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EVALUATION OF MACHINABILITY BY HIGH SPEED MILLING OF TWO STEELS BY MEANS OF CUTTING FORCES

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Abstract: *One of the criteria used in order to evaluate the materials machinability by milling is the size of mechanical solicitation of the milling technological system. Usually, this mechanical solicitation is evaluated by means of cutting forces and moment. By knowing the sizes of milling forces and moments, one can adequately establish the values of milling process parameters and design or test the behavior of distinct components of the technological system under the action of the milling forces and moment. A systemic analysis of the end milling process highlighted the main groups of factors able to exert influence on the sizes of milling force components and moments. Taking into consideration the available conditions, an experimental plan was elaborated and materialized, in order to establish mathematical empirical models which could highlight the influence exerted by the workpiece material hardness and the parameters of milling process on the sizes of milling force components. Power type empirical models were determined by mathematical processing of the experimental results. The empirical models allowed the highlighting of the influence order of the considered factors. A more suggestive illustration of the influence exerted by the input factors on the sizes of the end milling force components was obtained by means of some graphical representations.*

Key words: *end milling process, milling force components, influence factors, milling parameters, workpiece material hardness, empirical mathematical models.*

1. INTRODUCTION

The milling is a machining process based on material removal from workpiece as a consequence of a rotation movement achieved by the cutting tool, while the workpiece or just the tool achieves a feed motion along a direction perpendicular on the rotating cutting tool axis. The milling processes could be classified if the shape of the surface to be obtained by milling is taken into consideration. Thus, there are milling processes allowing the obtaining of plane surfaces or profiled surfaces, but there are yet milling processes applied in order to obtain cylindrical surfaces, as there are many milling processes used in order to generate the gaps between the teeth of a gear.

In order to remove the machining allowance, the clearance surface of the mill tool presses a thin layer of the workpiece material up to the moment when a shearing phenomenon is initiated and a chip appears gradually. As a consequence, during the milling processes, cutting forces and moments could be highlighted.

On the other hand, it is known that a significant property of the workpiece material is its capacity to be machined in the most convenient conditions for the producer; this technological property is called *machinability*. Distinct criteria could be used in order to characterize the machinability of a material by different machining methods. Actually, the main such criteria are the workpiece material capacity to wear the cutting tool, the sizes of forces and moments generated during the machining process, the roughness of the surfaces obtained by machining, the capacity to easily remove the chips from the machining zone, the temperature reached in the cutting zone etc.

The knowledge of the cutting forces and moments sizes is important when the problem of establishing the sizes of the machining parameters is formulated; it is necessary that the machining process does not involve for a long time a power higher than the nominal power of the machine tool.

The sizes of the cutting forces and moments are also used in order to establish the adequate dimensions of cutting tools or in order to verify the cutting tool behavior under the action of cutting forces and moments. Of course, the integrity of the cutting tool must not be affected by the cutting forces. One must take into consideration the elastic deformation of the tool as a consequence of the cutting tool forces and moments. Due to existence of cutting forces and moments, the components of the technological system (including the machine tool, the devices, the cutting tool and the workpiece) are affected by elastic deformations. These deformations must not generate dimensional or shape or position errors of ma-

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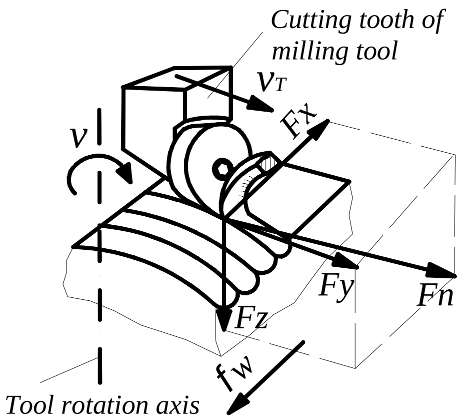

Fig. 1. Developing of the end milling process.

chined surfaces higher than those considered as acceptable.

As above mentioned, the sizes of the cutting forces and moments could be considered as machinability indexes.

