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CALCULATIONS FOR THE OPTIMIZATION OF THE CUTTING REGIME WHEN PROCESSING CERTAIN COMPONENTS OF THE 3RUU PARALLEL MANIPULATOR

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Abstract: *The paper presents more difficult theoretical concepts regarding Taylor's relationship (which is based on the tool wear characteristic), economic and optimal cutting speeds (established on the basis of fair economic criteria: the minimum manufacturing cost, respectively the minimum processing time of a part) and related calculations in the case of processing with two types of tools. The value of the exponent (k) and the constant (C_T) from Taylor's formula were experimentally determined and, also, the times for the processing of the two types of forks included in the 3RUU manipulator were calculated.*

Key words: *parallel manipulator, optimal and economic cutting speed, tool durability, incomplete operative time, technological cost.*

1. INTRODUCTION

Figure 1 shows the kinematic diagram of the 3RUU space manipulator which has 3 degrees of freedom in translation. Figure 2 highlights the constructive (practical) form of the manipulator. Considering that certain parts of the manipulator are already on the market, it was decided to replace them with purchased ones (such as the passive universal joints from the levels II (Ci), the passive universal joints from the levels III (Ai) and the robot gripper h), and the other parts that are customized were processed in the BAGS laboratory (BAGS is the abbreviation in Romanian for Basics of Cutting and Surface Generation) of TUCN (such as the base platform, the rotational motor joints from the base (Bi), the fork of length H, the fork of length L and the mobile platform).

This construction leads to a variant of the Delta-type robot, studied geometrically, kinematically and dynamically by numerous researchers [1], [2], [3], [4] and [5]. The Delta-type structure is the basis of more complex robots with applicability in medical robotics [6]. The parts of the manipulator, numbered from 1 to 9 in figure 2, are described in chapter 2 of the article. Some of the previously mentioned parts, the fork of length H and the fork of length L, were executed by milling on the FUS-22 universal milling machine for tooling from the equipment of the BAGS laboratory of TUCN, with end-mill cutters made of metal carbides.

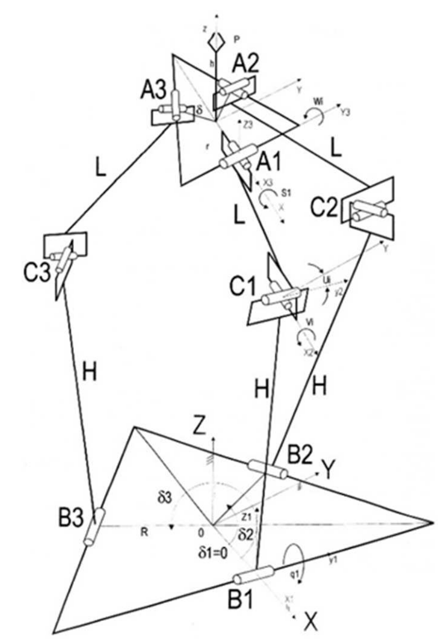

Fig. 1. Kinematic diagram of the mechanism [7]

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The depth and feed were established experimentally, starting from the size of the blank and the roughness imposed on the parts. The cutting speed was chosen from the catalog of the company producing the cutting tools. The paper proposes the calculation of the optimal speed and the economic cutting speed and their comparison with the range of speeds recommended by the tool manufacturer.

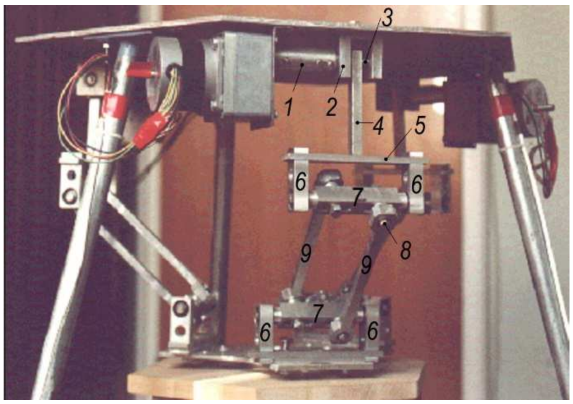

Fig. 2. The 3-RUU mechanism [7]

2. DESCRIPTION OF THE SCALE MODEL OF THE 3RUU MANIPULATOR

Some of the components of the manipulator in figure 2 were manufactured on universal machine tools, the material being duralumin (to have a reduced weight).

