EXPERIMENTAL PROCEDURE IN INDUSTRIAL ENVIRONMENT AIMING MILLING PROCESS OPTIMIZATION

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Abstract. *The emphasis in continuous improvement, prioritized by the organizations, has motivated the development of this intrinsic experiment applied to the manufactory process optimization, which involving the cutting parameters in factory floor and verifying advantages and disadvantages of the procedure used. Four variables had been used: Material's hardness of the parts and the cutting parameters of the milling process in high speed machine of hardened steel (Cutting speed, feed per tooth and cutting depth). The optimization procedure aimed to minimize the cost and/or to increase the production in the milling process of forging tools currently used. Two stages had been used: a first one based in factorial experimental procedure (delineation of experiments) and, in one second stage, experiments had been carried through for determination of the coefficients of the Taylor's equation in manufactory environment, what allowed the determination of the Maximum Efficiency Interval. The descriptive statistic analysis showed that both the cutting parameters and the hardness of the manufactory material had generated great influence in the variables of reply, those variables having been the cutting tool life, the volume of material removed until the end of the cutting tool life and the cost for part. It was possible to conclude that the method of delineation of experiments allowed optimizing the cutting process and found the base point to started the procedure of define cutting speed optimized by Taylor. Concerning to the procedure based on Taylor, though this considers only the cutting speed optimization, it was possible to carry through its optimization using a lesser number of experiments. As final result, it was obtained 10% to variance between the values optimized by the two different procedures. Finally this research allowed verifying that both methods can bring economic and technical benefits for the milling process of forging tools.*

Keywords*: High speed milling, cutting process optimization, DOE, cutting tool life*

1. INTRODUCTION

From the operating conditions, cutting depth and the feet per tooth are the most easily optimized: we can have values so closer to the best value, just pondering the machine power, the over metal dimension to be removed, the chip shape and quality of the final piece required for the specific target of the operation optimization (Diniz, Marcondes e Coppini, 2006).

The cutting speed has more significant influence on tool life, when compared with depth of cut and feed, and also it exercises larger influence on the costs and production. The cutting speed optimization allows having respectively a optimized removal chip tax and then (Coppini and Baptista, 1998).

To find the optimized cutting speed, the Maximum Efficiency Interval knowledge is one of the most convenient way. However the use of the values of (x) and (K), constants in the Taylor equation, obtained from the literature or other sources from testing laboratory under ideal conditions, has making difficult the task of optimizing the cutting speed, because are different from the reality, causing distortions in the calculation of the optimum cutting speed.

The authors consider the best option the use of these constants from its determination in a factory floor. In this case there will be greater confidence in selecting the optimum cutting speed, because the procedure will be performed in real time with the occurrence of the process, with data obtained from the own machine-tool-part, targets of the optimization.

This work aims to optimize the cutting parameters used in the milling process of engraving the dies for forge, aiming to reduce the cost of the process and the maximum efficiency of inputs such as machinery, tools and labor. It will be used for these purposes, Design of Experiment and Taylor theory.

2. MATERIALS AND METHODS

The experimental procedure was performed at the XZY Industry.

The milling tests were performed in horizontal machining center CNC, model MC 98 – A40, manufactured by Makino Inc., in 2000, projected to machining molds and matrices with power in the axis tree of 15 Kw, torque 32 N. m, programmable rotation of 200 to 15000 rpm, course of the axles x=915 mm, y=810 mm and z=750 mm, feed speed programmable of 1 to 24000 mm/min, equipped with numeric command Fanuc 16M.

The carries tools type used was HSK 100-A. Its fixing system is by thermal interference, known as Shrink Fit System, which demands a special device for fixation; it allows a maximum radial deviation of the mill cutter of 0,003 mm in high-speed centrifuges.

The cutting tools used in the tests are from the company Hanita Cutting Tools, and are recommended for use in milling, both for roughing and finishing of hardened steel. Its specification is HN44105522022S HN series of 7151, which corresponds to a mill cutter to top-edge of spherical solid carbide (micro grains). Its nominal diameter is 6 mm. Cutting tool with two edges, coating of TiNAl and angle of de helices of 15º. Its total length of 50 mm allows for sure work with the free length (balance of the tool in the process) of 27 mm. These values were determined measuring the depth of the cavity to be cut. It was possible to maintain that condition for all tests. Only new tolls were applied to each test.