The researches developed in the last decades took into consideration the so-called *high speed cutting*. The high speed milling involves the use of milling speed higher than those usually used of about 5–10 times [1]. At such high cutting speed, the phenomena specific to the initiation and development of cutting process have distinct characteristics in comparison with those met in the case of milling at common cutting speed.

Over the years, the experimental evaluation of milling forces and moments constituted a preoccupation for the researchers in the field of cutting processes, inclusively by taking into consideration the evolution of devices used within experimental tests. If initially mechanical transducers were essentially used, nowadays there are advanced transducers able to ensure a good registration of the cutting forces and moment variation and modern instruments were designed and built by specialized companies in order to ensure the best experimental conditions and an adequate measuring of cutting forces and moments.

Thus, Zhang et al. investigated the correlation between the tool wear and cutting forces variation in the case of high-speed end-milling Ti-6Al-4V alloy, by using uncoated tungsten carbide tools. They highlighted the significance of the cutting force component F_y, whose variation could be connected with the tool wear propagation [6].

In the case of the same material (Ti-6Al-4V titanium alloy), Wang et al. took into consideration the influence exerted by cutting parameters (cutting speed, feed per tooth and depth of cut) on cutting forces, tool wear and surface integrity. They noticed the increase of the cutting forces in three directions when the cutting speed, feed per tooth and depth of cut increase also [5].

Cui et al. [3] approached a research concerning the influence of the cutting speed on cutting forces, chip formation and tool wear in high speed face milling of test pieces made of AISI H13 steel with CBN tools. They took into consideration the cutting speed variation in a wide range, namely 200 – 1200 m/min; a minimum of mechanical load was observed for a cutting speed of about 800 m/min and the authors explained this phenomenon by the distinct evolution of phenomena such are the fracture, chipping, adhesion, oxidation and thermal crack.

Guan et al. investigated the process of high speed milling for end mill, in order to elaborate a theoretical three-dimensional model which could be applied in order to calculate the cutting forces. The calculus of instantaneous chip thickness was considered in establishing the theoretical model. The software Matlab was used in order to find the correspondence between the theoretical and experimental results; a maximum error value of 7.5 % was observed between the simulation and measurement results [4].

2. THEORETICAL CONSIDERATIONS

A machining schema corresponding to the considered milling process is presented in Fig. 1. On can see that under the action of the milling tool rotation, the workpiece material is pressed up to the moment when a crack develops along the so-called shearing plane. One can approximate that the trajectory of the cutting tool corner as an arc of circle, if only the milling tool rotation is considered. In fact, due to existence of feed movement, the cutting tool corners moves along an arc of a certain type of cycloid.

The milling force could be decomposed in components placed along the axes of a coordinate system; if the coordinate system proposed by the international standard organization for the machine tools which use the computer numerical control machine is considered, the components presented in Fig. 1 could be taken into consideration. Thus, there is a component F_z, which acts along the milling tool axis, a component F_x, acting along the feed movement and a component F_y, acting along a direction perpendicular on the above mentioned two components.

The shaft on which the milling tool is assembled (by means of a milling tool holder) is affected by a torsional moment M_t.

There are many groups of factors able to affect the sizes of the milling force components and moment.

The main such groups of factors could be considered;

- mechanical properties of workpiece material (hardness, ultimate strength, shearing strength etc.);
- sizes of milling parameters (milling speed *v*, milling feed *f*, depth of cut a_p);
- geometrical parameters of the tool active zone (tool corner radius, side relief angle, side rake angle, back rake angle, side cutting edge angle, end cutting edge angle etc.);
- friction properties of workpiece and tool materials corresponding to the surfaces found in contact;
- presence, nature and properties of machining fluids;
- rigidity of the technological system components etc.

A graphical representation corresponding to a systemic analysis of process of generation the cutting / milling forces and moment is presented in Fig. 2.