The coupling between the electric motor shaft and the first shaft of the motor joint of the manipulator (*Component 1*), the shaft bearing of the motor joints of the manipulator (component 2) and the first motor shaft of the manipulator rotational joint (*Component 3*) which formed the rotational motor joints from the base (B_i) were replaced with the following components purchased from the market and adjusted by mechanical processing to fit:

- Guide axle support SK 12 – 2 pieces
- Shaft WRA10 – 1 piece
- Bearing Union CB-060 6700 2RS – 2 pieces

In total, 3 rotational motor joints from the base (B_i) are used , the joint further noted as *Component 1-2-3* and which are attached to *Component 4*.

Component 4 was executed in 3 pieces, being the motor arm (the arm that leaves the motor joint of the robot) and hereinafter referred to as the fork of length H. This piece is mounted on axis 1, between *Component 1-2-3* and *Component 5-6-7*.

The upper part of the universal joint in the kinematic chain (*Component 5*), the part of the universal joint in which its axis will be mounted (Component 6), the axis of the universal joint (*Component 7*) which formed a passive universal joints from the levels II (Ci) and the fastening piece (*Component 8*) were replaced with such a market available universal joint, further referred as *Component 5-6-7*. A total of 3 such joints are used in the manipulator, *Component 9* will be mounted on each joint.

Component 9 represents the fork of length L, it was executed in 3 pieces, on which the passive universal joints from the level III (A_i) is mounted.

Components 6 and 7 which formed the 3 passive universal joints from the level III (A_i) and to which the mobile platform is attached have been replaced with universal joints purchased from the market.

3. BASIC CONCEPTS REGARDING TOOL DURABILITY

The *durability of a cutting tool* means the effective cutting time, under certain well-defined conditions (*depth = cst., feed = cst., speed = cst.*), necessary to reach the wear limit. At the end of the durability of a cutting tool, as a rule, it has not lost its entire cutting capacity, but it no longer ensures the satisfaction of the requirements of the adopted wear criterion. The durability of the tool, denoted by T and measured in *minutes*, is influenced by many factors: parameters of the cutting regime, the geometry of the cutting tool, the limit wear value, the pair of tool-blank materials, etc. The tool durability can also be expressed in other forms: the effective cutting path corresponding to the tool durability ($L_T = T \cdot v$ [m]), the chipped area during the tool durability ($S_T = T \cdot v \cdot b$ [m^2]), the number of pieces executed in the time corresponding to durability ($N_T = T/t_b$ [m^2]), the volume of chips removed related to durability ($S_T = t \cdot s \cdot v \cdot T$ [m^3]), etc. Of all the influencing factors of durability, Taylor realized that the cutting speed has the greatest influence, and experimentally established the relationship (1) – which bears his name. Represented in double logarithmic coordinates, Taylor's equation is a straight line, as can be seen from figure 3. The exponent *(k)* is a synthetic indicator of the wear sensitivity of the tool material. The (C_T) constant represents the durability corresponding to a speed of 1 m/min.

$$T = C_T \cdot v^k \tag{1}$$

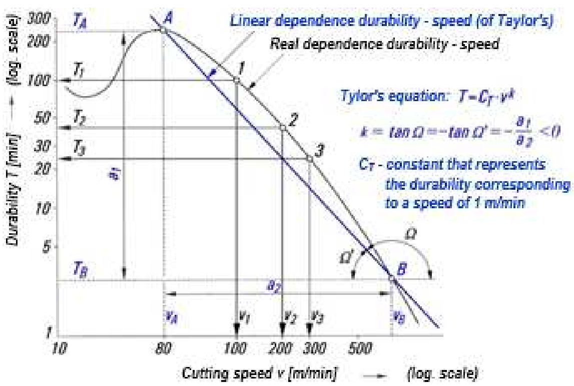

Fig. 3. Durability-speed diagram [8]

The great advantage of Taylor's relation is that it can be linearized by logarithmization, a form in which it is easy to use in practice. At the same time, it was found that, in a wider range of cutting parameters (especially in the case of cutting speed), the durability calculated with Taylor's relation (T_{calc}) differs a lot from the effective one (T_{ef}), established by measurements.

