the program NC
T02 M06;- Call tool nr 2
N01 G04 P50000 G21-Insert manualy the print-head,
time=50 second
N5 M27;- start heating hot-end
N10 G0 G54 G90 G80 G18;-select the working plane XZ
N25 G54 G0 X0 Z0;- go in X0 Z0 with fast feed
G54 Y0;- go in Y0
N30 G43 X10 H0; -taking tool length and go at X10
N40 #1=0.5; -first step on the Y axis
N50 #2=15;- total height of part =15mm
N60 #3=0.8; - increment print on the Y axis =1mm
N70 G01 Y#1 F800 M23; - positioning on the Y axis at
0.3mm, starting the filament (stepper Nema)
N80 G1 G40 X0 Z0; -feed work on X and Z=800mm/min
N90 G1 X40; - feed work on X40 =800mm/min
N100 G1 Z40; - feed work on Z40 =800mm/min
N110 G01 X0; - feed work on X 0=800mm/min
N120 G1 Z0; - feed work on Z0=800mm/min
N130 #1=#1+#3; -increment calculation on Y
N140 IF [#1LE#2] GOTO 70; -condition of incrementing
N150 G0 Y100; -retract on Y100
N160 M24; -Stop stepper Nema-filament
M28;  -stop heating
M30; -STOP PROGRAM
```
Fig. 9. Explanation of the square shape printing program 40x40x15.

3.2 Using M and G codes in the part program obtained in MATLAB. 4-axis printing with parameterized part program

The presented simulation programs were made based on direct and inverse kinematic analyses for both chip machining and additive manufacturing. The role of these programs is twofold: 1 - to validate the relationships obtained and 2 - to generate the part program sequence that achieves the desired trajectory.

After obtaining the part programs using Matlab calculation tools, they were verified using the TMA-AL-550 numerical control machine (Fig. 10.).

```
%
O2021(Helix)
T02M6
G0G54G90G80G17
G54X0Y0Z0B0C0
G01X0.5000Y2.5000Z1.0000B-0.0000C-
300.F1000
X4.7635Y2.1224Z1.0865B2.2469C-317.2741
X4.7638Y2.1228Z1.0869B2.2474C-317.2745
.
.
X5.5286Y-0.5920Z4.6713B87.7478C-402.7493
X5.5000Y-0.6213Z4.7071B90.0000C-405.000
G0X0Y0Z0B0C0
M30
%
```

Fig. 10. Part programme-Matlab.

```
%
O1319 (4-C AXIS PROPELLER PRINTING)
N5 T2 M06 (PRINT HEAD CALL)
N10 G0 G54 G90 G80 G18; (work system setting,
work plan, absolute programming)
N15 G0 X0 Z0; (rapid traverse to X0 and Z0)
N20 Y0 H0 T2; (tool length pick-up)
N25 G43 Y10. H0 M27; (tool length compensation
pickup, heating start)
N30 G0 G54 X0 Z0 C0 M23; (filament feed start)
N35 G0 X0 Z0; (move to print start point)
N40 Y0 H0 T2; (movement to printing start point)
N45 G43 Y20 H0; (retract to Y20 before printing so
that there is filament in the extruder when it reaches
the printing surface and possibility of moving the C
axis to 0 to avoid collisions)
N50 G54 G90;
#1= 0.5 (first increment on y)
#2= 15 (last increment on y)
#3= 0.8 (y increment)
N55 G0 G54 X0 Z0 C0 M23 ; (axis positioning at
START point)
N60 G0 X0 Z0 C0;
N65 G01 Y#1 F800; (printing at feedrate F=800
mm/min)
N70 Y#1 X0 Z25. C70; (printing/moving according to
coordinates)
N75 X0.5 C71; (print/move according to coordinates)
N80 Y#1 X0.5 Z0 C1; (print/move according to
coordinates)
N85 X0 C0 M24; (stop filament feed for repositioning)
#1=#1+#3 (INCREMENT ON Y)
IF [#1 LE #2] GOTO 55 (increment calculation
condition)
N90 G0 Y100. (retract to Y100 after completion of
printing)
N95 C0 (rotate C axis to 0)
M24 (stop filament feed)
M28 (heating stop)
M30 (PROGRAM STOP)
%
```

Fig. 11. Part programme-propeller.

Figure 11 shows the parameterized program according to which the propeller blade was printed using the 4 axes of the TMA-AL-550 machine, while figure 12 shows the actual model.

Fig. 12. Part printing.

4. PRINTING AND CRUSHING TESTING OF THE PRINTED PART

4.1 Materials, technical characteristics

Based on the program shown in figure 9, I printed a square piece with the dimensions of 40x40x15 mm and 1 mm wall, the piece that I analyzed with a finite element [19].

a) left view   b) corner view
Fig. 13. Printed sample, microscope analysis

As the TMA-AL-550 is a horizontal machine, the printing equipment has been fixed in a horizontal position so that printing is done vertically (figure 4), which is why the programs will have the XZ-G18 work plane.

The printing equipment is equipped with filament feeding, cooling and filament heating systems respectively, the filament melting nozzle having an inner hole of 0.8 mm.

The material used to print this sample was PLA, which was printed at a temperature of 240 °C, more details are specified in PhD thesis [16].

4.2 Testing the printed sample

It was also analyzed this sample under a microscope (Fig. 13.) to observe the glueing of the material layers together, and then this piece was subjected to crushing, using a Schmidt servo-press, to determine the point of failure/damage.