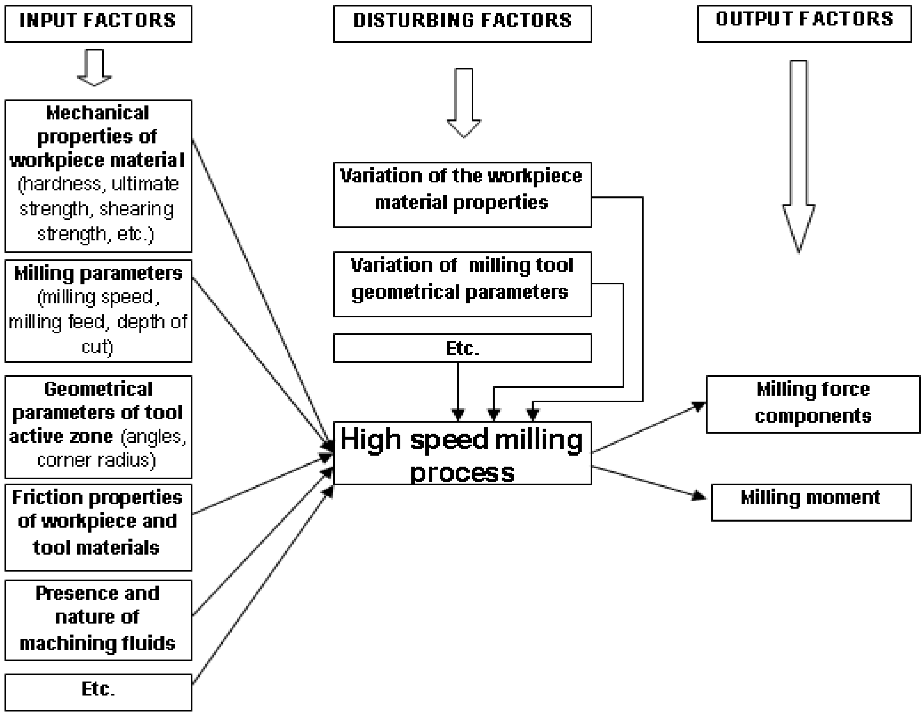

Fig. 2. Some results of systemic analysis applied to process of generation of cutting forces and moments.

As one can see, there are many factors able to exert influence on the size of milling tool forces and moment, but one can consider that some of them exert a dominant influence; within this paper, intending to develop a set of experiments concerning the milling forces and moment, one appreciated that such factors could be the workpiece material hardness and the parameters of milling process (milling speed v, milling feed f and milling depth of cut a_p).

3. EXPERIMENTAL SETUP

In order to evaluate the machinability by milling using the sizes of cutting force components, an experimental research was designed and applied.

As a machine tool, one used a FU 25 type vertical milling machine; this equipment is characterized by a high rigidity and relatively large possibilities to select the values of the milling parameters.

A Kistler type 9257B dynamometer facilitated the measurements of milling force components; this instrument has four force piezoelectric sensors placed in the corners of a rectangular surface. The measurement of forces is characterized by an accuracy of about 1% of the measured values. The software Dinowave attached to the dynamometer allows measuring and registering of milling force components variation.

Within experiments, test pieces made of two steels were used; one of these steels was the tool steel X210Cr12. By adequate heat treatment applied to test pieces, the hardness belonged to three groups: 18–22 *HRC*, 50–52 *HRC* and 58-59 *HRC*. The second material was the medium carbon steel C45U, thermal treated so that hardness was included also in three groups: 18–21 *HRC*, 25–28 HRC, 42–46 *HRC*. The second steel is sometimes used as a standard material in comparing the material machinability of metallic materials.