4. BASIC CONCEPTS REGARDING THE CALCULATION OF OPTIMUM SPEED AND ECONOMIC CUTTING SPEED

In the scientific literature [9], [10] it is shown that the optimal speed (v_{opt}) represents the speed at which a part from a very large batch of parts (n_p) should be chipped, so that the processing time (of the part) to be minimal (t_{opi}). The formulas of the incomplete operative time (t_{opi}) and the optimal speed (v_{opt}) were derived in [8] and given by formulas (2) and (3).

$$t_{opi} = \frac{t_{pi}}{n_p} + t_a + t_b + \frac{t_b}{T} \cdot t_s \tag{2}$$

$$v_{opt} = \sqrt[k]{-(k+1) \cdot \frac{t_s}{C_T}} \tag{3}$$

By canceling the derivative of the first order of the incomplete operative time (in relation to the cutting speed), an equation is obtained whose solution is the optimal cutting speed (v_{opt}) which ensures the minimum time for processing the part and implicitly a maximum productivity of the processing, from the mathematical point of view.

Substituting relation (3) into Taylor's formula (1) arise the expression of optimal durability (T_{opt}), meaning relation (4).

$$T_{opt} = -(k+1) \cdot t_s \tag{4}$$

In the previous relations, (t_{pi}) represents the preparation-to-finish time for processing a batch of (n_p) parts, (t_b) the basic time or effective cutting time, (t_a) the auxiliary time, (t_s) the tool change time.

The economic speed (v_{ec}) is the speed at which a part should be chipped from a very large batch of parts (n_p) so that the manufacturing cost (of the part) is minimal *(C)*. The formulas of technological cost *(C)* and economic speed (v_{ec}) were derived in [8] and reproduced by formulas (5) and (6).

$$C = C_{RM} \cdot \left(\frac{t_{pi}}{n_p} + t_a\right) + C_{RM} \cdot t_b + \frac{t_b}{T} \cdot (C_{RM} \cdot \cdot t_s + C_{ST}) \tag{5}$$

$$v_{ec} = \sqrt[k]{-(k+1) \cdot \frac{t_s + \frac{C_{ST}}{C_{RM}}}{C_T}} \tag{6}$$

By canceling the derivative of the first order of the technological cost *(C)* (in relation to the cutting speed) an equation is obtained whose solution is the economic cutting speed (v_{ec}) that ensures the minimum manufacturing cost of the part, from the mathematical point of view.

Substituting relation (6) into Taylor's formula (1) arise the expression of economic durability (T_{ec}), meaning relation (7).

$$T_{ec} = -(k+1) \cdot \left(t_s + \frac{C_{ST}}{C_{RM}}\right) \tag{7}$$

In the previous relations, *(C_{RM})* represents the specific expenses related to the cutting process (with the machine-tool, with the operator, etc.) and *(C_{ST})* the cost of a durability *(T)* of the tool.

5. CALCULATION OF THE OPTIMAL AND ECONOMIC CUTTING SPEED OF CERTAIN PARTS OF THE 3RUU MANIPULATOR

The machine-tool from the BAGS laboratory on which the parts of the 3RUU manipulator (for the 15 constructive variants) were processed is the FUS-22 milling machine.

5.1 Setting the spindle speed and cutting speed for the FUSS-22 milling machine

From the catalogs of the tool manufacturers, the cutting speed recommended (v_{rec}) for front milling (with carbide milling cutters), with a depth of t < 8 mm, when cutting duralumin is included in the range (v_{min} = 30 m/min and v_{max} = 65 m/min). The diameter of the cutter used is 16 mm. (D_{frez} = 16 mm). Under these conditions, the recommended speeds for the minimum and maximum cutting speed will be determined with relation (8), obtaining the following values: n_{min} = 596.831 rpm respectively n_{max} = 1293.134 rpm.

$$n_{rec} = \frac{1000 \cdot v_{rec}}{\pi \cdot D_{frez}} \tag{8}$$

Based on the speeds provided in the milling machine book, table 1, the values of the speeds closest to the previously determined values will be chosen, thus for FUSS-22 we will have n_{min} = 630 rpm and n_{max} = 1250 rpm.

