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ESTABLISHING THEORETICAL PRECISION MACHINING OF A RECONFIGURABLE ALUMINIUM PROFILE CNC ROUTER VIA FINITE ELEMENT ANALYSIS

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Abstract: This study investigates the theoretical precision machining of a reconfigurable CNC router system constructed using aluminium structural profiles. A Finite Element Analysis (FEA) approach was employed to simulate the mechanical response of the machine under representative cutting forces corresponding to critical machining scenarios according to the intended application. This paper investigates the theoretical static response behavior of the machine structure, with the objective of assessing the achievable precision machining, specifically in applications involving moderate tolerances and precision requirements. The material grades of the semifinished products proposed for machining on this CNC router are as follows: EN AW 6012-T6, EN AW 6060-T6 and PA46, and the milling operations on the router are slot, contour and planar milling for both roughing and finishing operations. The proposed solution meets the ever increasing need in the educational environment for low-cost and reconfigurable CNC platforms.

Key words: Precision machining, structural displacements, influence of the cutting forces, low-cost CNC

1. INTRODUCTION

In today's context of digitization and automation of industrial processes, CNC routers have become essential tools in the makerspaces of technical schools and universities.

This equipment enables students to acquire practical skills in materials processing, easing the transition from theory to practice and preparing them for the demands of modern industry.

CNC routers refer to a combination of engineering and artistic creativity, merging digital precision with mechanical functionality.

They offer significant advantages in terms of precision, efficiency, and versatility in relation to the cost of their production. [1] The integration of CNC routers in the academic environment offers a practical, accessible and efficient method for the development of skills in mechanical engineering and mechanical machining, contributing significantly to bridging the gap between academia (theory) and industry (manufacturing). [2]

2. PRECISION ASPECTS OF CNC MACHINES

In the modern engineering and machining industry, there are several issues related to increasing product quality and productivity. To overcome these problems, it is necessary for CNC machines to meet the precision and accuracy required by the intended applications for which they were designed.

In reality, due to various combined sources of error (see figure 1), CNC machines may not meet the preset requirements in certain situations. These resulting errors propagate as a whole and determine the precision machining of the CNC equipment.

Among the main sources of error are: those introduced by cutting forces, thermal expansion, kinematic and geometric inaccuracies, errors during stock clamping, human errors, by the value of the stiffness or the radial or axial deflections of the main spindle and so on.

Kinematic and geometric errors are primarily caused by the structure's geometry, including

factors related to assembly quality, design, and the components and solutions used (such as ball screws, linear guides, etc.). [3]

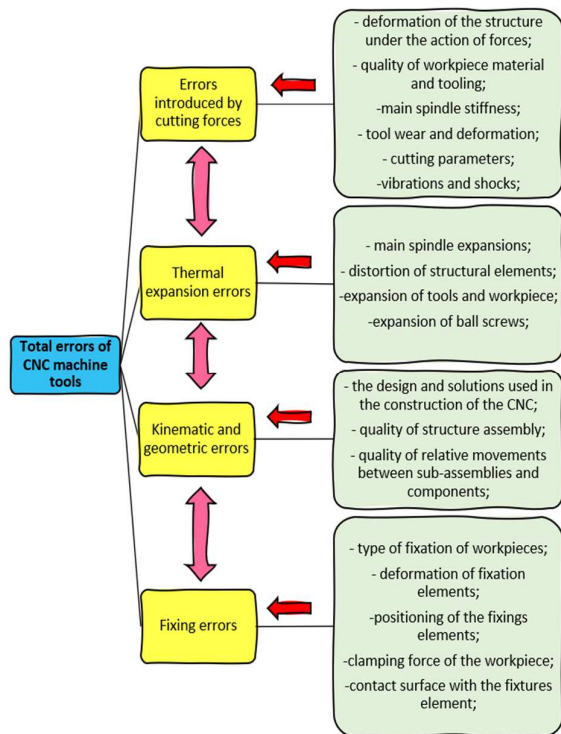


Fig. 1. Total errors of CNC machine tools and the factors involved [5]