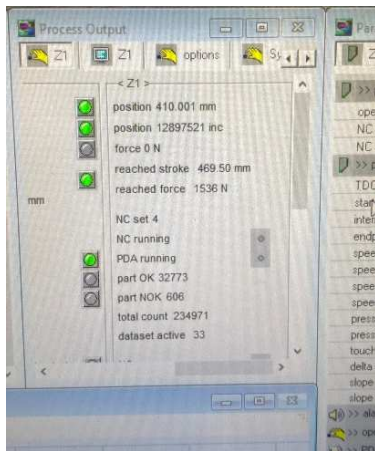
Fig. 14. Result of crushing force Servo-press.
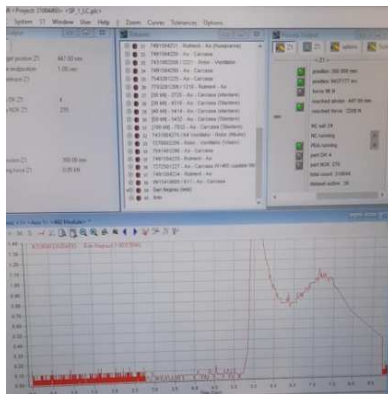
Fig. 15. Deformation evolution chart.

After testing the part in crushing is accomplished, the press provided the force to which the part yielded, namely the force of 1536 [N] (Fig. 14.), a fairly reasonable force for a part of this shape and material - polylactic acid (PLA), [6,20].

Figure 15 shows the graph of the evolution of the force during the compression test, which provides details on the evolution of the state of elastic deformation until the appearance of plastic deformation of the specimen.

5. CONCLUSIONS

The authors of this paper present a variant approach to the procedure of testing, experimenting and validating modifications to a CNC machine to transform it into a mixing machine.

By converting a CNC machine into a mixed machine, retaining the chipper character and adding printing equipment, it has been shown that by combining subtractive and additive manufacturing processes, parts can be produced with greater dimensional accuracy and surface quality than parts produced by other traditional machining methods, for example.

Combining mechanical, electrical, and PLC programming, in the research laboratory at the University of Oradea it has been demonstrated that a CNC milling machine can be transformed into a mixing machine;

The following conclusions should be highlighted regarding the sequences of transforming a classic CNC machine into a hybrid one with the possibility of additive manufacturing:

- Mechanical and electrical design of a plastic printing equipment using the FDM (fused material deposition) manufacturing process to be connected to the TMA-AL-550 machine, in order to obtain a viable equipment, three equipment variants were built, analysed and tested;
- Obtaining part programs using Matlab (using the TMA-AL-550 machine kinematics mathematical package) for additive manufacturing and 5-axis chipping, which

were simulated on the TMA-AL-550 CNC machine;

- Connecting the printing equipment to the CNC machine; the TMA-AL-550 results in a combination machine capable of printing plastic parts;

- Writing and testing parameterised programs for printing with the TMA-AL-550 combination machine, programs that can be used in the absence of a post-processor;

- Printing parts with different configurations on a carrier part in different areas of the part, demonstrating that, as a result, printing times will be significantly shortened and material consumption will be reduced.

Future plans and research approaches in additive manufacturing:

- -3D printing and machining, to be run concurrently on the same machine
- -to create a post-processor for FDA (Fusion Deposition Adhesion) printing, allowing monitoring and control actions of the additive manufacturing process
- -research and study of the state of the additively processed surfaces, in the case of printing head variants, the processing having as variables: deposition speed; workpiece configuration; thickness of the deposited layer; non-linear behaviour, in general, of the deposition material (PLA)
- -experiments focused on the analysis of static mechanical properties (tensile, compression, bending, twisting);
- -a sensitive and scientifically challenging objective is to investigate and analyse the level of adhesion of the deposited layer to the substrate. These objectives are achievable to the extent that research, in general, is at least considered necessary and its development is a national objective.

All these objectives will be able to generate research reports containing measurement data and results useful for the engineering environment and beyond.

The applications of this research can be extended to sensitive areas: bioengineering; orthopaedic surgery, mechanics of aerospace structures, active maintenance of interventions, etc.

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SUCCESIUNEA DE FAZE ÎN PROCESUL DE TRANSFORMARE A UNEI MAȘINI CNC OBIȘNUITE ÎNTR-O MAȘINĂ CNC HIBRIDĂ PENTRU FABRICAREA ADITIVĂ 3D

Această lucrare de cercetare prezintă pașii necesari pentru a transforma o mașină de frezat cu CNC într-o mașină hibridă de printat 3D cu CNC. Pentru această cercetare a fost utilizată o mașină de frezat CNC cu 5 axe, TMA-AL-550, care aparține Universității din Oradea, echipată cu o comandă numerică FANUC 310i-A5, iar pentru a face posibilă conectarea unui echipament de printat, au fost efectuate unele modificări în PLC (Programmable Logic Controller) al mașinii CNC. De asemenea, din punct de vedere mecanic și electric a fost proiectat un echipament de printat, care ulterior a fost conectat la mașina cu CNC, după câteva modificări ulterioare dovedindu-se a fi funcțional. Evident, pentru programul NC s-a folosit programarea parametrizată, cu condiții logice, și programarea asistată de Matlab.

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