Table 1

The speeds that can be achieved on the FUS-22 milling machine [rpm] [11]

Range 1	63	100	160	250	400	**630**
Range 2	125	200	315	500	800	**1250**

We recalculate the two cutting speeds using the speeds on the FUSS-22 milling machine and relation (8) from which the cutting speed is extracted, thus obtaining v_{min} = 31.67 m/min and v_{max} = 62.83 m/min.

Considering that the recommended cutting speed *(v_{rec})* must fall within the previously determined range, in the following, we will choose for an average value from this range: v_{rec_med} = 45 m/min, which we will have to adapt to the FUS-22 milling machine, so we recalculate the speed with relation (8) and obtain n_{rec_med} = 895.25 rpm.

From the machine book, we choose the speed for FUSS-22: n_{rec_MU} = 800 rpm, in which case the cutting speed will be v_{rec_MU} = 40.21 m/min.

5.2 Establishing the feed rates for the FUSS-22 milling machine

The feed rates for the FUSS-22, mentioned in its book, are presented in table 2. Considering that the speed set for the FUSS-22 is 800 rpm, that is, a value from the 2nd range, it turns out that the forward speed *(v_f)* of the machine can only be chosen from range 2 (the machine tool having a single motor, with 2 speeds - range 1 and 2 respectively, mentioned above), thus we establish the range (40, 160) mm/min, with the 2 extreme values v_{f_min} = 40 mm/min and v_{f_max} = 160 mm/min.

Table 2

Feed rates achievable on the FUS-22 milling machine [mm/min] [11]

Range 1	12.5	20	31.5	50	80	125
Range 2	25	**40**	63	100	**160**	250

From the formula (9) of the feed rate, the processing time (for one pass) can be determined:

$$v_f = \frac{L}{\tau} \tag{9}$$

where:

L = length of the processed part,
τ = processing time in one pass.

5.3 Determination of processing times on the FUSS-22 milling machine for the forks of the manipulator

The parts processed by milling to bring them to the required dimensions are the fork of length H and the fork of length L for the 15 constructive variants in table 3.

It can be seen that the fork of length L will have only 3 values for the 15 constructive variants of the manipulator. Also, the fork of length H has only one length value. Taking into account these aspects, table 4 shows the dimensions of the two types of forks.

Table 3

The values of (r) and (L) [mm] for the 15 constructive variants

	r/R= 1/3	r/R= 1/2	r/R= 2/3	r/R= 5/6	r/R= 1
L/R =1	r1= 65.07	r2= 97.61	r3= 130.15	r4= 162.69	r5= 195.23
	L1= 195.23	L2= 195.23	L3= 195.23	L4= 195.23	L5= 195.23
L/R =3/2	r6= 65.07	r7= 97.61	r8= 130.15	r9= 162.69	r10= 195.23
	L6= 292.85	L7= 292.85	L8= 292.85	L9= 292.85	L10= 292.85
L/R =2	r11= 65.07	r12= 97.61	r13= 130.15	r14= 162.69	r15= 195.23
	L11= 390.47	L12= 390.47	L13= 390.47	L14= 390.47	L15= 390.47

Table 4

The dimensions of the forks processed in the BAGS laboratory

No. crt.	Type of fork	No. of pieces / manipulator	Dimensions [mm]	
			a x b	l
1	Fork of length H	3	9.91 x 9.83	110
2	Fork of length L	3	9.25 x 8.24	195.23
				292.85
				390.47