These factors can affect both the accuracy and precision of the relative motion between subassemblies and the overall positioning accuracy. The ISO 230 standard addresses the regulation of axis geometry through measurement and evaluation, with the caveat that it does not cover functional tests (such as vibration, feed rates, loads, etc.). Geometric errors can be amplified during machining operations that involve interpolation using all three axes of the machine. Errors caused by thermal expansion within the machine tool system contribute significantly to the reduction of machining precision. [4]

These errors may originate from the expansion of key components such as the main spindle, tooling, workpiece (semi-finished part), and kinematic elements. Fixture-related errors can be influenced by human factors as well as by technical aspects, including the fixture system design, clamping forces, and the size of the contact surface between the fixture and the stock. Errors induced by cutting forces have a

considerable impact on both machine tool performance and overall precision machining.

The mechanical stresses generated during the cutting process lead to structural displacements in the machine tool frame and in the spindle assembly. To mitigate these displacements, most machine tool and CNC equipment manufacturers use cast iron for the structural elements, as it offers high rigidity and excellent vibration damping properties. While cast-iron constructions significantly increase the weight of machine tools, this characteristic contributes positively to overall rigidity and stability. From an economic perspective, manufacturing the frame of a CNC router from aluminium profiles is a more cost-effective solution.

However, aluminium structures inherently provide lower rigidity, which adversely affects precision machining. To compensate for this deficiency and improve structural stiffness and thus accuracy it is common practice to reinforce the frame with a greater number of cross beams, ribs, and structural profiles.

According to the specialized literature, CNC routers intended for machining complex part, including demanding applications where high surface quality is required, must conform to a precision class with tolerances of approximately $\pm 130 \mu\text{m}$. [5]

3. THE DESIGN OF THE CNC ALUMINIUM PROFILE ROUTER

The CNC milling router made of aluminium profiles, figure 2, has three linear kinematic axes, and its gantry-type structure ensures a sufficiently large workspace and good access to the work surface, as well as decent rigidity for easy light machining. [6]

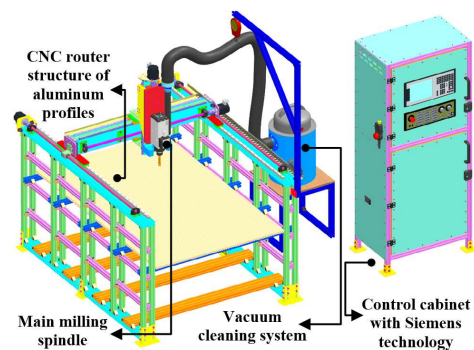


Fig. 2. CNC router type equipment completes with controller cabinet

For the construction of the structure and its three subassemblies, 40x40 mm Bosch aluminium profiles were used, thus enabling the possibility of reconfigurability and height adjustment of the worktable.

The main milling spindle built into the structure is commercially available from HITECO® (catalog code: QN-13/18 18 18 BT ER32DX 220/380), and the used power is set to 3.6 kW, respectively the torque to 1.9 Nm.

The working travels for the X-axis are 900 mm, for the Y-axis 1350 mm and for the Z-axis 320 mm, the maximum speed supported by the kinematic axes is 7.5 m/min. They are driven by a ball screw mechanism with a diameter of 20 mm and a pitch of 5 mm. The router has an overall dimensions 2051x1530x1844 mm and a weight of the structure without the control cabinet of about 260 kg. The control cabinet includes Siemens technology components, presented as follow: controller-driver (SINAMICS S120 COMBI POWER), motor (SIMOTICS 1FK2104-5AF) and programming interface (SIEMENS SINUMERIK 828D), etc.

4. METHODOLOGY FOR OBTAINING ROUTER PRECISION

The precision, respectively the deflections of machine tools are very difficult to determine only by analytical calculation variants, this is due to the complexity of the systems that make up the machine: structure, mechanical elements, main spindle, etc.