Table 1

Values of the process input parameters and experimental results corresponding to the test pieces made of steel X210Cr12

Exp.No.	Hardness *HRC*		Milling speed, v		Machining feed, f		Depth of cut, a_p		Cutting force components		
	Coded value	Proper value	Coded value	Proper value, m/min	Coded value	Proper value, mm/rev	Coded value	Proper value, mm	F_x, N	F_y, N	F_z, N
1	2	3	4	5	6	7	8	9	10	11	12
1	1	22	1	408.4	1	0.16	1	0.2	70.08	27.65	44.19
2	1	22	2	571.7	2	0.25	2	0.5	110.18	58.41	68.52
3	1	22	3	817	3	0.63	3	0.8	137.15	62.13	44.05
4	2	53	1	408.4	2	0.25	3	0.8	152.85	86.06	74.57
5	2	53	2	571.7	3	0.63	1	0.2	57.59	23.90	39.10
6	2	53	3	817	1	0.16	2	0.5	85.24	54.95	56.07
7	3	59	1	408.4	3	0.63	2	0.5	184.98	97.77	95.17
8	3	59	2	571.7	1	0.16	3	0.8	113.39	70.08	72.74
9	3	59	3	817	2	0.25	1	0.2	40.42	19.96	39.13

Table 2

Values of the process input parameters and experimental results corresponding to the test pieces made of steel C45U

Exp. no.	**Hardness *HRC***		**Milling speed, *v***		**Machining feed, *f***		**Depth of cut, a_p**		**Cutting force components**		
	Coded value	**Proper value**	**Coded value**	**Proper value, m/min**	**Coded value**	**Proper value, mm/rev**	**Coded value**	**Proper value, mm**	F_x**, N**	F_y**, N**	F_z**, N**
1	2	3	4	5	6	7	8	9	10	11	12
1	1	21	1	408.4	1	0.16	1	0.2	64.58	30.74	38.31
2	1	21	2	571.7	2	0.25	2	0.5	121.99	65.88	71.45
3	1	21	3	817	3	0.63	3	0.8	188.2	114.17	105.33
4	2	28	1	408.4	2	0.25	3	0.8	264.26	177.52	202.97
5	2	28	2	571.7	3	0.63	1	0.2	95.35	39.87	74.53
6	2	28	3	817	1	0.16	2	0.5	126.66	90.55	156.97
7	3	46	1	408.4	3	0.63	2	0.5	180.59	117.97	113.34
8	3	46	2	571.7	1	0.16	3	0.8	143.69	116.41	139.69
9	3	46	3	817	2	0.25	1	0.2	50.26	28.47	67.02

One adopted the test pieces shape so that they could be placed on the table of Kistler dynamometer and fix by means of clamps.

As a cutting tool, a tipped solid cutter was used; 9603A KC1 IC123 type circular carbide tips made by the company Franken were applied on the cutting tool. The tips had a thickness of 4.5 mm and a diameter of 12 mm. The carbide tips are covered with a thin layer of titanium and aluminum nitride, able to ensure a high wear resistance, inclusively in the case of materials machined at high milling speed.

The experimental setup established for measuring the sizes of milling force components could be observed in Fig. 3.

As process input parameters, one selected the test piece material hardness *HRC*, the cutting speed *v* (m/min), the machining feed *f* (mm/rev) and depth of cut a_p (mm). The values of these input parameters were established in accordance with the requirements specific to a Taguchi orthogonal array L9, with four independent variables at three levels. The values of the input parameters were included in Table 1 for the test pieces made of steel 2X210Cr13 and in Table 2 for the test pieces made of steel C45U. In both tables, the coded and proper values were mentioned.

4. EXPERIMENTAL RESULTS

The values of milling force components determined by means of the Kistler dynamometer and the attached specialized software were included in the columns No. 10, 11 and 12 for each of the steels from which the test pieces were made.

The experimental results were processed by means of the function LINEST from software Excel Microsoft Office. One preferred power type empirical models due to the fact that one can suppose that in the research interval for the input factors, a monotone variation of the forces sizes is expected; it is known that generally, after the exceeding of the speed zone where the built-up edge appears, the sizes of cutting forces are affected by a continuous diminishing at the cutting speed increase.