Table 5

Processing time for forks

No. crt.	Type of fork	Processing time per piece [min]		Processing time per manipulator (3 pieces) [min]	
		For minimum speed (v_f)	For maximum speed (v_f)	For minimum speed (v_f)	For maximum speed (v_f)
1	Fork of length H	11	2.75	33	8,25
2	Fork of length L	19.52	4.88	58.56	14.64
		29.29	7.32	87.87	21.96
		39.05	9.76	117.15	29.28

The two types of forks, having the shape of a rectangular parallelepiped with the dimensions axlxb, a = width, l = length and b = thickness, were processed from square duralumin bars of 10x10 mm, these being the closest in size to the required ones. Thus, for each piece of each type of fork, two millings of two passes will be made (two passes on the width *(a)* and two on the thickness *(b)*), the results being provided in table 5.

5.4 Experimental determination of the value of the exponent *(k)* and the constant *(C_T)*

Carrying out an experimental study on the wear of cutting tools refers to raising the wear characteristics under the action of a factor, usually the cutting speed. By imposing a limit criterion (a certain value of the measured wear parameter, usually (VB_{lim})), tool durabilities are defined for different values of speed or feed. Using the construction of the Taylor diagram in double logarithmic coordinates (figure 3) the pairs of values (v_i - T_i) are represented. Using the linear regression procedure, the slope of the regression line and implicitly the value of the *(k)* exponent is determined. The ordinate at the origin of the regression line will determine the logarithm of the constant in equation (1).

The experiment to determine the *(k)* and (C_T) parameters was carried out on the FUS-22 milling machine (the machine-tool on which the forks from duralumin bars of the 3RUU manipulator were processed), according to table 6.

Table 6

Centralizing table with experimental data

No. crt.	D [mm]	n [rpm]	t [mm]	s [mm/rot]	v [m/min]	T [min]
1	16	630	1	0.1	31.66	**35**
2	16	960	1	0.1	48.25	**12**

Table 7

Evolution of wear over time (measured under a microscope)

Time [min]	0	2	4	6	8	10	12	14	16	18	20	25	30	35	40
VB_1 [mm]	0	0,05	0,1	0,12	0,13	0,16	0,18	0,19	0,23	0,26	0,27	0,28	0,29	0,34	0,39
VB_2 [mm]	0	0,1	0,15	0,19	0,28	0,31	0,34	0,38	0,45						

Two identical end-mill cutters made of metal carbides were used, whose wear evolution over time was measured (under a microscope) according to table 7. Imposing a wear limit VB_{lim} = 0.34 mm, the durabilities T_1 = 35 min, T_2 = 12 min (which represents 2 points on Taylor's line), according to table 7.

- for n_1 = 630 rpm we have v_1 = 31.66 m/min to which corresponds T_1 = 35 min,
- for n_2 = 960 rpm we have v_2 = 48.25 m/min to which corresponds T_2 = 12 min.

$$|k| = \left|\frac{log(T_2)-log(T_1)}{log(v_2)-log(v_1)}\right| \tag{10}$$

where:

k = the value of the exponent in Taylor's relation (1).

$$logC_T = \frac{\sum log(T)-k\cdot\sum log(v)}{2} \tag{11}$$

where:

C_T = the constant in Taylor's relation (1).

With the help of relation (10) the value k = -2.54 was obtained and with relation (11) the value C_T = 227829.89.

For the recommended cutting speed (established in subchapter 5.1) v_{rec_MU} = 40.21 m/min, with the help of *(C_T)* and *(k)* values established above, we obtain with formula (1) the durability (corresponding to the carbide milling cutter) T_{rec_MU} = 19.17 min, a value that confirms the correctness of the calculations performed so far.

5.5 Calculation of the optimal and the economic cutting speed, respectively the durabilities corresponding to these speeds

The following input data are known: t_s = 5 min, C_{ST} = 10 Euro, C_{RM} = 150 Euro and the previously determined parameters, *(k)* and *(C_T)*.

With the help of relations (3) and (8), the values v_{opt} = 57.44 m/min and n_{opt} = 1142.74 rpm were obtained.

Based on relations (6) and (8), v_{ec} = 57.14 m/min and n_{ec} = 1136.8 rpm were determined.