The paper treats a study related to the analysis of the errors introduced by the cutting forces on the router structure, resulting in a certain value of the structural displacements. In order to have an overview of the effects resulting from this method, several machining scenarios on some materials, such as aluminium and plastic material will be considered. In addition, we will consider both roughing and finishing machining situations on three types of processes: slot milling, contour milling and planar milling, as shown in figure 3.

The cutting parameters for these operations will be correlated with the spindle capability to perform these machining operations. The tools used for this study are end mills with four flute

($z=4$) and the diameters used to calculate the cutting forces will be 10 and 20 mm.

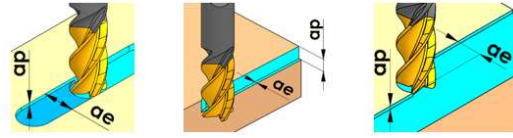


Fig. 3. Milling operations performed on the CNC router for numerical simulations [5]

The maximum diameter of 20 mm is imposed by the holder form of the main spindle, which is ER32 type. The used feed per tooth will be 0,1 mm/tooth for the 10 mm end mill cutter and 0,2 mm/tooth for the 20 mm end mill cutter, these values are recommended by the manufacturers in the industry.

A machinability factor applied for aluminium of $C_m = 1.1$, an average tool wear of $W = 1.2$, and a main spindle with integrated motor with an equal efficiency of $E = 0.9$ shall be used to determine cutting forces, power and torque.

The cutting speed recommended by the tool manufacturers for milling the mentioned materials is $v_a = 500$ m/min, resulting in a tool speed of $n_s = 15916$ rpm for the 10 mm end mill and $n_s = 7958$ rpm for the 20 mm. [7]

In order to reduce the number of simulations performed on the CNC router structure we will realize in the first phase a number of ten cases, these simulations will take into account the position of the main spindle in its workspace, as shown in Table 1.

Table 1

Check cases for finding the critical spindle position

Position of spindle	Main Spindle coordinate		
	AXIS X	AXIS Y	AXIS Z
Case 1	X= +450	Y= -675	Z= -160
Case 2	X= +450	Y= -675	Z= +160
Case 3	X= 0	Y= -675	Z= -160
Case 4	X= 0	Y= -675	Z= +160
Case 5	X= 0	Y= 0	Z= -160
Case 6	X= 0	Y= 0	Z= +160
Case 7	X= 0	Y= +675	Z= -160
Case 8	X= 0	Y= +675	Z= +160
Case 9	X= +450	Y= +675	Z= -160
Case10	X= +450	Y= +675	Z= +160

The goal in these cases is to observe in which of these situations the router structure is most influenced, i.e., in which coordinates of the main spindle the router has the worst rigidity.

The cutting forces and the cutting torque will be applied at a central point on the spindle flange, figure 4, and as a working hypothesis it will be considered that the spindle will have infinite stiffness, i.e. we exclude it from the analysis.

The point of application of the shearing forces will be linked in this case to the spindle attachment area directly on the Z-axis plate using the “remote load/mass” function. [5]

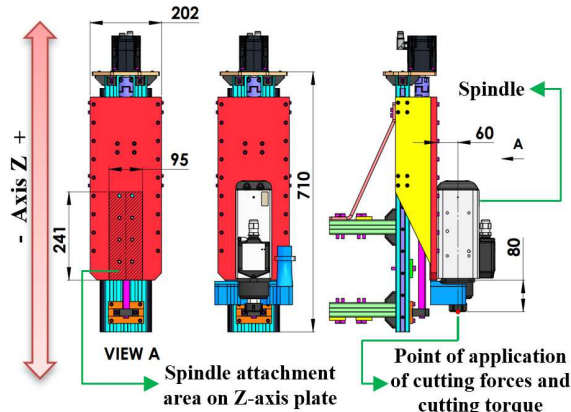


Fig. 4. Highlighting the attachment area of the main spindle and the point of application of cutting forces

The cutting forces, whose values depend on the operations that we will apply on the parts, will have different orientations depending on the direction of the cutting feed of the main spindle. Orientations depending on the direction of the feed will be tangential and radial cutting forces.