The raw materials for testing, consisted of blocks of DIN 1.2367 steel, vacuum treated, with hardness from 49 to 53 HRc, supplied by Villares Metals Company. Its average chemical composition is described in Table 1 and their mechanical properties in Table 2, the data was also supplied by Villares Metals Company.

Table 1. Chemical Composition of Steel DIN 1.2367.

%C	%Si	%Cr	%Mo	%V
0.36	0.30	3.80	2.50	0.50

Table 2. Mechanical Properties of Steel DIN 1.2367.

MATERIAL	MECHANICAL PROPERTIES					
	Sut (MPa) Tensile strength	Sy (MPa) Yield Strengt	RA% Area reduction	δ % Elongation	Hardness (HRc)	Joule Impact without notch
VHSUPER (1. 2367)	1200	1000	45	20 A 25	44.5 a 48.5	250

All machining programs were to cut a cavity of a die forging used produce an automotive connecting rod.

This cavity, specified by the customer, has volume of 55,287.93 mm^3, which was completely removed by each of the different sets of cutting parameters used in the tests. The cutting parameters selection was made considering several factors: tool maker catalogs (Sandvik Coromant, 2007), Makino's training manuals, from other industries and ThyssenKrupp experiences. So it was adopted the following data: cutting speed Vc = 155 m/min; feed per toof fz = 0.1 mm; depth of cut ap = 0,3 mm; width of cut ae = 2,4. The CNC programs were always the same. Only was changed the different values of (Vc), (fz) and (ap), selected to be tested. Each program includes the machining of only one cavity.

All programs were generated with the same level of safety of 10 mm (distance of approach of the tool part in the fast forward), 5 mm as value of the plan of retreat in case of change of trajectory and 1 mm for retroaction (change of levels of machining in Z coordinate). Besides, the same attack strategy was used (the initial approach of the tool part towards coordinated Z). This strategy foresaw a propeller with a diameter twice the nominal diameter of the cutting tool and angle of entry of 2º. The movement starts from the outside of the cavity to its interior and remains all the time towards in concordance with the cutting direction movement.

It was prepared a enough number of sheets for data collection to be used by the operators. In these sheets all the details of the experiment as well the CNC program to be executed was informed.

The operator performed this program as many times as necessary until the end of tool life. Then, he wrote down the following data: cutting time for one piece, tool life in minutes to cut pieces until the failure tool (T) and quantity of pieces that had been completed. Besides, the tool wear, volume of chip removal (V) and cost per piece were written down also.

Cutting tool wear was evaluated only at the end of each program, as to say, for the last piece cut after the tool failed. It was adopted as criterion of end of life, 0.03 mm of flank wear (VB). This value was determined by the experience of operators. Normally when the wear reaches VB> 0.03 mm, the tool is nearly to break. The wear was measured by a pre-set laser system which enables a measurement of the wear into a reliable standard of accuracy.

The maximum net cutting power consumption was also monitored at each depth of cut in order to check its development and do not compromise the equipment.

Assigned end of experimental procedures the exact moment they were finished all the tests, and assessed as sufficient, the number of replication according to the results.

The DOE experiments were performed with the aid of Minitab 15 Statistical Software. This software provides tools that allow graphical analysis of the effect of fractionated factorial design, and even showing the full factorial statistical accuracy. It was used Pareto Charts to identify the factors of greatest influence on the statistics of response variables.

Another tool used was the "Response Optimizer." This tool allows identifying which combination of imputed variables induces the desired responses (Campos, 2003).

3. THEORETICAL BASES

The experience was developed in two steps: The first was for the use of DOE and the second was for the determination of Maximum Efficiency Interval, based on Taylor equation coefficients. In both steps the data were obtained in shop floor.

3.1. First stage (DOE)

The objective of using the method of design of experiments is to identify the variables of greatest influence (effect) on the cutting tool life, on the chip removed volume and the cost/piece. The results will be compared with Taylor equation coefficients determination.