Regarding the durability of the tool for the two cutting speeds, it can be stated that in the case of the optimal speed the durability T_{opt} = 7.71 min was obtained while for the economic speed the durability T_{ec} = 7.81 min was obtained.

Next, we proposed to study the option of processing the forks of the manipulator with a 16 mm diameter end-mill cutters made of high-speed steel (the values of the *(t_s)*, *(C_{ST})* and *(C_{RM})* parameters remain unchanged). In this case, the value of *(k)* was taken from the table of indicative values for the exponent *(k)* [12] for the high-speed steel cutting tool in the case of processing light alloys, its values falling within the range (-9,-5). Thus, k = - 6.5 was chosen, a value close to the average, and C_T = 8000000.

With the formula

$$v = \sqrt[k]{\frac{T}{C_T}} \tag{12}$$

the values of the cutting speeds were determined:

- v_1 = 7.12 m/min with the related speed n_1 = 141.66 rpm to which corresponds T_1 = 23 min,
- v_2 = 9 m/min with the related speed n_2 = 179.15 rpm to which corresponds T_2 = 5 min.

With the help of relations (3) and (8), the values v_{opt} = 6.93 m/min and n_{opt} = 137.82 rpm were obtained.

Based on relations (6) and (8), v_{ec} = 6.91 m/min and n_{ec} = 137.54 rpm were determined.

The tool durability for the two cutting speeds resulted as follows, in the case of the optimal speed the durability T_{opt} = 27.5 min was obtained while for the economic speed the durability T_{ec} = 27.87 min was obtained.

Based on the values determined in this paper, we were able to create the durability-speed diagram for the two types of tools, metal carbide and high-speed steel, used to process the 3RUU manipulator parts (Figure 4).

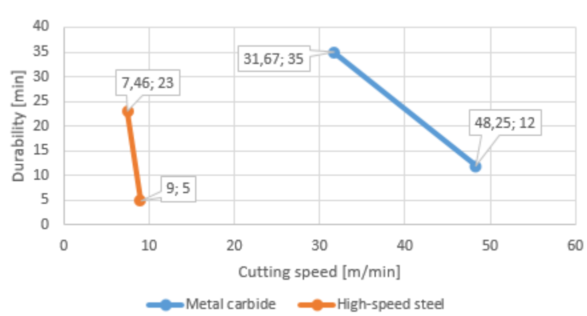

Fig. 4. Durability-speed diagram for the two types of tools

Also, having the speeds achievable on the FUS-22 milling machine, we were able to represent another diagram (Figure 5) with these speeds between which the economic and optimal speeds determined in the present study were interspersed, for the two types of processing: with the tool from metal carbide, respectively with the high-speed-steel tool.

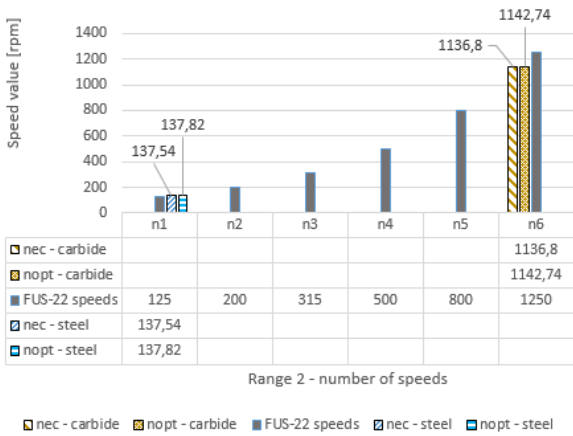

Fig. 5. Speeds diagram for the two types of tools

6. CONCLUSIONS

Following the study regarding the processing of the two types of forks included in the 3RUU manipulator, the following were found:

- The optimal speed for the FUSS-22 milling machine in order to process the forks of the manipulator (with carbide milling cutter) is n_{rec_MU} = 800 rpm, and the cutting speed will be v_{rec_MU} = 40.21 m/min.
- The indicated feed rates (when processing with metal carbide) are: minimum feed rate v_{f_min} = 40 mm/min and maximum feed rate v_{f_max} = 160 mm/min.
- The times for processing the duralumin forks with the 16 mm diameter end-mill cutters (made of metal carbides) are:
  - fork of length H: for $v_{f\_min} - \tau = 11$ min and for $v_{f\_max} - \tau = 2.75$ min,
  - fork of length L1: for $v_{f\_min} - \tau = 19.52$ min and for $v_{f\_max} - \tau = 4.88$ min,
  - fork of length L2: for $v_{f\_min} - \tau = 29.29$ min and for $v_{f\_max} - \tau = 7.32$ min,
  - fork of length L3: for $v_{f\_min} - \tau = 39.05$ min and for $v_{f\_max} - \tau = 9.76$ min.
- The value of the exponent *(k)* and the constant *(C_T)* from Taylor's formula were determined experimentally, for the processing of the forks from duralumin bars used in the 3RUU manipulator, when using the end-mill cutters made of metal carbides.
- The optimal cutting speed, economic cutting speed and durabilities corresponding to these speeds were determined for the same parts of the 3RUU manipulator, for the two types of tools used.
- It is experimentally proven that the value of the economic cutting speed is lower than the value of the optimal cutting speed, $v_{ec} < v_{opt}$, as well as the fact that the tool durability for the economic speed is greater than the tool durability for the optimal speed, $T_{ec} > T_{opt}$ (according to theoretical concepts presented in [8], [9] and [10]).
- The economic durability value *(T_{ec})* calculated with formula (7) is close to one of the durability values *(T)* calculated with formula (1) for both types of tools: - for metal carbide T_{ec} = 7.81 min and T_2 = 12 min , - for high-speed steel T_{ec} = 27.87 min and T_1 = 23 min, which confirms the validity of the study.
- The optimal durability value *(T_{opt})* calculated with formula (4) is close to one of the durability values *(T)* calculated with formula (1) for both types of tools: - for metal carbide T_{opt} = 7.71 min and T_2 = 12 min, - for high-speed steel T_{opt} = 27.5 min and T_1 = 23 min confirming, once again, the validity of the study.
- The optimal and economic cutting speed values determined in the paper are at the upper end of the range recommended by the tool manufacturing companies. The two values are very close due to the fact that the *(C_{RM})* value (150 Euro) is much higher compared to the *(C_{ST})* value (10 Euro), the ratio between the two being C_{ST}/C_{RM} = 0.066; If, for example, the values of the two parameters had been inverse (C_{RM} = 10 Euro, C_{ST} = 150 Euro) then the ratio would have been C_{ST}/C_{RM} = 15 and the two cutting speeds would have had the values: v_{opt} = 20.17 m/min and v_{ec} = 11.2 m/min.
- Figure 4 (experimentally obtained) confirms the superiority of the metal carbide tools over high-speed steel tools in terms of tool durability

variation with cutting speed, in the case of processing light alloy parts such as duralumin.

- The optimal speed *(n_{opt})* and the economic speed *(n_{ec})* for processing with the high-speed steel tool are located towards the lowest speed of the FUS-22 machine, while the optimal speed *(n_{opt})* and the economic speed *(n_{ec})* for processing with the metal carbide tool is located towards the highest speed of this machine, being included between the available speeds of the FUS-22 machine, and not outside them (figure 5).

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CALCULE DE OPTIMIZARE A REGIMULUI DE AȘCHIERE LA PRELUCRAREA ANUMITOR COMPONENTE ALE MANIPULATORULUI PARALEL 3RKK

Rezumat: *Articolul prezintă concepte teoretice mai dificile ce privesc relația lui Taylor (ce are la bază caracteristica de uzură a sculelor), viteza economică și optimă de așchiere (stabilite pe baza unor criterii economice juste: costul minim de fabricație, respectiv timpul minim de prelucrare al unei piese) și calculele aferente în cazul prelucrării cu două tipuri de scule. S-au determinat experimental valoarea exponentului (k) și a constantei (C_T) din formula lui Taylor și, de asemenea, s-au calculat timpii pentru prelucrarea celor două tipuri de furci care intră în componența manipulatorului 3RKK.*

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