As a consequence of the mathematical processing of the experimental results by means of specialized software [2], the following empirical models were determined [1]:

- In the case of test pieces made of steel X210Cr12:

$$F_x = 8834.95 HRC^{0.007} v^{-0.542} f^{0.43} a_p^{0.605}, \quad (1)$$

$$F_y = 1881.42 HRC^{0.02} v^{-0.352} f^{0.376} a_p^{0.914}, \quad (2)$$

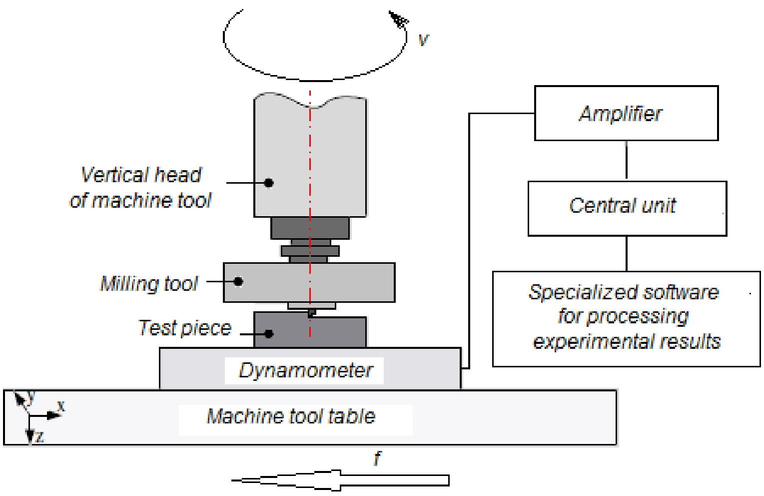

Fig. 3. Experimental setup for measuring the milling force components.

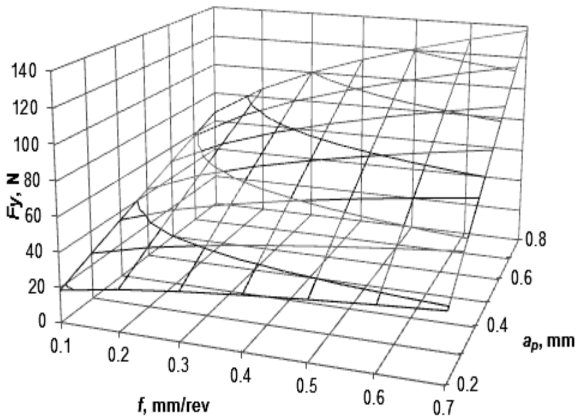

Fig. 4. Influence exerted by the machining feed *f* and depth of cut a_p on the size of component F_y, in the case of steel X210Cr12 (*HRC* = 59, *v* = 817 m/min).

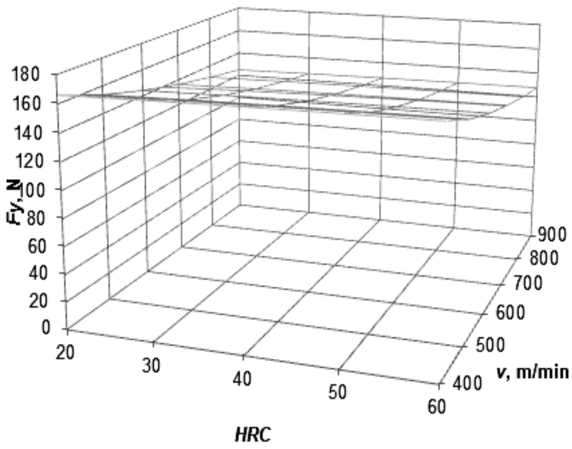

Fig. 5 Influence exerted by the hardness *HRC* and cutting speed *v* on the size of component F_y, in the case of steel X210Cr12 (*f* = 0.63 mm/rev, a_p = 0.8 mm).

$$F_z = 4.4 HRC^{0.174} v^{0.082} f^{0.217} a_p^{0.516}. \tag{3}$$

- In the case of test pieces made of steel C45U:

$$F_x = 8771.4 HRC^{0.393} v^{-0.7} f^{0.525} a_p^{0.711}, \tag{4}$$

$$F_y = 1253.93 HRC^{0.581} v^{-0.536} f^{0.445} a_p^{0.881}, \tag{5}$$

$$F_z = 169.28 HRC^{0.557} v^{-0.256} f^{0.258} a_p^{0.583}. \tag{6}$$

The mathematical empirical models were used in order to graphically highlight the influence exerted by the process input variables on the sizes of milling force components; in this way, the diagrams from Figs. 4, 5, 6 and 7 were elaborated.