This statistical approach, known as a Design of Experiments (DOE), consists in to plan experiments of to produce data appropriated for one statistical efficient analysis, which results in valid and objective conclusions (Paiva at al., 2007). The use of statistical techniques, added up to methodology of inquiry, provides, when they resulted with elevated levels of reliability and costs reduction, analyze very efficiently all the influence factors involved in the process (Ribeiro at al., 2007).

Factorial analysis was performed to split, thereby avoiding the need for carrying out further tests, which would increase the cost of the experiments (Barros Neto, Scarminio e Bruns, 2002).

For the experiments the following conditions were adopted:

- cutting fluid: dry; width ae = 40% of the cutting tool diameter; part of cutting tool balanced equal to 27mm, CNC program;
- variable response limited to wear (VB = 0.03 mm):
- chip removed volume (cm^3): obtained by multiplying the number of pieces machined by the chip removal volume of one piece;
- tool life measure in time [min];
- Cost per piece (R$) obtained through Equations 1, 2 and 3. To implement these equations were given the values of Table 3.

$$Kp = Kus + Kum + Kuf \tag{1}$$

$$Kuf = \frac{Kft}{Zt} \tag{2}$$

$$Kft = \frac{Vsi}{Nfp} + \frac{Kpi}{Ns} \tag{3}$$

Where:

Kp = production per piece cost[R$];
Kus = machining labor cost [R$];
Kuf = tool cost (depreciation, exchange, grind, etc.) [R$];
Kum = machine cost (depreciation, maintenance, etc.) [R$];
Kft = cutting tool life cost [R$];
Zt = number of pieces machined per cutting tool life;
Vsi = tool holder cost [R$];
Nfp = average tool holder life, in quantities of cutting edges;
Kpi = acquisition cost/per cutting edge [R$];
Ns = number of cutting edges/ per insert;

Table 3. Data used for calculations and its origin

Nomenclature	Values	Origination
Kus	R$ 17,09	Database Manufactures X
Kum	R$ 42,90	Database Manufactures X
Nfp	5000 min	Database Manufactures X
Vsi	R$ 530,00	Database Manufactures X
Ns	R$ 1,00	Database Manufactures X
Kpi	R$ 40,00	Database Manufactures X
Zt	As each test	

- Factors and levels of input parameters:

- Cutting speed (155 and 255 m/min), feed rate per edge (0.1 and 0.2 mm/edge), depth of cut (8 and 10% diameter of the cutting tool), hardness of the material (49 and 53 HRC);

- Format design of experiment: Fractionated 2^4 Factorial and 0 Midpoint (8 rounds).

3.2. Second stage (Determination of Maximum Efficiency Interval)

Based in the results obtained in the first stage some data were followed, as (Santos, At al., 2005 and Baptista, Coppini, 2002):

- best machining conditions determinate (cutting speed, feed rate per edge, and depth of cut): obtained when was searching for the cutting conditions to maximize the chip removed volume, cutting tool life and minimize the cost per piece;
- as the first cutting speed Vc1 was choose155 m/min and its tool life (T1), according the results from DOE;
- the second cutting speed Vc2 was calculated as 20% bigger than Vc_1 and keeping the same values for all others cutting condition and the same tool life criterion, tests were done to determinate tool life (T2);
- with these data, the constant K and the coefficient x of Taylor tool life equation were calculated in accordance with the equations 4 and 5 (Dinis, Marcondes and Coppini, 2006).

$$x = \frac{\log\left(\frac{T_1}{T_2}\right)}{\log\left(\frac{V_{c1}}{V_{c2}}\right)} \tag{4}$$

$$K = T_1.V_{c1}{}^{x} \tag{5}$$

Where:

T_1 = cutting edge life for Vc_1 [min];
T_2 = cutting edge life Vc_2 [min];
Vc_1 = First cutting speed [m / min];
Vc_2 = Second cutting speed [m / min];