According to these statements, two other cases, named A and B, will be taken into account in the studies.

Case A is shown in figure 5, when the spindle feed advances parallel to the Y-axis in the negative direction from the origin. The cutting forces are concentrated at the flange of the spindle and are arranged as follows: the tangential cutting force (F_T) is parallel to the X-axis of the CNC router in the negative direction, the radial cutting force (F_R) is parallel to the Y-axis of the CNC router in the positive direction and the axial cutting force (F_A) is parallel to the Z-axis of the CNC router in the positive direction. The required cutting torque (M_A) is always arranged against the tangential cutting force because it opposes this force.

Case B is shown in figure 6, when the feed of the main spindle advances parallel to the X-axis in a negative direction with respect to the origin

and the cutting forces are concentrated at the flange of the spindle. The forces are arranged as follows: the tangential cutting force (F_T) is parallel to the Y-axis of the CNC router in the positive direction, the radial cutting force (F_R) is parallel to the X-axis of the CNC router in the positive direction.

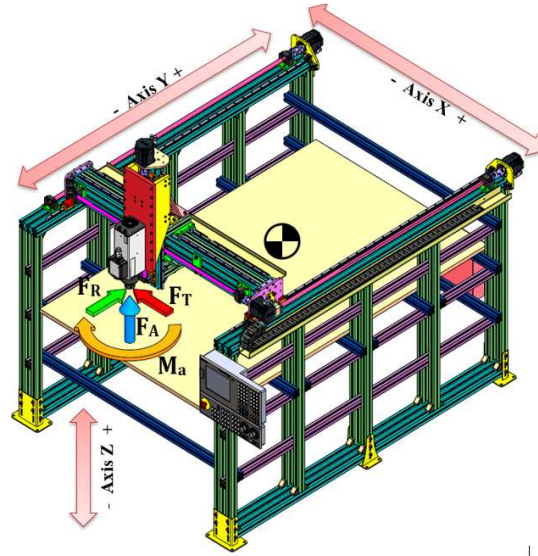


Fig. 5. Case A - the radial cutting force is parallel to the Y axis of the CNC

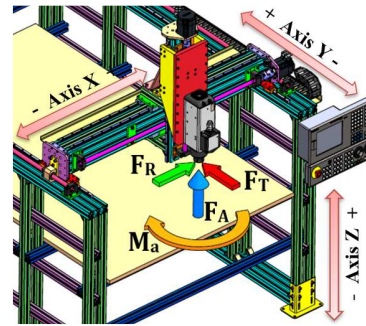


Fig. 6. Case B - the radial cutting force is parallel to the X axis of the CNC

The cutting forces presented in Table 2 were obtained taking into account the following parameters, depending on the type of operation:

- For slot type roughing milling, the depth of cut (axial cutting) is $a_p = 1$ mm and the width of cut (radial cutting), $a_e = 10$ mm for the 10 mm tool and $a_e = 20$ mm for the 20 mm tool;
- For slot type finish end milling, $a_p = 0.2$ mm will be used, and $a_e = 10$ mm for the 10 mm tool and $a_e = 20$ mm for the 20 mm tool;
- For contour type rough milling, $a_p = 5$ mm and $a_e = 1$ mm for both 10 mm and 20 mm diameter tools;

- For contour type finish end milling, $a_p = 5$ mm and $a_e = 0.2$ mm for both tools;
- For rough milling, planar type, $a_p = 1$ mm and $a_e = 8$ mm for the 10 mm tool and $a_e = 16$ mm for the 20 mm tool;
- For finish milling, planar type, $a_p = 0.2$ mm and $a_e = 8$ mm for the 10 mm tool and $a_e = 16$ mm for the 20 mm tool.