In the case of steel X210Cr12, one noticed an increase of the milling forces when the workpiece material hardness *HRC*, the machining feed *f* and the depth of cut a_p increase. In the case of components F_x and F_y, one can remark a decrease of the cutting force when the milling speed *v* increase and this fact could be explained by the improvement of the chips generation, due to the increase of the material plasticity determined by higher temperatures developed in the machining zone. In the case of the component F_z, one can notice that practically the size of the cutting speed does not exert a significant influence, since the value of the exponent attached to the variable *v* is very low.

The analysis of the empirical mathematical models valid for the steel C45U confirmed the decrease of the milling forces when the cutting speed increases, due to higher temperature developed in the machining zone and increase of the workpiece material plasticity. As expected, the milling force components increase when the workpiece material hardness increases. It was also a normal situation the increase of milling force components at increase of machining feed *f* and depth of cut a_p.

If one tries to establish an order of influences exerted by the process input factors on the sizes of the milling force components, one can notice that the most significant influence is exerted by the depth of cut a_p; indeed, the values of the exponents attached to the variable a_p has the maximum value, if compared with values of exponents corresponding to other independent variables (workpiece material hardness *HRC*, cutting speed *v* and machining feed *f*).

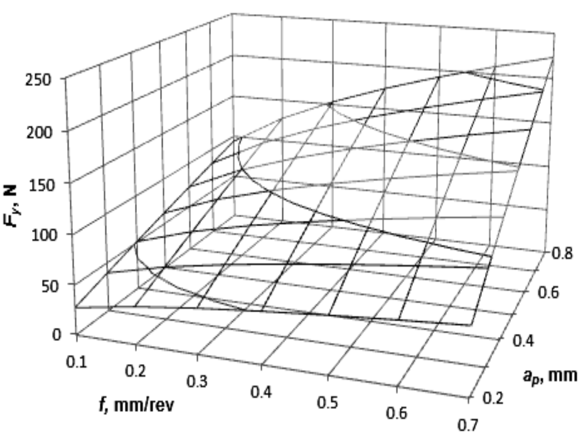

Fig. 6. Influence exerted by the machining feed *f* and depth of cut a_p on the size of component F_y, in the case of steel X210Cr12 (*HRC*=46, *v* = 817 m/min).

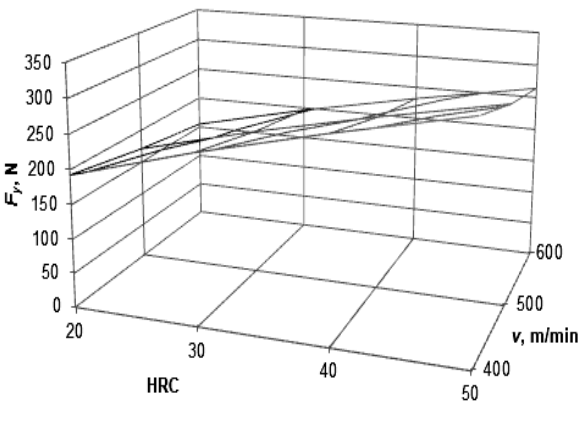

Fig. 7. Influence exerted by the hardness *HRC* and cutting speed *v* on the size of component F_y, in the case of steel C45U (*f* = 0.63 mm/rev, a_p = 0.8 mm).