Obtained the coefficients of Taylor equation, was possible to calculate the cutting speeds of minimum cost (V_{co}) and maximum production (V_{cmxp}) through equations 6 and 7 as shown below (Batista e Coppini, 2002 e Dinis, Marcondes e Coppini, 2006).

$$V_{co} = \left\{ \frac{K.(Sh+Sm)}{60.(x-1).\left[Kft + \left(\frac{Sh+Sm}{60}\right).tft\right]} \right\}^{\frac{1}{x}} \tag{6}$$

$$V_{cmxp} = \sqrt[x]{\frac{k}{(x-1).tft}} \tag{7}$$

Where:

t_{ft} = cutting edge change time [min];
S_h = man (operator) cost [R$/h];
S_m = cost time / machine [R$/h];

3. RESULTS AND DISCUSSIONS

3.1. First Stage - DOE

The matrix of design of experiments and their results is presented in Table 4. It is possible to observe, after the experiments, that material hardness seen as an influence factor.

Table 4. Parameters tested X obtained Answer

Blocks	Vc [m/min]	fz [mm/tooth]	ap [mm]	Material hardness [HRc]	Life [min]	Chip removed volume [mm3]	Cost/Piece [R$]
1	255	0,2	0,48	49	39,2	221152	70,021
1	155	0,1	0,48	49	309,1	608167	63,641
1	255	0,2	0,6	53	15,6	110577	80,048
1	255	0,1	0,6	49	75	276440	68,016
1	155	0,1	0,6	53	136,8	331728	66,679
1	155	0,2	0,6	49	150	663455	63,337
1	155	0,2	0,48	53	31,2	110576	80,048
1	255	0,1	0,48	53	57,6	165864	73,363

Where, for convenience, it will be used the following notation:

Vc (cutting speed)	A
fz (feed rate per tooth)	B
ap (depth of cut)	C
Material hardness	D

It is clear the greater influence of factor A (Vc) over tool life, followed by B factor (fz), then D (hardness). It can be seem also an important influence when the interaction of A (Vc) with D (hardness) in Figure 1a is considered. This enhances the influence of hardness on tool life (statistical accuracy 96.13%).

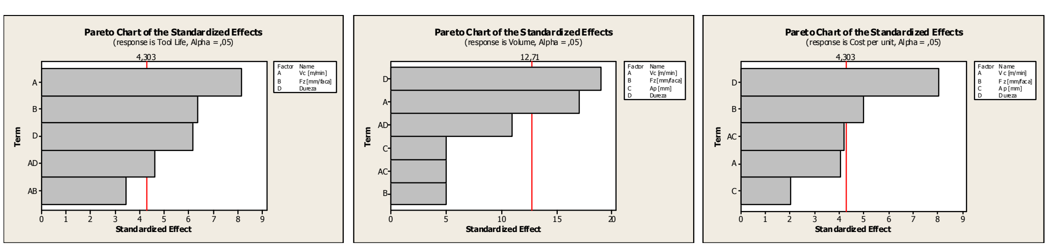

Figure 1. Pareto plot approach for Tool life (a), Volume (b) and cost per unit (c) ware produced for answer for the Minitab

The analysis of response shows that the the material hardness is the factor of greatest influence in relation to the chip remove volume, followed closely by the cutting speed as shown in Figure 1b (statistical accuracy 99.17%).

The analysis of response about cost per piece shows that the material hardness is the factor of greatest influence in relation to cost followed by the knife as shown in step 1c (statistical accuracy 94.59%).

The cutting speed has actually be the factor of greatest influence on the results of both time and volume. About the response relating to cost per piece, the hardness of the material proved to be the factor of greatest influence over the chip removed volume followed by cutting speed. About tool life, the cutting speed continued showing greater influence in the response, followed closely by the factors feed per tooth, and material hardness. In response of cost per piece, the material hardness showed again to be the biggest factor of influence, this time followed by the factor of feed per tooth.

3.1.1. Evaluating Best Answers

The influence of hardness in the responses is a factor that should be considered.

Knowing that the tolerance to material hardness is from 49 to 53 HC (tolerance of project) will be adopted in the optimization procedure only the higher value was considered, as a factor of safety about the conditions to be recommended for use as optimization results.