Table 2
Value of cutting forces used in FEA analysis [5]

Type of operation	Roughing		Finishing	
End mill tool diameter, mm	10	20	10	20
Slot milling operation - EN AW 6012-T6				
Tangential cutting force, F_T [N]	78.1	156.2	15.6	31.2
Radial cutting force, F_R [N]	43	85.9	8.6	17.2
Axial cutting force, F_A [N]	19.5	39	3.9	7.8
Cutting torque, M_m [Nm]	0.39	1.56	0.08	0.31
Motor cutting power, P_m [Kw]	1.14	2.30	0.23	0.46
Contour milling operation - EN AW 6012-T6				
Tangential cutting force, F_T [N]	74.4	111.6	37.2	111.6
Radial cutting force, F_R [N]	40.9	61.4	20.5	61.4
Axial cutting force, F_A [N]	18.6	27.9	9.3	27.9
Cutting torque, M_m [Nm]	0.37	1.12	0.19	1.12
Motor cutting power, P_m [Kw]	1.09	1.66	0.56	1.66
Plane milling operation - EN AW 6012-T6				
Tangential cutting force, F_T [N]	54.7	109.4	10.9	21.9
Radial cutting force, F_R [N]	30.1	60.2	6	12
Axial cutting force, F_A [N]	13.7	27.4	2.7	5.5
Cutting torque, M_m [Nm]	0.27	1.09	0.05	0.22
Motor cutting power, P_m [Kw]	0.8	1.61	0.14	0.32
Slot milling operation - EN AW 6060-T6				
Tangential cutting force, F_T [N]	47.9	95.8	9.6	19.2
Radial cutting force, F_R [N]	26.3	52.7	5.3	10.6
Axial cutting force, F_A [N]	12	24	2.4	4.8
Cutting torque, M_m [Nm]	0.24	0.96	0.05	0.19
Motor cutting power, P_m [Kw]	0.71	1.41	0.14	0.28
Contour milling operation - EN AW 6060-T6				
Tangential cutting force, F_T [N]	47.9	71.8	23.9	23.9
Radial cutting force, F_R [N]	26.3	39.5	13.1	13.1
Axial cutting force, F_A [N]	12	18	6	6
Cutting torque, M_m [Nm]	0.24	0.72	0.12	0.24
Motor cutting power, P_m [Kw]	0.71	1.06	0.36	0.36
Plane milling operation - EN AW 6060-T6				
Tangential cutting force, F_T [N]	33.5	67	6.7	13.4
Radial cutting force, F_R [N]	18.4	36.9	3.7	7.4
Axial cutting force, F_A [N]	8.4	16.8	1.7	3.4
Cutting torque, M_m [Nm]	0.17	0.67	0.03	0.13
Motor cutting power, P_m [Kw]	0.5	0.99	0.09	0.19
Slot milling operation - PA46				
Tangential cutting force, F_T [N]	25.2	50.4	5	10.1
Radial cutting force, F_R [N]	13.9	27.7	2.8	5.6
Axial cutting force, F_A [N]	6.3	12.6	1.25	2.5
Cutting torque, M_m [Nm]	0.13	0.5	0.03	0.1
Motor cutting power, P_m [Kw]	0.38	0.73	0.09	0.14
Contour milling operation - PA46				
Tangential cutting force, F_T [N]	25.2	37.8	12.6	12.6
Radial cutting force, F_R [N]	13.9	20.8	6.9	6.9
Axial cutting force, F_A [N]	6.3	9.5	3.2	3.2
Cutting torque, M_m [Nm]	0.13	0.38	0.06	0.13
Motor cutting power, P_m [Kw]	0.38	0.56	0.18	0.19

Continue table 2				
Plane milling operation - PA46				
Tangential cutting force, F_T [N]	17.6	35.3	3.5	7.1
Radial cutting force, F_R [N]	9.7	19.4	1.9	3.9
Axial cutting force, F_A [N]	4.4	8.8	0.9	1.8
Cutting torque, M_m [Nm]	0.09	0.35	0.02	0.07
Motor cutting power, P_m [Kw]	0.27	0.51	0.06	0.1

5. RESULTS OF THE ROUTER PRECISION STUDY

In order to be able to establish the position where the main spindle of the CNC router at XYZ coordinates is most affected in terms of deformations at its flange, a number of ten simulations will be performed, as shown in Table 1. Initially these FEA simulations are applied considering a slot rough milling using a 10 mm end mill tool on an aluminium EN AW 6012-T6 type material. The orientation cases of forces A and B are also considered, and the results for deflections and von Mises stresses are highlighted in Table 3.