In order to obtain a general image concerning the machinability by a certain machining process and using a certain criterion of evaluation, the researchers use a relative value, determined as a ratio between the absolute value of the machinability index established for the studied material and the same value established for a material etalon. As above mentioned, in the case of metallic materials and especially in case of ferrous materials, as material etalon the medium carbon steel C45U found in delivering state is frequently used.

Such a way to evaluate the relative machinability could be applied in the case of the machinability of steel X210Cr12; the relation valid for a relative index of machinability could be determined as a ratio of the relationships valid for the steels X210Cr12 and C45U:

$$I_{Fy} = \frac{\mathrm{F_{y\ X210Cr12}}}{\mathrm{F_{y\ C45U}}} = \frac{Fy = 1881.42 HRC^{0.02} v^{-\ 0.352} f^{\,0.376} a_p^{\ 0.914}}{Fy = 1253.93 HRC^{0.581} v^{-0.536} f^{\,0.445} a_p^{\ 0.881}},$$

or

$$I_{Fy} = 1.5 HRC^{0.581} v^{-0.184} f^{\,-0.069} a_p^{\ 0.033}. \quad (7)$$

The last mathematical relation highlights a similar variation of the machinability of the two studied steels, from the point of view of the size of milling force component F_y, when the machining parameters f and a_p change their values; this fact could be remarked due to the relative low values of the exponents attached to the variables f and a_p in the relation (7). The relation (7) shows also a significant difference concerning the influence exerted by material hardness *HRC* and the cutting speed v on the size of the milling force component F_y, this fact being highlighted by the high values of the exponents attached to the variables *HRC* and v in the relation (7) (Fig. 8).

5. CONCLUSIONS

One of the criteria that could be used in order to evaluate the materials machinability from the point of view of mechanical solicitations generated in the technological system is the size of the cutting force components. The objective of the research presented in this paper was to obtain more information concerning the evaluation of the machinability of some steels by high milling speed and when the criterion of cutting force is considered. The sizes of the milling force components were experimentally determined by means of Kistler dynamometer and by using a factorial experiment corresponding to a Taguchi array L9. The experimental results were processed by means of an adequate software and power type mathematical empirical relations were determined, in order to highlight the influence exerted by material hardness *HRC*, cutting speed v, machining feed f and depth of cut a_p on the sizes of the components F_x, F_y and F_z of the cutting force at end milling. The maximum milling speed was of 817 m/min. Within experiments, test pieces made of two steels (X210Cr12 and C45U) were used. The mathematical empirical models and the graphical representations elaborated on the base of these models facilitated the establishing of some remarks concerning the influence exerted by the input variables *HRC*, v, f and a_p on the size of milling force components. One discussed also some aspects concerning the possibility to use a relative index of machinability evaluation, determined as a ratio between the relations valid for the component F_y in the case of the two steels taken into consideration within the experimental research. In the future, there is the intention to extend the experimental research on other steels, in order to obtain supplementary information concerning the influence exerted by the machining conditions on the sizes of milling force components during the process of high speed milling.

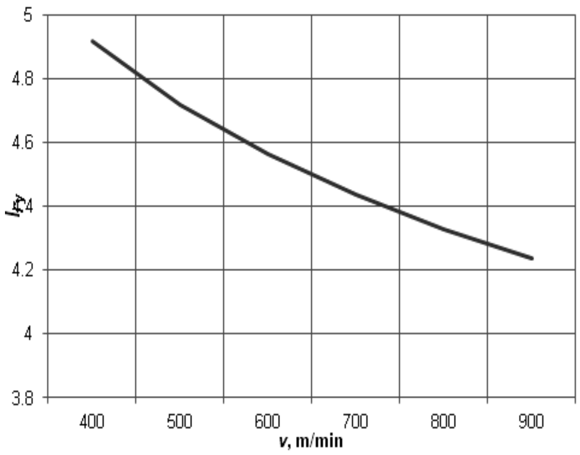

Fig. 8. Influence exerted by milling speed v on the value of the relative machinability index I_{Fy} (*HRC* = 48, f = 0.4 mm/rev, a_p = 0.5 mm).

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