Valuing the answers using the resource "response optimizer" in the material of bigger hardness, according to figure 2, aiming to maximize cutting tool life and chip removed volume and to minimize the cost per units, we found:

Vc = 155 m/min
Ap = 10% of the diameter of the tool (0.6 mm)
Fz = 0.1 mm / edge

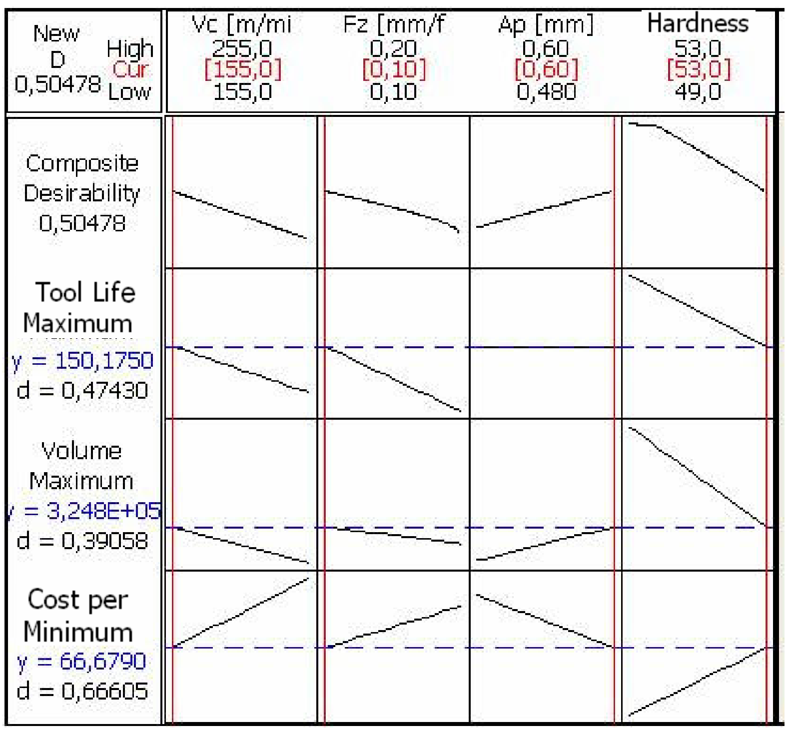

Figure 2. Answers using the output of the "response optimizer"

The graphic, in Figure 2, demonstrates that the cutting tool life reduces as Vc is increasing, lessen with the increase of fz and it remains relatively stable with the variations of ap. So maximum value of ap could be used as an optimized result. This information ratifies what describes the consulted literature, and it is accepted as true.

The chip removed volume also lessens with the increase of Vc. This is a perfectly understandable fact because tool life also decrease due to the increase of Vc. So, the number of pieces machined/toll life decreases and, consequently, the chip removal volume became smaller. With the increase of fz this volume also reduces for the same reason presented regarding to Vc. In the other hand, with the increase of ap, an increase takes place in the chip removed volume, since ap does not present high influence over tool life.

The best conditions for the cost per piece are the minor value of Vc, minor value of fz and bigger value of ap.

This analysis justifies the presented results, where we have Vc, fz minimum and ap maximum.

3.2. Second Stage - Maximum Efficiency Interval Determination

For x and K determination were used the best cutting conditions found by the method of design of experiment, as already mentioned on Materials and Methods. As shown, the best conditions are: cutting speed = 155 m/min, depth of cut= 0.6 mm and feed per tooth = 0.1 mm/rot. So these values will be used as the initials data for the Maximum Efficiency Interval determination, as proposed above.

So:

$Vc_1 = 155$ m/min
$T_1 = 136.8$ min

Again, following the proposed procedure to Maximum Efficiency Interval, another test was done for the second cutting speed Vc2 = 1.2 *Vc1. The test showed T2=77,2 min. So:

$Vc_2 = 186$ m/min
$T_2 = 77.2$ min

Replacing these values in equations 4 and 5 is possible to find:

$x = 3.1$
$K = 10.2 \times 10^7$

3.2.1. Determination of Maximum Production Cutting Speed (Vcmxp)

To determine the maximum production cutting speed is considered that the change tool time (tft) is 15 min. This value was obtained in the real working environment, timing the activity during its accomplishment.