According to figure 7, only the critical case identified from these simulations, where the critical position of the main spindle is identified as case 3A and case 3B, where the position of the router has coordinates on the $X = 0$, $Y = -675$, and $Z = -160$ mm, will be shown. The maximum deflections and stresses identified on the structure in the area of the main spindle mounting flange for cases 3A and 3B when slot milling with 10 mm rough milling on EN AW 6012-T6 type material, have values of $137 \mu\text{m}$ for case 3A and $153 \mu\text{m}$ for case 3B, respectively stresses of 8.6 MPa for 3A and 10.2 MPa for 3B.

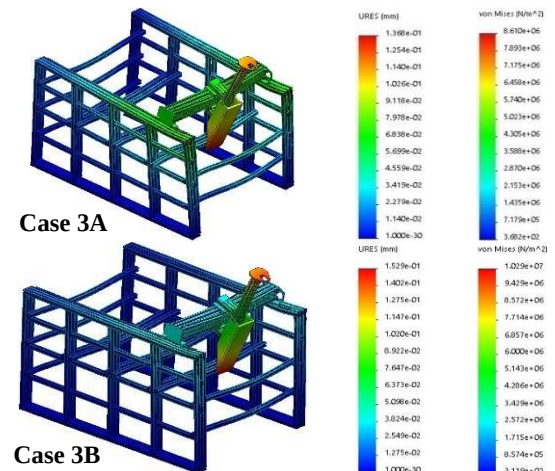


Fig. 7. Displacements and von Mises stresses observed on the CNC structure for case 3A and 3B

Table 3

FEA result for CNC structure under slot-type rough milling using 10 mm tool on EN AW 6012-T6 material

Cases	Force orientation	Von Mises Stress MPa	Deflections URES μm
Case 1	A	10.3	110
	B	10.9	109
Case 2	A	8.3	98
	B	7.8	77
Case 3	A	8.6	137
	B	10.2	153
Case 4	A	6.0	108
	B	5.5	103
Case 5	A	7.3	114
	B	10.2	140
Case 6	A	3.6	84
	B	3.2	85
Case 7	A	5.2	128
	B	8.0	148
Case 8	A	4.6	97
	B	3.7	93
Case 9	A	6.6	102
	B	10.6	104
Case 10	A	5.4	88
	B	4.8	72

Identifying the critical position of the main spindle where the cutting forces have the most negative impact on the router structure, we consider for the following simulations only for cases 3A and 3B.

Thus, in the following tables, we will synthesize the results of the FEA simulations for the maximum deflections and the maximum stresses recorded on the structure for the three types of proposed materials.

Table 4

Synthesis of results from FEA analysis applied on the CNC structure for milling set on EN AW 6012-T6

Type of milling	Tool diam. mm	Direction of forces	Von Mises stresses MPa	Deflections URES μm
Slot roughing	10	Case 3A	8.6	137
		Case 3B	10.2	153
	20	Case 3A	17.5	224
		Case 3B	21.1	245
Finishing slot	10	Case 3A	5.1	75
		Case 3B	4.8	82
	20	Case 3A	5.6	88
		Case 3B	5.1	98
Contour roughing	10	Case 3A	8.4	131
		Case 3B	9.9	148
	20	Case 3A	12.6	173
		Case 3B	15	192
Finishing contour	10	Case 3A	5.8	93
		Case 3B	5.2	105
	20	Case 3A	5.8	93
		Case 3B	5.3	104
Plane roughing	10	Case 3A	6.3	112
		Case 3B	7.3	123
	20	Case 3A	12.3	170
		Case 3B	14.6	190

Continue table 4

Plane Finishing	10	Case 3A	5.0	72
		Case 3B	4.7	77
	20	Case 3A	5.3	80
		Case 3B	4.8	88

Table 5

Synthesis of results from FEA analysis applied on the CNC structure for milling set on EN AW 6060-T6

Type of milling	Tool diam. mm	Direction of forces	Von Mises stresses MPa	Deflections URES μm
Slot roughing	10	Case 3A	6.1	102
		Case 3B	6.4	115
	20	Case 3A	10.8	155
		Case 3B	12.8	174
Finishing slot	10	Case 3A	4.9	72
		Case 3B	4.7	75
	20	Case 3A	5.3	77
		Case 3B	4.8	85
Contour roughing	10	Case 3A	6.1	103
		Case 3B	6.4	116
	20	Case 3A	8.2	128
		Case 3B	9.6	142
Finishing contour	10	Case 3A	5.4	82
		Case 3B	4.9	90
	20	Case 3A	5.4	80
		Case 3B	4.9	90
Plane roughing	10	Case 3A	5.7	90
		Case 3B	5.2	100
	20	Case 3A	7.7	121
		Case 3B	8.9	137
Plane Finishing	10	Case 3A	4.9	70
		Case 3B	4.7	73
	20	Case 3A	5.0	74
		Case 3B	4.7	79

Table 6

Synthesis of results from FEA analysis applied on the CNC structure for milling set on PA46 material

Type of milling	Tool diam. mm	Direction of forces	Von Mises stresses MPa	Deflections URES μm
Slot roughing	10	Case 3A	5.0	82
		Case 3B	4.9	91
	20	Case 3A	5.7	106
		Case 3B	6.7	119
Finishing slot	10	Case 3A	4.3	69
		Case 3B	4.3	71
	20	Case 3A	4.5	71
		Case 3B	4.5	75
Contour roughing	10	Case 3A	5.0	82
		Case 3B	4.9	92
	20	Case 3A	5.3	94
		Case 3B	5.3	105
Finishing contour	10	Case 3A	4.6	73
		Case 3B	4.5	78
	20	Case 3A	4.6	73
		Case 3B	4.5	78
Plane roughing	10	Case 3A	4.7	77
		Case 3B	4.7	83
	20	Case 3A	5.3	91
		Case 3B	5.2	102
Plane Finishing	10	Case 3A	4.3	68
		Case 3B	4.3	69
	20	Case 3A	4.4	70
		Case 3B	4.4	73

In the case of milling of the proposed materials, according to Tables 4-6, the maximum deflections and stresses are recorded for slot type roughing milling with a 20 mm tool, and the values recorded after FEA are for:

- EN AW 6012-T6: 224 μm and 17.5 MPa for case 3A, respectively 245 μm and 21.1 MPa for case 3B;
- EN AW 6060-T6: 155 μm and 10.8 MPa for case 3A, respectively 174 μm and 12.8 MPa for case 3B;
- PA46: 106 μm and 5.7 MPa for case 3A, respectively 119 μm and 6.7 MPa for case 3B.

6. CONCLUSION

In this article, the authors established a working methodology for obtaining the theoretical precision of a CNC router. The aim is to predict the values of the deformations in some machining applications chosen to be used on it and help the designer to optimize the router structure to obtain the required rigidity. The theoretical precision obtained resulted only from the deformations of the router due to the action of the cutting forces, the stiffness of the main spindle being considered infinite, without taking into account the geometrical errors of the router.

It is recommended that we designing a CNC milling router to consider the feed direction of the main spindle, because from the studies carried out, the direction of the cutting forces influences the amount of structure deformation, see figure 8. Considering all the cases presented, the most negative one was case 3B, where the tangential force direction is parallel to the Y-axis of the CNC. In terms of the educational machining applications used on the CNC router designed and analyzed, authors recommend that its machining precision should be $\pm 150 \mu\text{m}$.