By using this information and the values of x and K determined above, and following the equation 6 above is possible to calculate Vcmxp as:

Vcmxp = 246 m/min

As this value is outside of the cutting speed interval used for the coefficients determination [155,186], the maximum cutting speed must be considered or another test using a new cutting speed interval, for instance [186,223], or to consider a maximum value of 10% about the largest cutting speed (186 m/min) as an extrapolation to adopt the cutting speed of maximum production in an approximate way as 205 m/min.

It is good remembering that this work has the objective to optimize the process and reduce costs, so the maximum production cutting speed is presented only to give consistence to the proposed procedure of x and K determination. In this paper only the minimum cost cutting speed will be considered. This is because the actual target is the cost and not the question of a machine bottleneck analyze.

3.2.2. Determination of Minimum Cost Cutting Speed (Vco)

Before determining the minimum cost cutting speed is necessary to know the tool cost for cutting tool life (Kft), which is obtained by replacing in equations 3 the values presented in table 6. After the calculation was found that the (Kft) value is:

Table 6. Data to be used for Vco calculation

Nomenclature	Values	Origination
Nfp	5000	Database Manufactures X
Vsi	R$ 530,00	Database Manufactures X
Kpi	R$ 40,00	Database Manufactures X
Ns	1	Database Manufactures X

Kft = R$ 40,11

Others required information to Vco calculation are presented in table 7:

Table 7. Data to be used for Vco calculation

Nomenclature	Values	Origination
hour/man	R$ 17,09	Database Manufactures X
hour/machine	R$ 42,90	Database Manufactures X
tft	15 [min]	Timed
x	3,137975334	calculated
K	1021628361	calculated

Replacing these values in the equation 7 we have:

Vco = 162 m/min

The Vco value was found to be in the interval [155,186] used to its determination with data from the shop floor. So, is a very reliable value.

From data in table 8 is possible to compare the cut parameters found during these experiences with previously used to cut this piece.

Table 8. Cutting conditions before and after the experiences

	Cutting Conditions Before the Experiences	Cutting Conditions After the Experiences
Cutting Speed [m/min]	155	162
Depth of Cut [mm]	0,3	0,6
Feed Rate per Tooth [mm/rot]	0,1	0,1

It is possible to see that the cutting speed (155 m/min) and depth of cut (0,3) were respectively inferior to the minimum cost speed found during Taylor tests (162 m/min), and inferior to depth of cut (0,6) found during DOE tests. It is possible to see as well, that the feed of rate per tooth was found to be the same, as to say, the minor values between the tests used in the experiences.

The consequence of the adoption of these new cut conditions is that an increase of 64 % observed on the efficiency of the process. This occurred because costs were reduced and productivity was increased with the new cutting condition.

It is important to stand out that the new optimized cut conditions are in use by the industries at this moment.

4. CONCLUSION

From the results of this work it was possible to conclude that the two procedures used to optimize the cutting conditions (DOE and x and K determination), presented relatively near values. For practical or even scientific effect, the difference between the considered values can be considered normal and inside the expectation of mistakes accumulated during the attainment and the handling of data, or even of respected hypotheses.

The use of two proceedings is relatively exhaustive. It presents an advantage of allowing optimizing the values of cut parameters under hardness influence simultaneously. Although it is possible to optimize depth of cut and feed rate per tooth safely considering only the machine, tool and piece system constraints. The hardness must be determined by project and its imperative the material reception control to ensure its value.

It is important to point out that the work does not suggest that two proceedings must be always used. In fact, the work adds his contribution while showing that the cutting process optimization based on Taylor's equations determination, was ratified by the proceeding of DOE

The cutting process optimization based on Taylor's equation was showed to be less exhaustive than DOE. Besides, it needed only two tests instead of eight.

To apply the optimized cutting conditions bring to the industry an increase of 64% in process efficiency.

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6. RESPONSIBILITY NOTICE

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