To obtain this value and not to exceed certain deformations for the proposed applications it is necessary to consider the following:

- milling tools less than 10 mm in diameter should be used for roughing operations, applicable to all types of operations carried out on it;
- if 20 mm cutters are still used, the aim is to reduce the depth of cut below 1 mm and increase the number of passes;

- using milling tools with a smaller number of flutes, $z < 4$, or reducing the feed per tooth;
- increasing router rigidity by various ingenious methods, future research topics.

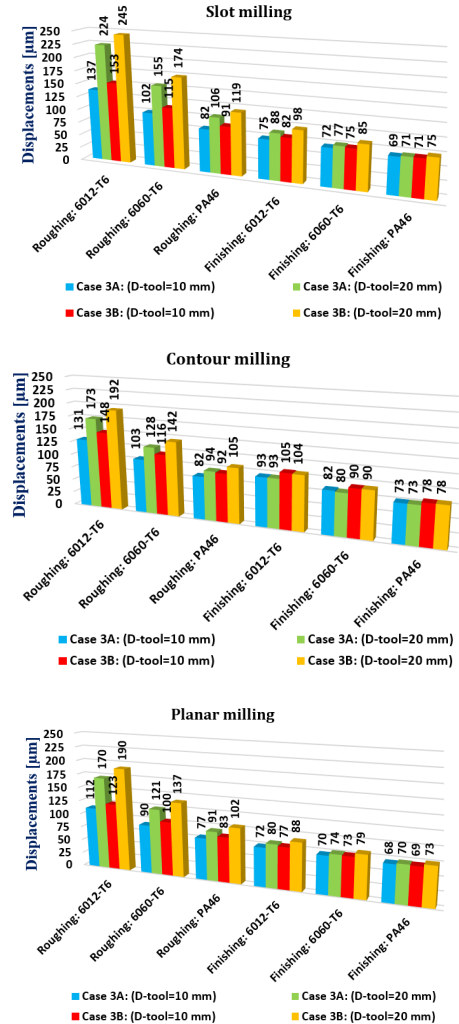


Fig. 8. The deformations recorded on the CNC router structure for all selected milling operations

The advantages of using CNC routers are multiple and studies show that such structures made of aluminium profiles are suitable for these applications. Future research will focus on the application of strain gauge sensors on the structure and the physical realization of the milling applications compared to theoretical ones.

7. ACKNOWLEDGEMENT

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Fig. 9. CNC router physically realized in the university laboratory of UTCN

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STABILIREA TEORETICĂ A PRECIZIEI DE PRELUCRARE A UNUI ROUTER CNC RECONFIGURABIL DIN PROFILE DE ALUMINIU UTILIZÂND ANALIZA ELEMENTELOR FINITE

Rezumat: Acest studiu investighează precizia teoretică de prelucrare a unui sistem de router CNC reconfigurabil construit utilizând profile structurale din aluminiu. A fost practică abordarea bazată pe analiză cu element finit (FEA) pentru a simula răspunsul mecanic al mașinii la forțele principale de așchiere corespunzătoare scenariilor critice de prelucrare în conformitate cu aplicația prevăzută. Acest studiu urmărește comportamentul teoretic static de răspuns al structurii mașinii, cu obiectivul de a înregistra precizia de prelucrare realizabilă, bineînțeles în cazurile de utilizare cu toleranțe și precizii moderate. Clasele de materiale ale semifabricatelor propuse pentru a fi prelucrate pe acest router CNC sunt următoarele: EN AW 6012-T6, EN AW 6060-T6 și PA46, iar operațiile de prelucrare prin frezare aplicate pe router, sunt frezarea de tip slot, pe contur și frezarea plană, atât pentru degroșare, cât și pentru operațiile de finisare. Soluția propusă răspunde nevoii tot mai mari în mediul educațional de platforme CNC reconfigurabile și cu costuri reduse.

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